How Accurately Should We Calibrate a Massive MIMO TDD System?

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Introduction

- **CSIT acquisition in Massive MIMO**
  - Large overhead if feedback CSIT from UE
  - Exploiting channel reciprocity in TDD system
  - Tx/Rx RF chains are not symmetric

- **TDD calibration**
  - Calibration stage: estimate calibration matrix
  - Beamforming stage: apply the calibration matrix on instantly measured UL channel to obtain CSIT

- **CSIT accuracy**
  - What are the joint impact of calibration matrix and UL CSI on CSIT?
  - What are their joint impact of on beamforming performance?
  - How accurately should we calibrate a Massive MIMO TDD system?
Calibration System Model

- Mx1 MISO system

\[
\begin{align*}
h^{T}_{A \to B} &= r_{B} c^{T} T_{A} \\
h_{B \to A} &= R_{A} c t_{B}
\end{align*}
\]

\[
h^{T}_{A \to B} = h^{T}_{B \to A} F
\]
Figure 1: Measurement of $F$ for a 4x1 MISO system on 300 different carriers.

CSIT Accuracy and Beamforming Performance

Joint Impact of UL CSI accuracy and calibration matrix accuracy on CSIT

UL CSI Accuracy  →  CSIT Accuracy  →  Beamforming Performance

Calibration Matrix Accuracy  →  CSIT Accuracy

Joint Impact of UL CSI accuracy and calibration matrix accuracy on beamforming performance
CSIT Accuracy

\[
\overline{\text{MSE}} = \frac{1}{M} \mathbb{E}_{h_{B \to A}, s_B, n_A} \left[ \| \hat{F}^T \hat{h}_{B \to A} - h_{A \to B} \|^2 \right]
\]

\[
= \frac{\sigma_{n,A}^2}{ML_B} \text{Tr} \left\{ F^T F^* \right\} + \frac{1}{M} \text{Tr} \left\{ \Delta F^T \left( V + \frac{\sigma_{n,A}^2}{L_B} I \right) \Delta F^* \right\} + \frac{\sigma_{n,A}^2}{MT_B} \text{Tr} \left\{ F^T \Delta F^* + \Delta F^T F^* \right\}
\]

where

\[ V = \mathbb{E} [ h_{B \to A} h_{B \to A}^H ] \]

\[ \hat{F} = F + \Delta F \]

\[ \sigma_{n,A}^2 \] is the variance of circular-symmetric complex Gaussian noise at A.

\[ L_B \] is the number of symbols used for UL channel estimation.
Figure 2: Calibrated CSIT averaged MSE as a function of UL CSI accuracy and calibration matrix accuracy in a 64x1 MISO system (LB = 10).
Figure 3: Conjugate beamforming SINR loss (in dB) due to joint impact of estimated $F$ and UL channel estimation inaccuracy in a 64x8 system with DL SNR=0dB (LB = 10).

Figure 4: ZF beamforming SINR loss (in dB) due to joint impact of estimated $F$ and UL channel estimation inaccuracy in a 64x8 system with DL SNR=0dB (LB = 10).
Figure 5: Conjugate beamforming SINR loss (in dB) due to joint impact of estimated $\mathbf{F}$ and UL channel estimation inaccuracy in a 64x8 system with DL SNR=20dB (LB = 10).

Figure 6: ZF beamforming SINR loss (in dB) due to joint impact of estimated $\mathbf{F}$ and UL channel estimation inaccuracy in a 64x8 system with DL SNR=20dB (LB = 10).
Conclusions

- **CSIT accuracy**
  - To improve CSIT, more resources should be allocated to the limiting factor.

- **Conjugate vs. ZF beamforming**
  - ZF is more sensitive than conjugate beamforming to the inaccuracy of calibration matrix and UL channel estimation, especially in high DL SNR region.

- **System design tool**
  - Given a certain beamforming SINR loss target, a calibration matrix and UL channel estimation accuracy can be derived.