ICASSP SPCOM
19/04/2018

# How to Interconnect for Massive MIMO Self-Calibration?

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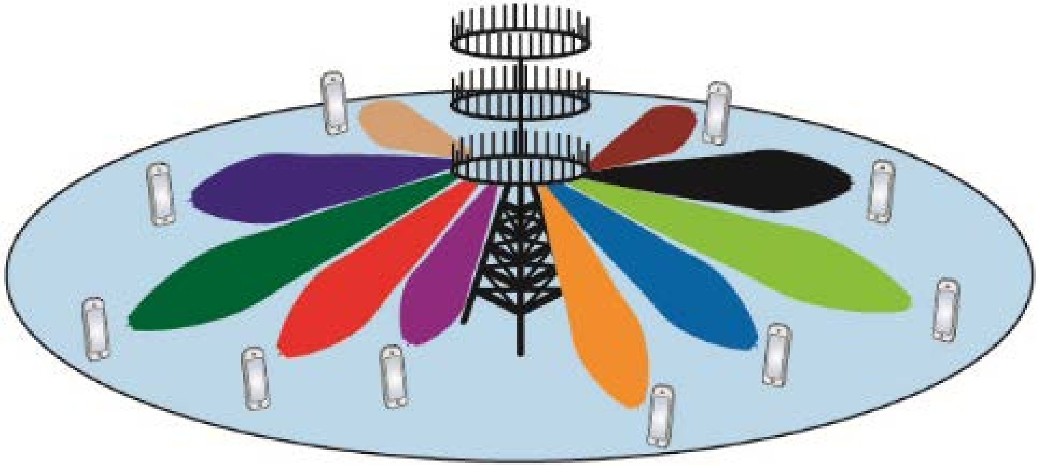
# Massive MIMO

- Massive MIMO [1]
  - Bring significant spectral efficiency gains
  - Channel estimation is important
  - TDD reciprocity: DL channels can be obtained by UL channel estimation
  - mmWave+ massive MIMO

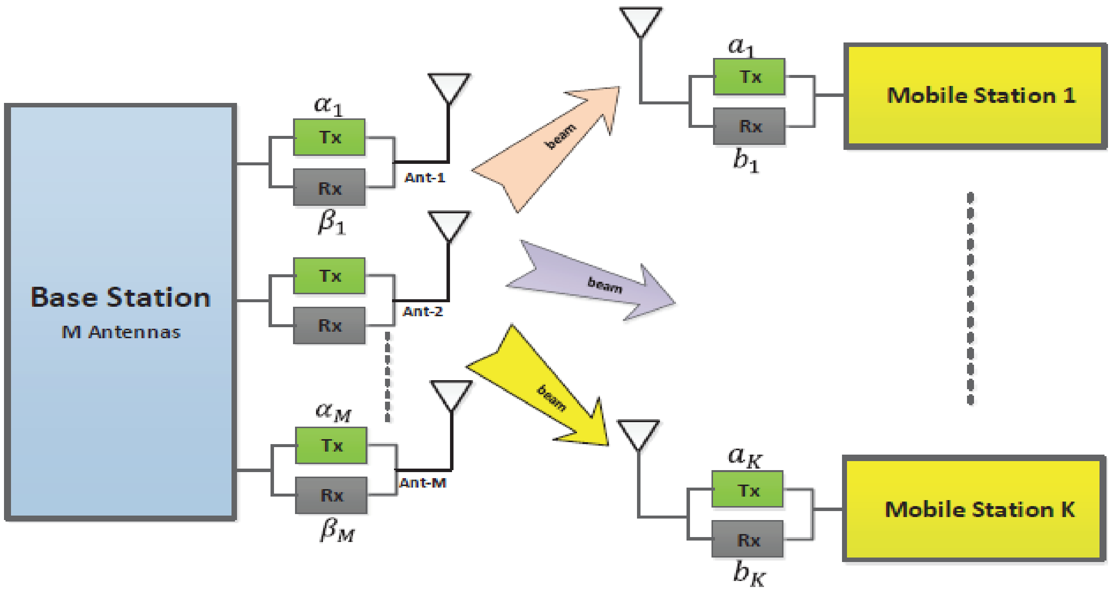


[1]E. G. Larsson, O. Edfors F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186-195, Feb. 2014.

# Massive MIMO Calibration

## Calibration in Massive MIMO [5]

- DL & UL channels: $H_{DL} = R_{MS} H_{PHY} T_{BS}, H_{UL}^{T} = T_{MS} H_{PHY} R_{BS}$
- TDD reciprocity is broken: RF mismatches
- Calibration is needed




[5] H. Wei, D. Wang, H. Zhu, J. Wang, S. Sun, and X. You, "Mutual coupling calibration for multiuser massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 606-619, Jan. 2016.

# Motivation

- Self-calibration vs. MS-aided calibration [5]
  - Self-calibration: Deployed at the BS using mutual coupling effects [5] or hardware interconnections [7]
  - MS-aided calibration: Signal exchanges between BS and MSs
- Self-calibration using hardware interconnections
  - Higher robustness and reliability (e.g. mmWave System)
  - Effective and stable
- No works addressing the optimal interconnection strategy via hardware interconnections

[7] A. Benzin and G. Caire, "Internal self-calibration methods for large scale array transceiver software-defined radios," in *Proc. IEEE Int. ITG Workshop Smart Antennas*, Berlin, Germany, Mar. 2017, pp. 1-8.

# Challenges and Contributions

## ☐Challenges:

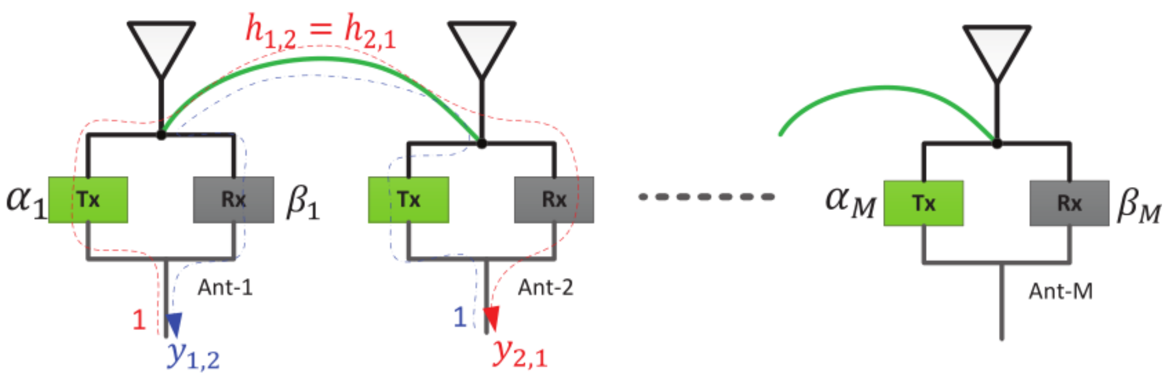
- The number of effective interconnection strategies becomes large when the number of antennas goes to large
- Exhaust searching for optimal interconnection strategy is not practical

## ☐Contributions:

- Under different constraints, this paper proved the optimality of star interconnection and daisy chain interconnection

# System Model

- System Model: (Self-calibration & hardware interconnections)
  - the received signal at the p-th antenna:




$$y_{p,q} = \beta_p h_{p,q} \alpha_q + n_{p,q} \Rightarrow \boldsymbol{Y} = \boldsymbol{RHT} + \boldsymbol{N}$$

- Optimization Problem: e.g. full calibration

$$[\widehat{\boldsymbol{\alpha}}, \widehat{\boldsymbol{\beta}}] = \arg\min_{\boldsymbol{\alpha},\boldsymbol{\beta}} \frac{1}{2} \|\boldsymbol{Y} - \boldsymbol{RHT}\|_F^2$$

# Calibration Methods

$$[\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\beta}}] = \arg\min_{\boldsymbol{\alpha},\boldsymbol{\beta}} \frac{1}{2} \|\boldsymbol{Y} - \boldsymbol{RHT}\|_F^2$$

- Calibration methods:
  - Select an antenna as the reference antenna, the calibration coefficients can be obtained via some intuitive algorithms [7].
  - The ML solution of the optimization problem can be solved by EM algorithm [10].
  - Note that we do not need the values of calibration channels, i.e. $h_{p,q}$ and the values of the transmit/receive gains of the reference antenna.

[10] J. Vieira, F. Rusek, O. Edfors, S. Malkowsky, L. Liu, and F. Tufvesson, "Reciprocity calibration for massive MIMO: Proposal, Modeling, and Validation," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 3042-3056, May 2017.

# Interconnection Strategy

- Different interconnection results in different calibration performance [7].
- What is the optimal interconnection strategy that minimizes the average CRLB?
- CRLB analysis:
  - Assuming $(M-1)$ transmission lines, the CRLB matrix for an interconnection strategy $H$ is [10] :

$$CRLB(\theta|H) = J^{-1}(\theta)$$

where $J^{-1}(\theta) = \frac{1}{\sigma_n^2}\begin{bmatrix} A & D^H \\ D & B \end{bmatrix}$, with $D = \mathrm{Diag}\{\beta\}(\bar{H} \odot \bar{H}^*)\mathrm{Diag}\{\alpha^*\}$, $A$ and $B$ are diagonal matrices.

# Closed-Form CRLB

- **Assumptions:** to focus on the interconnection strategy, we make the following assumptions
  - AS-1: all the transmission lines have the same length and damping, i.e. $h_{p,q} = h$ [7].
  - AS-2: the transmit and receive RF gains exhibit equal amplitudes, i.e. $= |\alpha_m| = a, |\beta_m| = b, \forall m \in [1, M]$.

- Closed-Form CRLB Expressions:

$$CRLB(\alpha_m) = d_m \frac{\sigma_n^2}{b^2|h|^2}, \; CRLB(\beta_m) = d_m \frac{\sigma_n^2}{a^2|h|^2},$$

where $d_m$ represents the number of antennas along the calibration path of an ordinary antenna excluding the reference antenna.

# Closed-Form CRLB

## ☐ Closed-Form CRLB Expressions:

$$CRLB(\alpha_m) = d_m \frac{\sigma_n^2}{b^2|h|^2}, \; CRLB(\beta_m) = d_m \frac{\sigma_n^2}{a^2|h|^2},$$

- $d_m$: reveals the error propagation effect
- $\frac{\sigma_n^2}{b^2|h|^2}, \frac{\sigma_n^2}{a^2|h|^2}$: represents the SNR in the measurements

## ☐ The closed-form CRLB shows:

- the CRLB is minimized when $d_m$=1, i.e. all the antennas are directly interconnected to the reference antenna ( the star interconnection)

# Optimal Interconnection

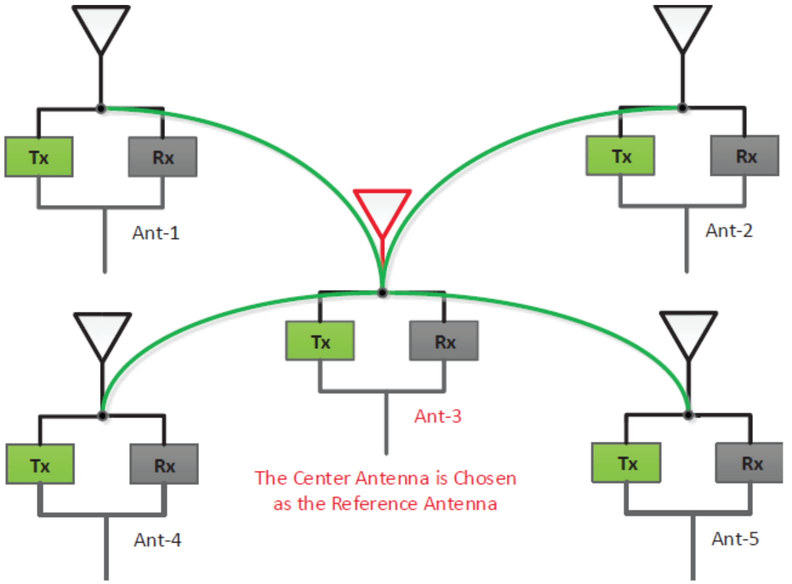
## Optimality of Star Interconnection

- Assuming $2(M-1)$ calibration measurements are available, under AS-1 and AS-2, the star interconnection minimizes the average CRLB for all the unknown calibration coefficients.

- CRLBs for Star Interconnection:

$$CRLB(\alpha_m) = \frac{\sigma_n^2}{b^2|h|^2}$$

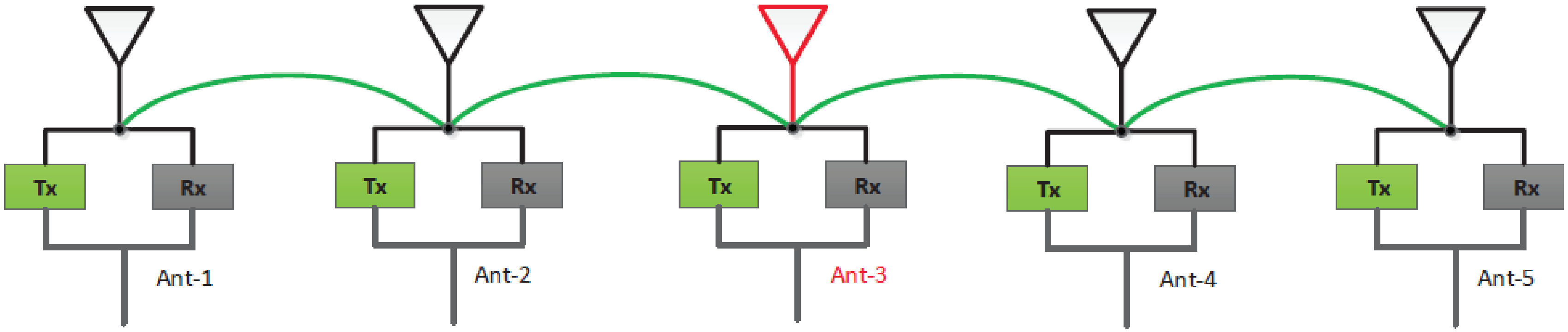
$$CRLB(\beta_m) = \frac{\sigma_n^2}{a^2|h|^2}$$



# Optimal Interconnection

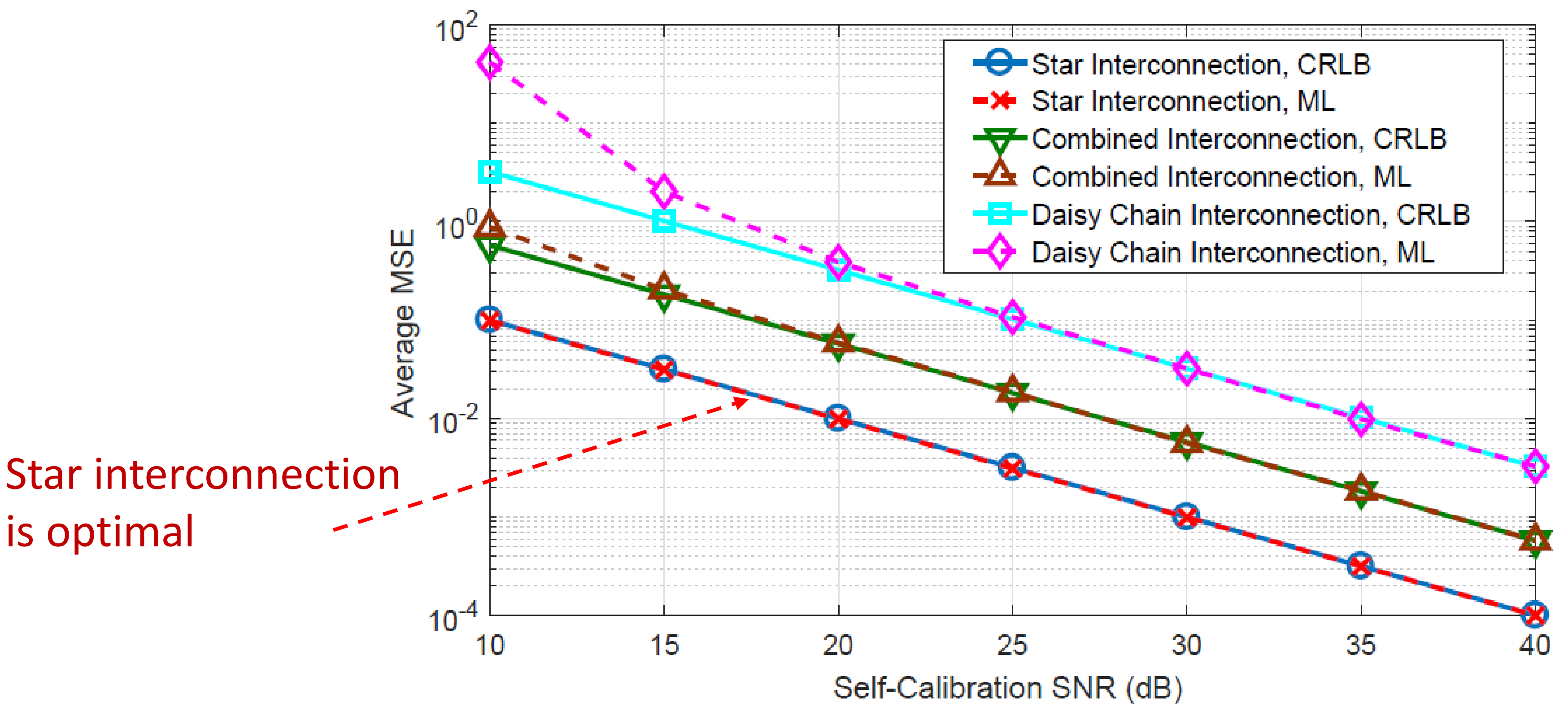
## Optimality of Daisy Chain Interconnection

- Assuming $2(M-1)T$ seconds are available to make the $2(M-1)$ calibration measurements, under AS-1 and AS-2, the daisy chain interconnection outperforms the star interconnection.
- Average CRLBs for the daisy chain interconnection can be reduced by averaging.



# Numerical Results

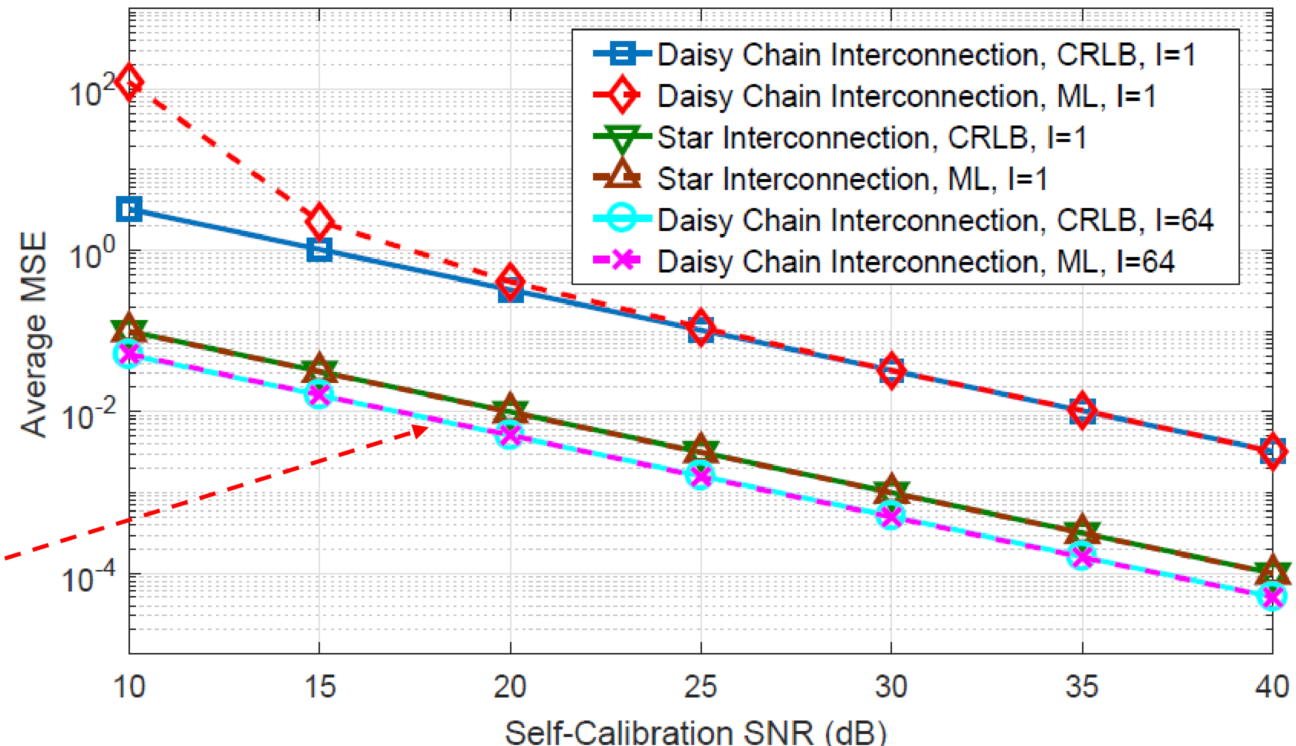
- Optimality of Daisy Chain Interconnection
  - $2(M-1)$ calibration measurements



# Numerical Results

- Optimality of Daisy Chain Interconnection
  - $2(M-1)T$ seconds for calibration measurements

Daisy chain interconnection has better performance



# Concluding Summary

- Self-calibration with hardware interconnections is an effective method for massive MIMO calibration.
- Based on the derived closed-form CRLB, we prove:
  - The star interconnection is optimal when $2(M-1)$ calibration measurements are available.
  - The daisy chain interconnection outperforms the star interconnection when $2(M-1)\mathrm{T}$ seconds are available for calibration measurements.
- The proved results can offer system designers a baseline philosophy to choose an appropriate interconnection strategy for self-calibration at the BS.

# Contact Information

*Thanks for your attention!*
*Questions?*

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