Real-time Performance Evaluation of Relative Calibration on the OAI 5G testbed.

Theoni MAGOUNAKI (ORANGE)

Florian Kaltenberger, Raymond Knopp (EURECOM)

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Outline

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- ❖ System Architecture
- ❖ Synchronization & Calibration
- ❖ OTA Reciprocity Calibration
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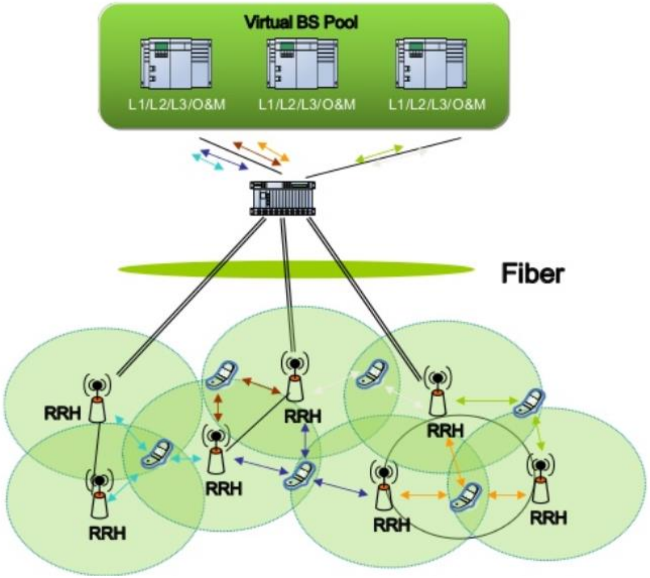
- ❖ Conclusion

Motivation

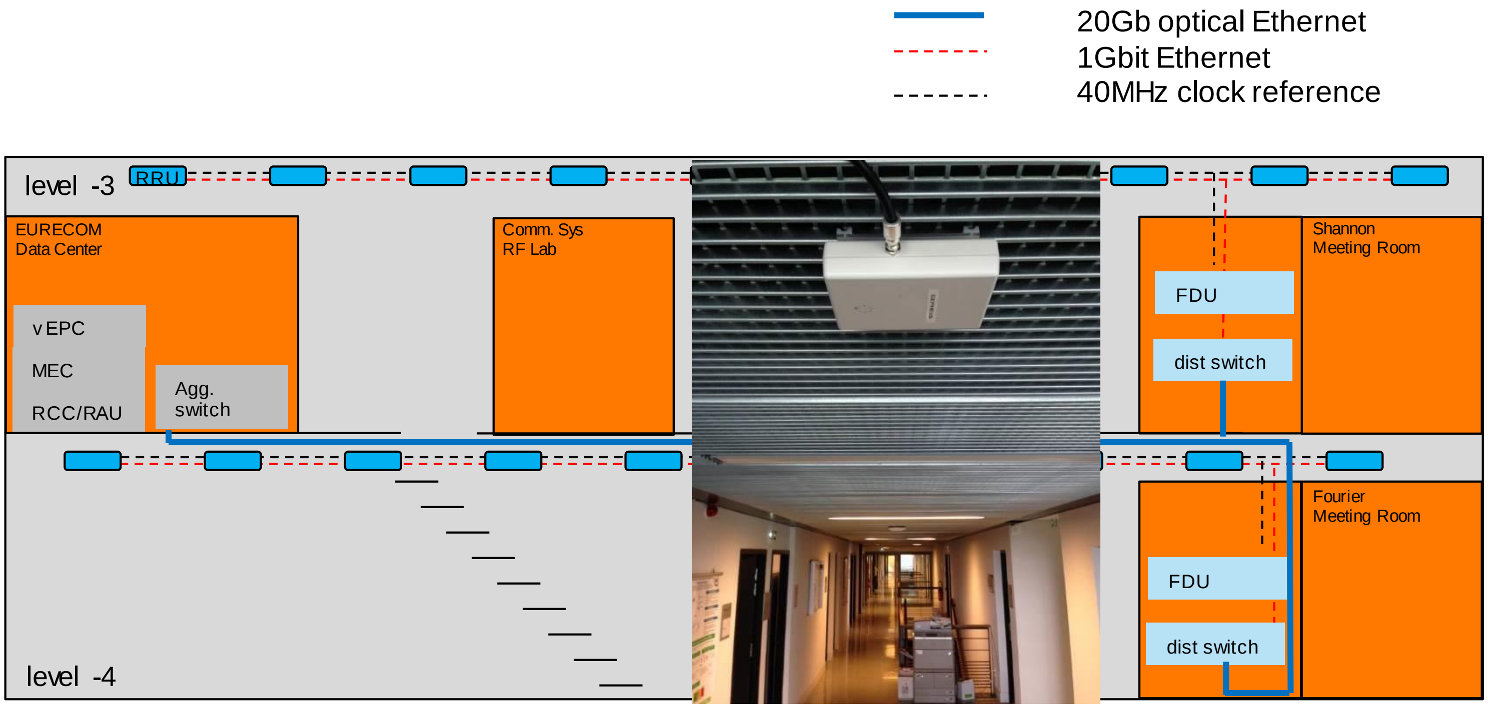
Distributed Multiuser MIMO (MU-MIMO)

- ❖ Spatially separated antennas improve indoor coverage.
  - Multiuser interference suppression through spatial precoding.
  - Dense coverage by reducing the average distance between Tx and Rx.
- ❖ Large number of Remote Radio Units (RRUs) form a distributed antenna system (DAS).
- ❖ Biggest challenges :
  - ❖ Synchronization of the RRUs
  - ❖ Reciprocity calibration in TDD.



System Architecture (1/2)

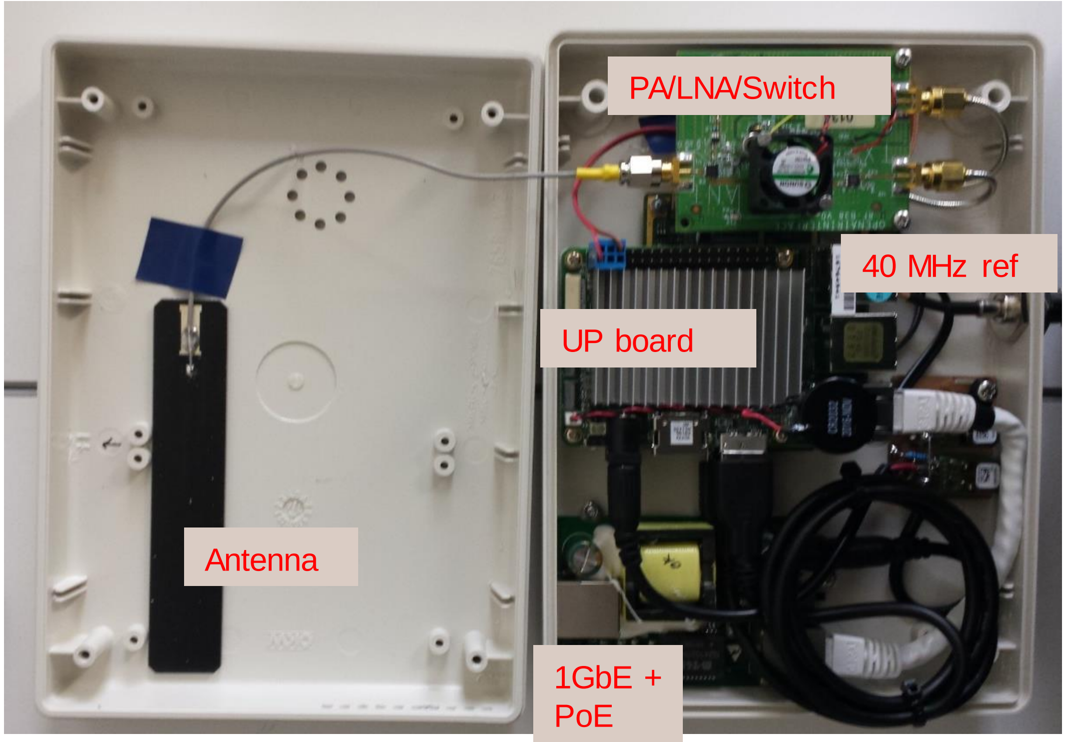
- Remote Radio Unit (RRU) : Radio transceiver – contains the RF processing circuitry.
- Radio Aggregation Unit (RAU) : Data processing unit – connects multiple RRUs to a baseband unit.
- Radio Cloud Center (RCC) : Centralized baseband processing – controls multiple RAUs.



System Architecture (2/2)

Remote Radio Unit (RRU)

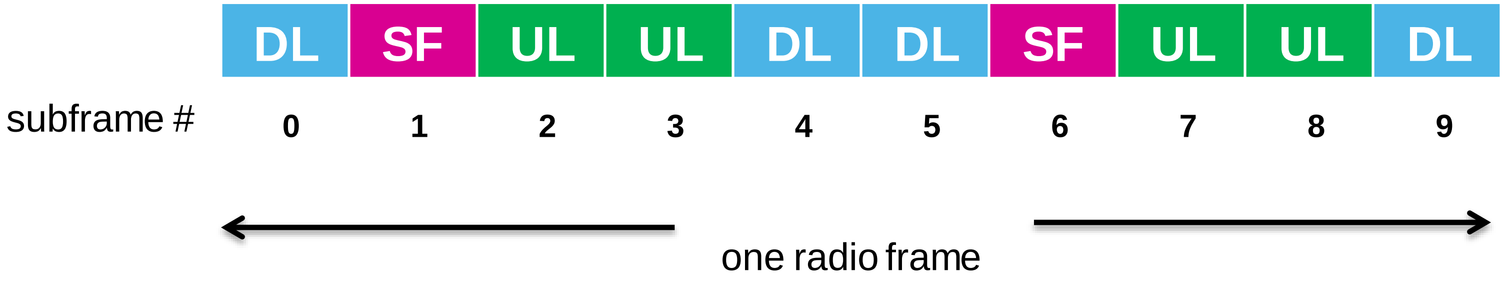
- Up-board from Intel.
- B200 mini from Ettus research.
- RF front-end designed by Eurecom.
- Band 38 (2.5GHz), TDD.
- Power Over Ethernet (POE).
- 40MHz reference for PLL



Synchronization & Calibration (1/4)

Three levels of synchronization

- Time synchronization
  - Frame alignment between RRUs up to within a sample.
- Frequency synchronization
  - Ensure that the RRUs stay synchronized in time and phase.
- Phase synchronization
  - Enable coherent transmission and precoding.
- LTE TDD configuration 1



Synchronization & Calibration (2/4)

Time Synchronization

- Over-the-air (OTA) trigger-based synchronization using a “master-slave” protocol.
  - One RRU acts as the master and the rest of the RRUs synchronize to it. (similar to eNB-UE synchronization)
  - Demodulation reference symbol (DMRS) in OFDM symbol 3 of the special subframe 1 (SF1).
  - Initial synch -> frame alignment -> slaves connect to RCC -> RCC sends back to slave RRUs frame resynchronization command

Frequency Synchronization

- All the RRUs form a single DAS.
  - RRUs have to stay synchronized in time and phase.
  - Achieved by 40MHz reference signal.

Phase Synchronization

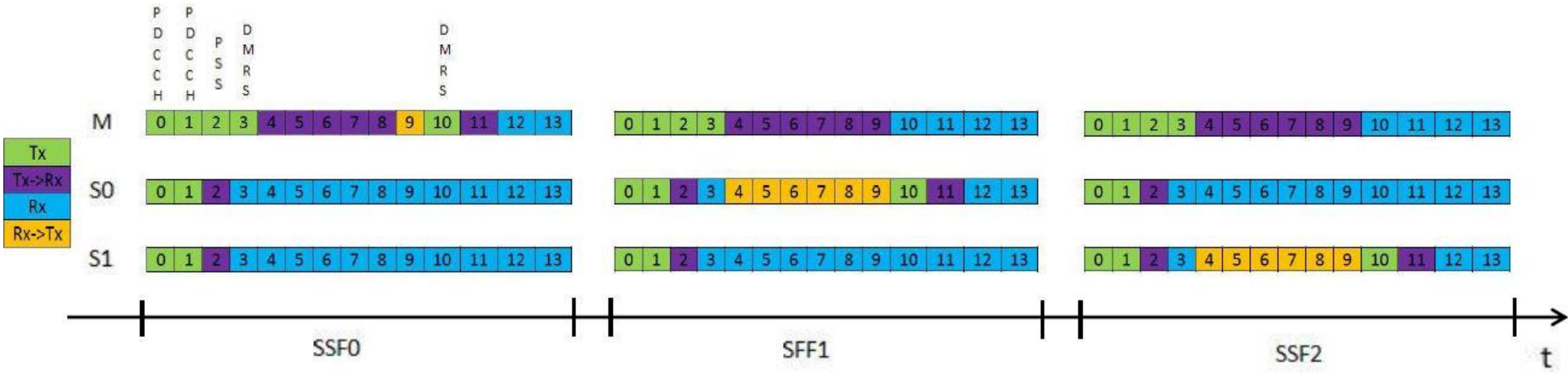
- Beamforming-capable
  - The system must maintain a known phase relationship between each RF chain.
  - Necessary for coherent transmission and precoding.
  - Achieved by reciprocity calibration.

Synchronization & Calibration (4/4)

Calibration of the C-RAN testbed

- Collect channel measurements between the master (M) and the slave RRUs (S0,S1).
- The synchronization symbol (3) is broadcasted to the slave RRUs every 10ms/frame.
- Assign a *tag* at each one of the *p* RRUs. Enable transmit mode if and only if RRU's

  tag == *frame* mod *p*



Over-the-air (OTA) Reciprocity Calibration (1/5)

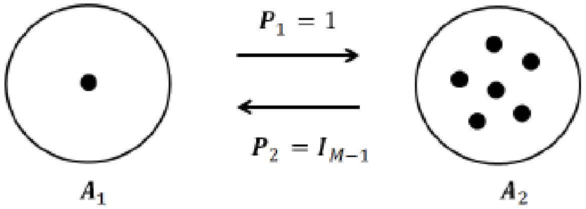
- Compensates asymmetric Tx/Rx paths as well as unknown phase offsets between RRUs.
- Allows to obtain DL Channel State Informaiton (CSI) based on UL channel estimates in TDD systems.
- Many works on reciprocity calibration. (Argos, Rogalin, Avalanche)
- Our work is based on a recently developed framework for fast calibration generalizing all these methods. [1]

[1] Jiang, X.; Decunringe, A.; Gopala, K.; Kaltenberger, F.; Guillaud, M.; Slock, D. & Deneire, L., "A Framework for Over-the-air Reciprocity Calibration for TDD Massive MIMO Systems," *IEEE Trans. on Wireless Communications,* July 2018

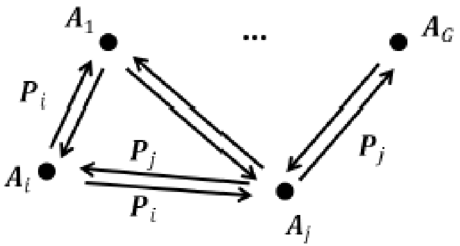
Over-the-air (OTA) Reciprocity Calibration (2/5)

Existing Calibration Methods

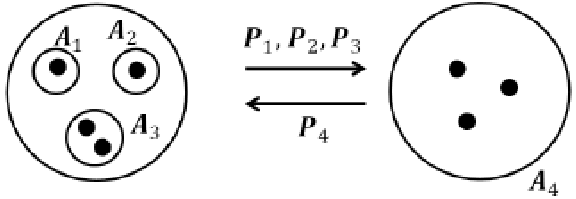
- ❖ Argos : Bidirectional transmissions between the reference antenna and the other antennas.



- ❖ Rogalin et al. : Bidirectional transmissions between each pair of antenna elements.



- ❖ Avalanche : Use already calibrated antenna elements to calibrate the uncalibrated ones.

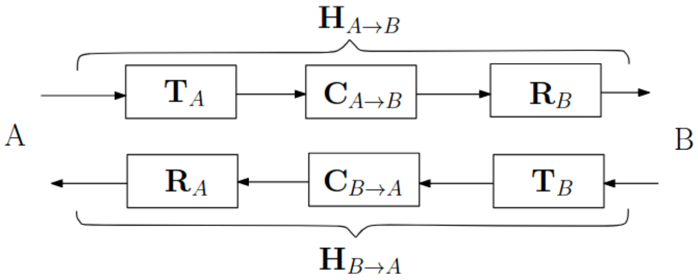


Over-the-air (OTA) Reciprocity Calibration (3/5)

Relative Calibration Scheme

- Calibration phase
  - Collect measurements.
  - Mainly the calibration at the BS side restores the hardware asymmetry.
  - Focus on the estimation of F_A .

- Data transmission phase
  - Measure UL channel.
  - Estimate DL channel.
  - Perform beamforming algorithms.



The measured UL and DL channels are modeled as :

$$H_{A\to B} = R_B C_{A\to B} T_A$$
$$H_{B\to A} = R_A C_{B\to A} T_B$$

Eliminate the physical channel **C** since we operate within the channel coherence time

$$\mathbf{H}_{A\to B} = \underbrace{\mathbf{R}_B \mathbf{T}_B^{-T}}_{\mathbf{F}_B^{-T}} \mathbf{H}_{B\to A}^{T} \underbrace{\mathbf{R}_A^{-T} \mathbf{T}_A}_{\mathbf{F}_A}$$

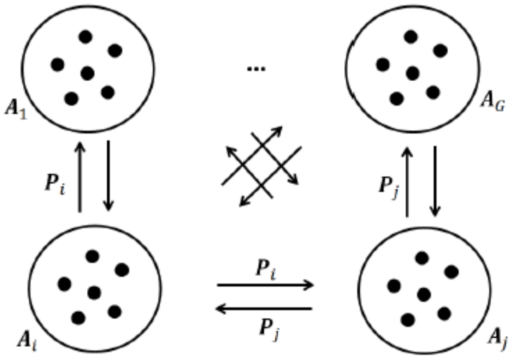
Over-the-air (OTA) Reciprocity Calibration (4/5)

Reciprocity calibration framework

- Bi-directional transmissions of pilots between RRU groups.

$$\mathbf{P}_i \in \mathbb{C}^{M_i \times L_i}$$

- When a group of RRUs transmits, all other groups are considered in receiving mode.



G : # groups
M : # RRUs
L : # channel uses

Received signal at RRU groups *i* and *j* :

$$\begin{cases} \mathbf{Y}_{i\to j} = \mathbf{R}_j \mathbf{C}_{i\to j} \mathbf{T}_i \mathbf{P}_i + \mathbf{N}_{i\to j} \\ \mathbf{Y}_{j\to i} = \mathbf{R}_i \mathbf{C}_{j\to i} \mathbf{T}_j \mathbf{P}_j + \mathbf{N}_{j\to i} \end{cases}$$

Eliminate the physical channel **C** :

$$\mathbf{P}_i^T \mathbf{F}_i^T \mathbf{Y}_{j\to i} - \mathbf{Y}_{i\to j}^T \mathbf{F}_j \mathbf{P}_j = \tilde{\mathbf{N}}_{ij}$$

The vectors of the diagonal coefficients of the calibration matrix :

$$\mathbf{F}_i = \mathrm{diag}\{\mathbf{f}_i\}$$

Vectorize into :

$$(\mathbf{Y}_{j\to i}^T * \mathbf{P}_i^T)\mathbf{f}_i - (\mathbf{P}_j^T * \mathbf{Y}_{i\to j}^T)\mathbf{f}_j = \tilde{\mathbf{n}}_{ij}$$

Over-the-air (OTA) Reciprocity Calibration (5/5)

- Collect sets of measurements in

$$\mathcal{Y}(\mathbf{P})\mathbf{f} = \tilde{\mathbf{n}}$$

$$\mathcal{Y}(\mathbf{P}) = \underbrace{\begin{bmatrix} (\mathbf{Y}_{2\to1}^T * \mathbf{P}_1^T) & -(\mathbf{P}_2^T * \mathbf{Y}_{1\to2}^T) & 0 & \cdots \\ (\mathbf{Y}_{3\to1}^T * \mathbf{P}_1^T) & 0 & -(\mathbf{P}_3^T * \mathbf{Y}_{1\to3}^T) & \cdots \\ 0 & (\mathbf{Y}_{3\to2}^T * \mathbf{P}_2^T) & -(\mathbf{P}_3^T * \mathbf{Y}_{2\to3}^T) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}}_{(\sum_{j=2}^{G}\sum_{i=1}^{j-1} L_i L_j)\times M},$$

- LS calibration parameter estimation assuming a unit norm constraint

$$\arg\min_{\mathbf{f}:\|\mathbf{f}\|=1} \|\mathcal{Y}(\mathbf{P})\,\mathbf{f}\|^2 = \hat{\mathbf{f}} = V_{min}(\mathcal{Y}(\mathbf{P})^H \mathcal{Y}(\mathbf{P}))$$

where $V_{min}(\mathbf{X})$ denotes the eigenvector of matrix $\mathbf{X}$ corresponding to its eigenvalue with the smallest magnitude.

Experimental Results (1/5)

Measurement Setup

- RCC and RRU running OpenAirInterface (IF4.5 split).
- Bandwidth: 10MHz.
- Calibration algorithms/groupings
  - Argos
  - Rogalin et al.
  - Avalanche
  - FC-I (fast calibration with Avalanche-like grouping)
  - FC-II (fast calibration with equally partitioned groups)
    - Interleaved
    - Neighbours
    - Random

Experimental Results (2/5)

Group 1

Group 2

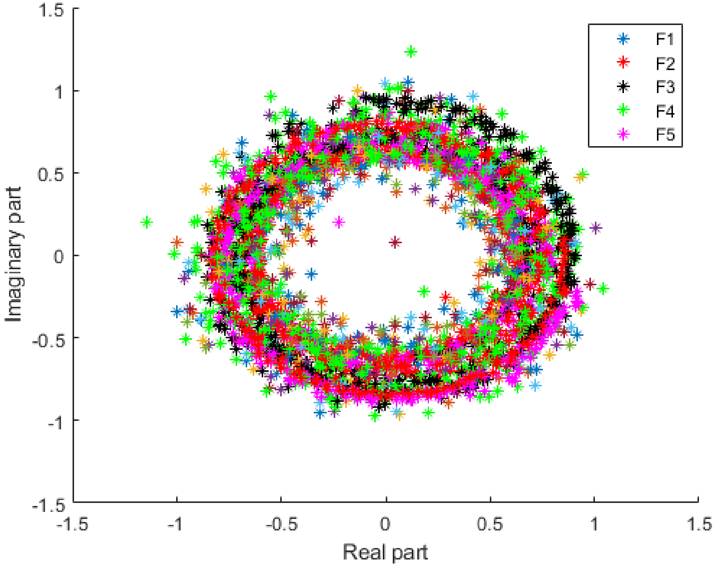
- Interleaved

- Neighbours

- Random

Experimental Results (3/5)

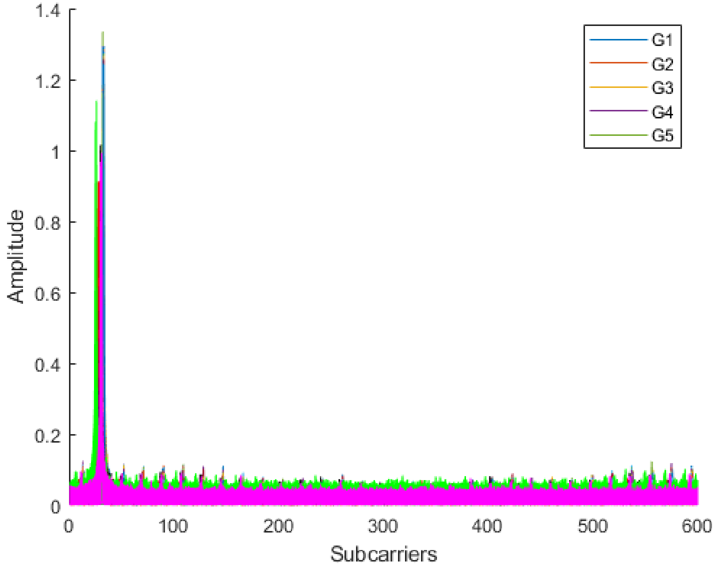
Calibration coefficients (frequency domain, all subcarriers)



$$\hat{\boldsymbol{f}}_j[l,k] \quad \begin{array}{l} j \text{ : RRU tag} \\ k = 1..600 \text{ : \# subcarriers} \\ l = 1..L \text{ : \# measurements} \end{array}$$

IFFT

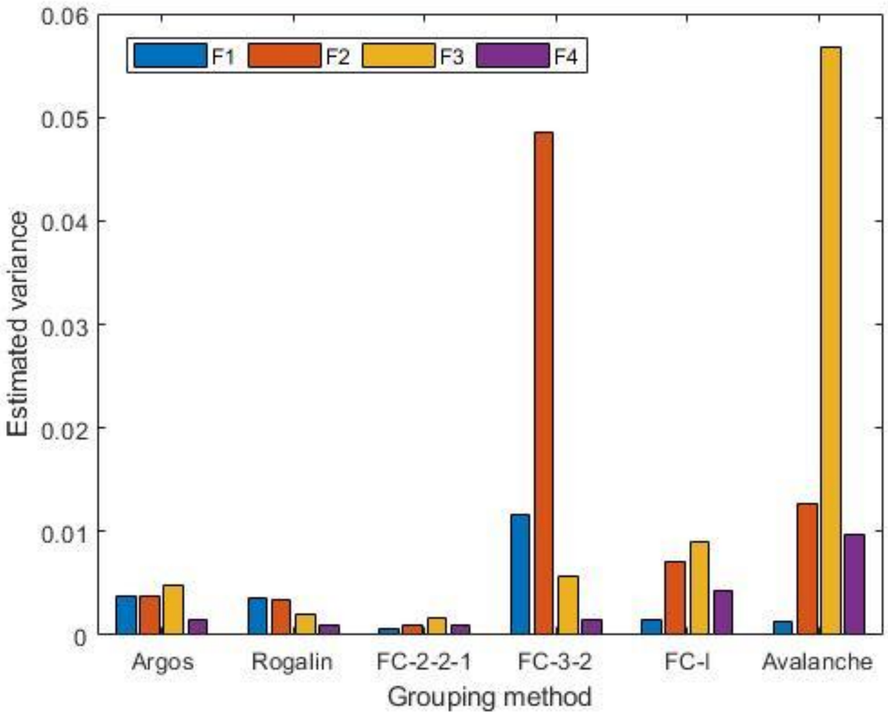
Calibration coefficients (amplitude, time domain)



$$\hat{\boldsymbol{g}}_j[l,k] = \underset{k}{IFFT}\{\hat{\boldsymbol{f}}_j[l,k]\}$$

Experimental Results (4/5)

❖ Variance of the time-domain calibration coefficients (computed at the maximum value)



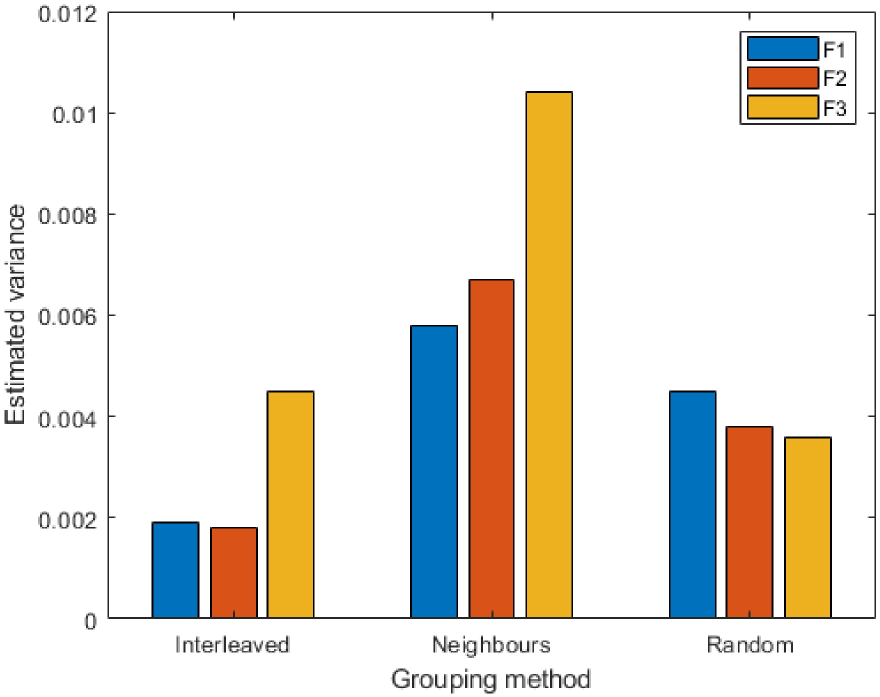
$$k' = \arg\max_{k} \hat{g}_j[l, k]$$

$$\tilde{g}_j = \underset{l}{var}(\hat{g}_j[l, k'])$$

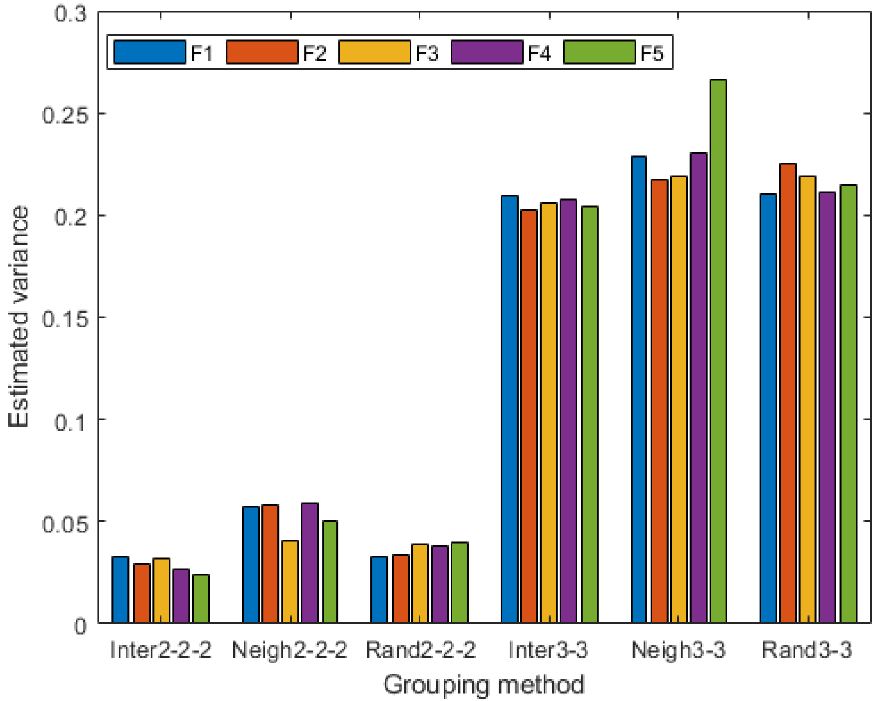
Experimental Results (5/5)

- ❖ F0=0 (LS-unit norm/reference RRU)
- ❖ FC-II (fast calibration with equally partitioned groups)

4 RRUs



6 RRUs



Conclusion

- ❖ Achieved to maintain OTA synchronization between several RRUs.
- ❖ Through real-time measurements on our C-RAN testbed and OAI software, we perform distributed channel reciprocity calibration.
- ❖ Presented an OTA calibration framework (grouping).
- ❖ Confirmed the efficiency of the proposed fast calibration schemes based on RRU grouping in real environment.
- ❖ Fast calibration with equally partitioned groups outperforms methods Argos, Rogalin and Avalanche.
- ❖ The overall estimation performance of our FC scheme improves when we try to minimize the size of the largest RRU group.
- ❖ Interleaving of the RRUs results in performance gains.
  - The channel from a group to the rest of the RRUs is as well-conditioned as possible.

Thank you