Experimental evaluation of reciprocity calibration for distributed massive MIMO systems

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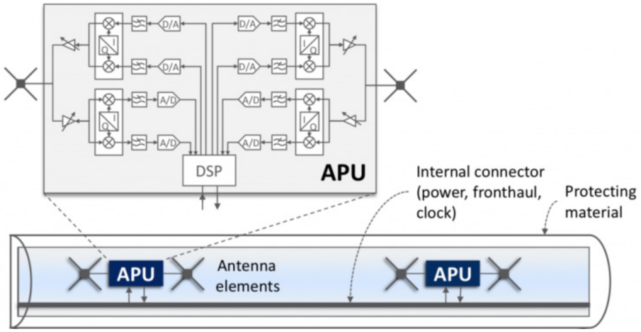
Distributed Massive MIMO

- **Benefits**
  - Combines the benefits of massive MIMO (beamforming gain and spatial interference suppression) with small cells (higher probability of being closer to an antenna)
  - Cell-free massive MIMO is the next step where even cell boarders disappear when all distributed antennas are connected to the same base band unit
- **Challenges**
  - Need phase coherence over a large number of BS
  - Building such a system is expensive
- **State of the art**
  - Classical c-RAN using CPRI: all the RRUs need to be connected to the BBU, which provides sync
  - Synchronization based on PTPv2 or White Rabbit
  - Artemis pCell
  - Ericsson radio stripes: serially connected radios
- **Our approach**
  - Inexpensive RRUs connected to a RAU
  - RAU provides frequency synchronizations
  - Fronthaul over standard switched Ethernet

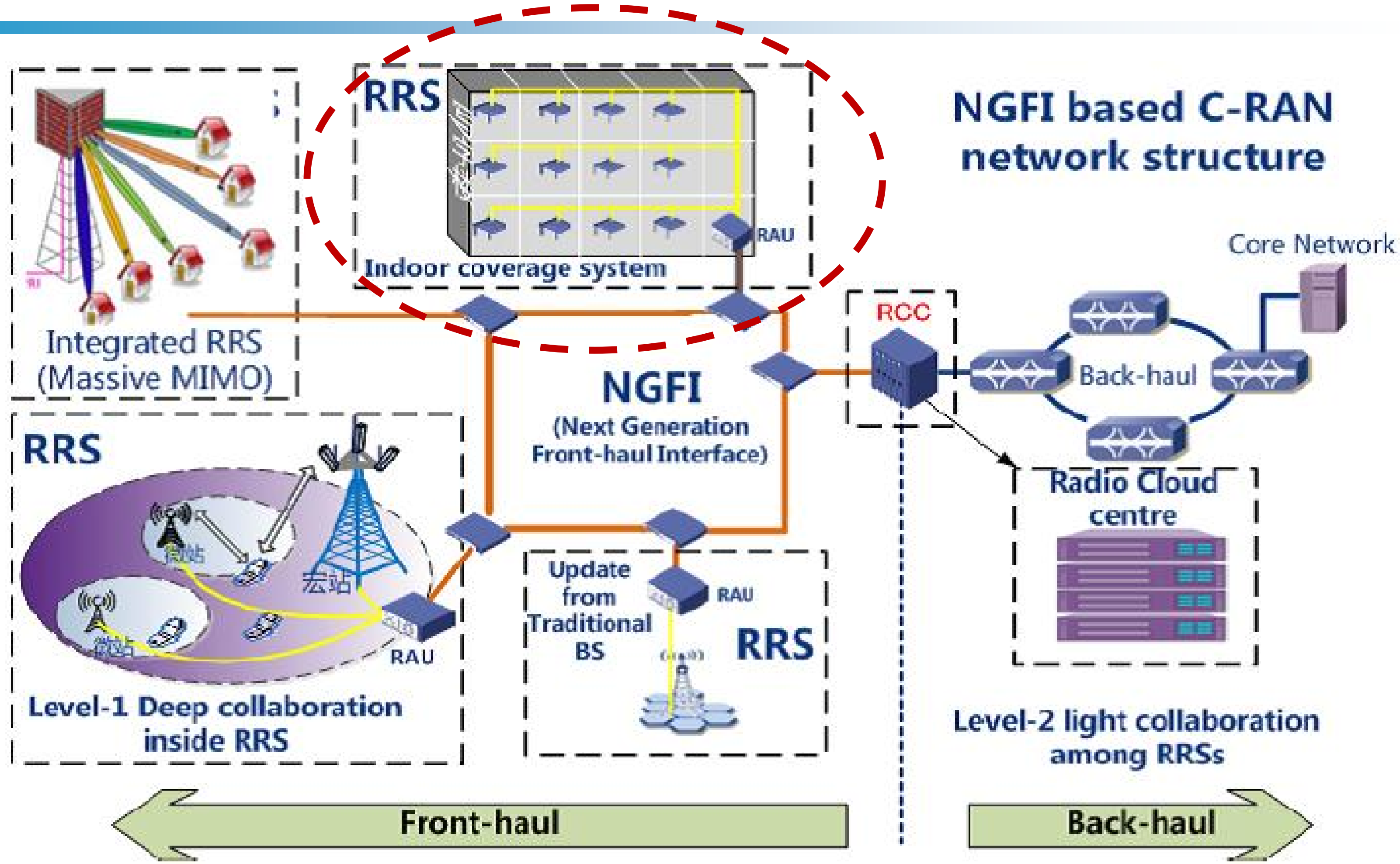


Ericsson Radio Stripes

What is OpenAirInterface?

- **Open-source software-based implementation of 3GPP systems**
  - Including features from LTE-Advanced (Rel 10/11/12), LTE-Advanced-Pro (Rel 13/14), going on to 5G Rel (15/16/…)
  - Spanning the full protocol stack of 3GPP standard
    - E-UTRAN (eNB, UE)
    - EPC (MME, S+P-GW, HSS)
  - Realtime RF using off-the-shelf SDR platforms (ExpressMIMO2, USRP, LimeSDR, …)
- **Makes it feasible to put a fully-compliant 4G eNodeB and EPC in a commodity x86-based computer (or data center)**
  - Flexible fronthaul interfaces over standard Ethernet provide inexpensive way to implement C-RAN
- **Objectives**
  - Building a community of individual developers, academics and major industrials embracing open-source for 5G → **OAI software alliance**
  - Become a strong voice and maybe a game-changer in the 3GPP world
  - Real impact from "the little guys" on 3GPP systems

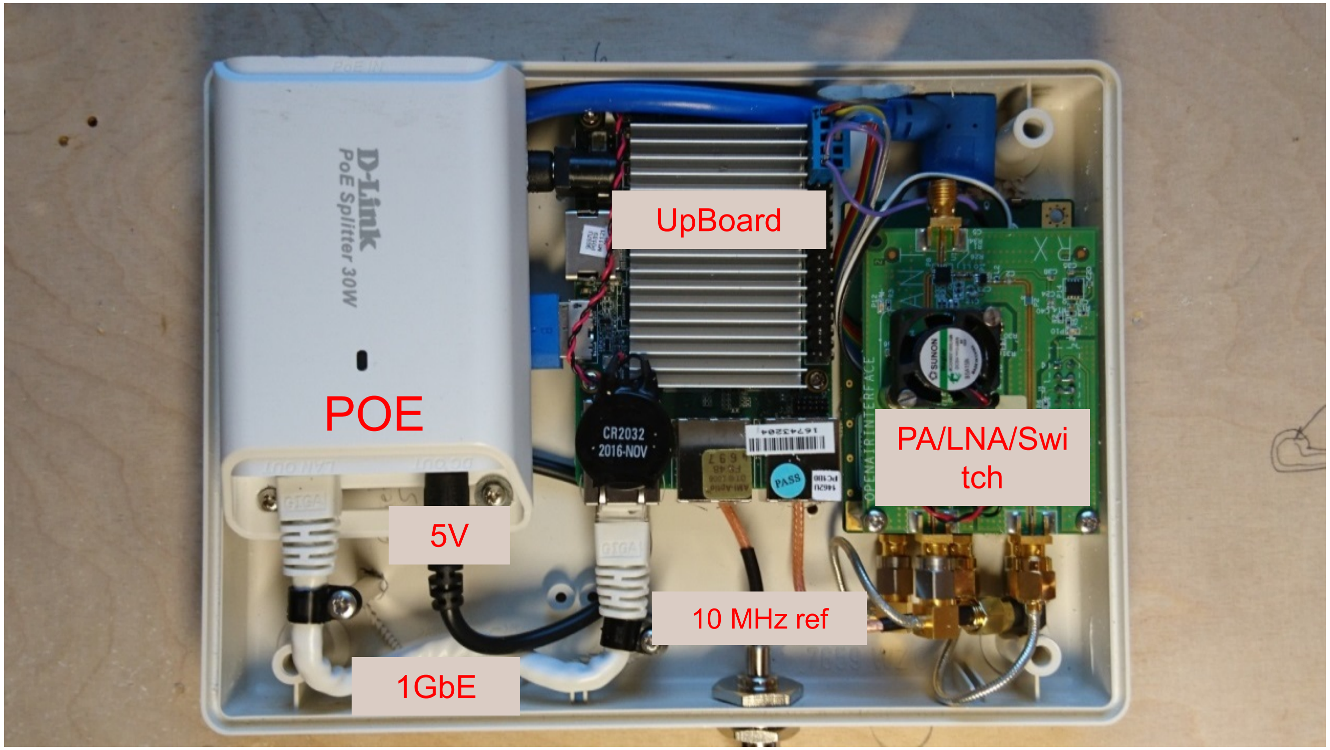
Next Generation Fronthaul Interface Architecture



Source:
China Mobile

RRS: remote radio system, RAU: radio aggregation unit,
RRU: remote radio unit, RCC: radio cloud center

Remote Radio Unit



- **Supports SISO 20 MHz**
- **Total cost: ~750$**
  - UPBoard (100$)
  - USRPB200-mini (500$ in quantities)
  - PA/LNA/Switch (100$)
  - PoE+ module (50$)

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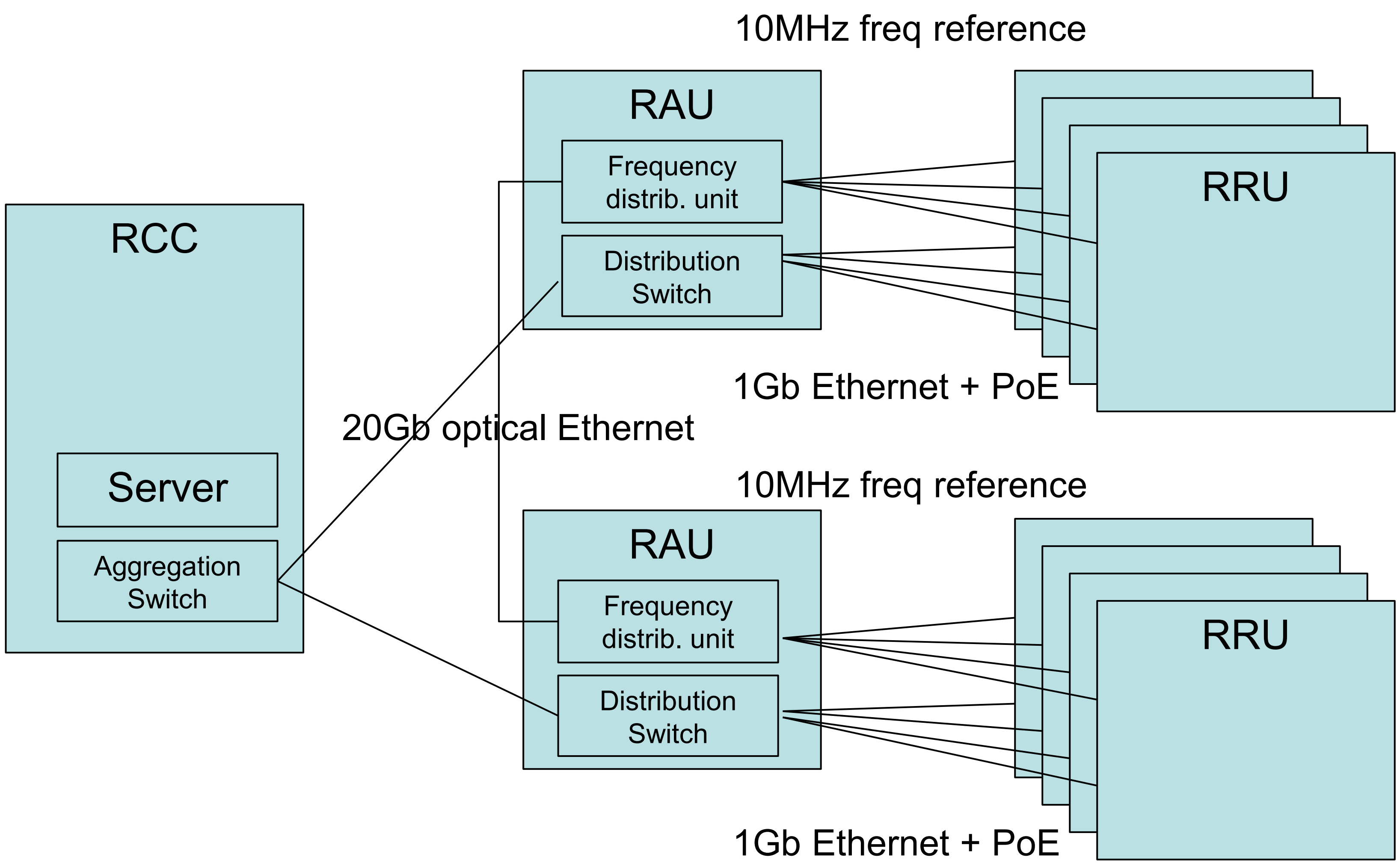
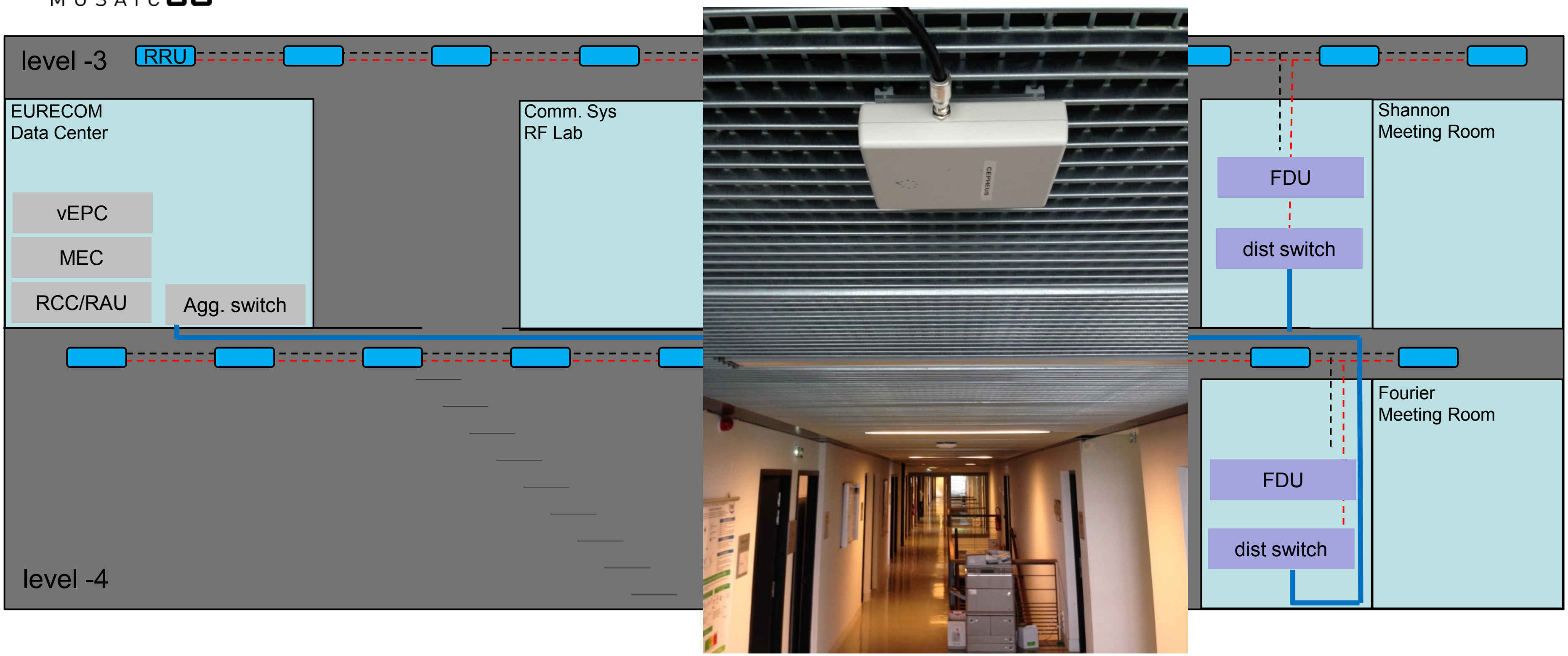
Physical Infrastructure



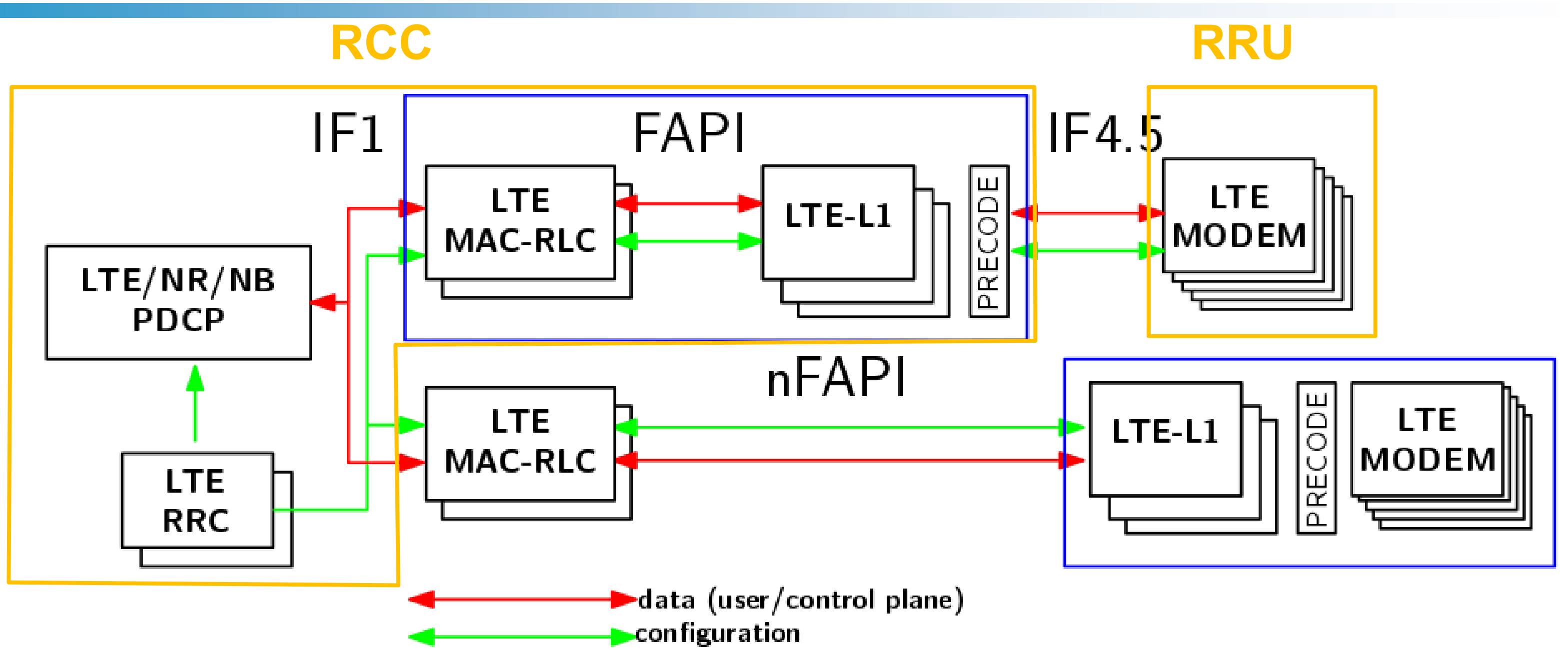
Eurecom C-RAN Deployment

Band 38 (TDD, 2.6 GHz)

20Gb optical Ethernet
1Gbit Ethernet
10MHz clock reference



Logical functional split options in OAI



- IF1: CU/DU interface also used in 3GPP 5G
- FAPI: PHY/MAC interface specified by small cell forum,
- nFAPI: networked FAPI, implementation (open-nFAPI) by CISCO
- IF4.5/IF5: similar to IEEE P1914.1 or O-RAN 7-2x

Three levels of synchronization

- **Time synchronization**
  - Align frames at RRUs up to within 1-2 samples
  - Achieved by over-the-air trigger-based synchronization using a “master-slave” protocol (similar to eNB-UE synchronization)
- **Frequency synchronization**
  - RRUs have to stay synchronized in time and phase
  - Achieved by 10MHz reference signal
- **Phase synchronization**
  - Necessary for coherent transmission and precoding
  - Achieved by reciprocity calibration

Frequency Synchronization Challenges

- **USRP B200 mini design flaws**
  - PLL that generates the 40MHz reference for the RF chip (AD9464) is done digitally in the FPGA (to save space) and thus has a poor phase stability
  - Makes it unsuitable for phase coherent applications
- **Modification 1:**
  - bypass the digital PLL and use a clock multiplier to generate the 40MHz reference
    - Unfortunately the component we selected has a too high phase noise, rendering the RRU useless
- **Modification 2:**
  - Use a signal generator & splitter to provide the 40MHz reference

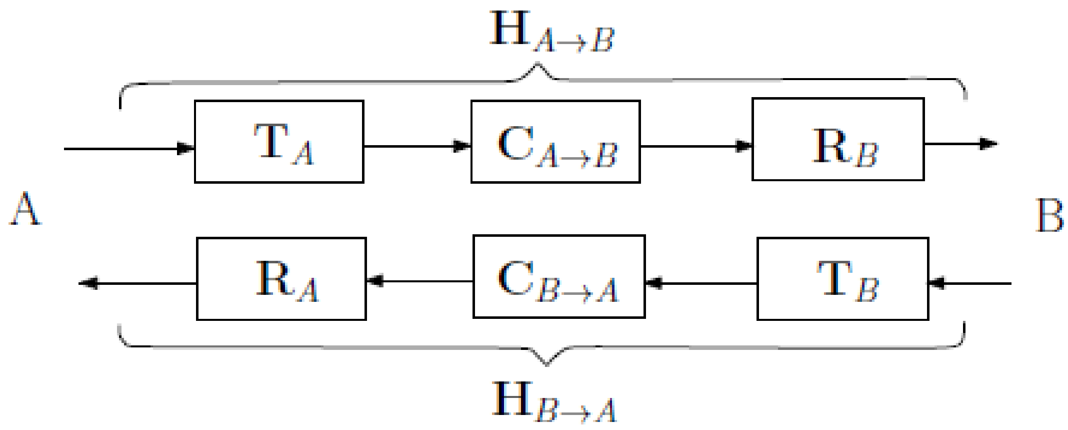
RECIPROCITY CALIBRATION FOR DISTRIBUTED MASSIVE MIMO

Reciprocity Calibration

- **Compensates asymmetric TX/RX paths as well as unknown phase offsets between RRUs**
- **Allows to obtain DL Channel State Information based on UL channel estimates in TDD systems**
- **Many works on calibration for distributed massive MIMO**
  - Argos [Rogalin 2014], Avalanche [Papadoupoulos 2014], [Vieira 2017]
- **We recently developed a framework for reciprocity calibration generalizing all these methods [1]**
  - Fast calibration with better MSE than Avalanche
  - Allows for distributed non-coherent accumulation

[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

Reciprocity Calibration Basics



$$\mathbf{H}_{A\to B} = \underbrace{\mathbf{R}_B \mathbf{T}_B^{-T}}_{\mathbf{F}_B^{-T}} \mathbf{H}_{B\to A}^T \underbrace{\mathbf{R}_A^{-T} \mathbf{T}_A}_{\mathbf{F}_A} . \qquad (1)$$

- Calibration phase:
  - Collect set of measurements
  - Estimate F_A and F_B (can safely be assumed diagonal)
- Operation phase:
  - Estimate UL channel
  - Compute DL channel based on (1)
  - Precoding/beamforming

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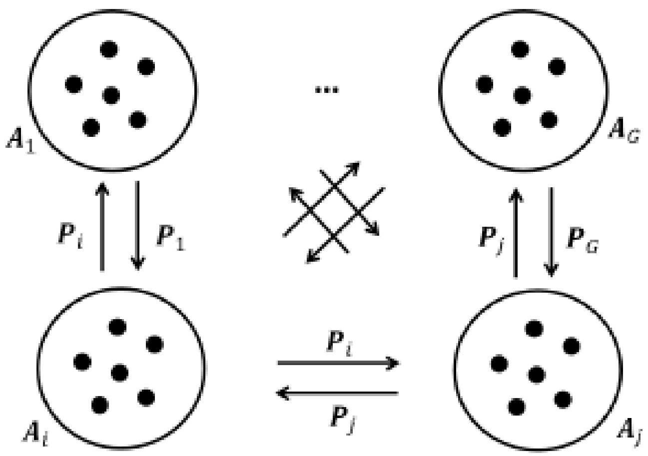
Framework for Reciprocity Calibration

- **Partition RRUs in groups**
- **Exchange pilots between groups**



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

$$\mathsf{P}_i^T \mathsf{F}_i^T \mathsf{Y}_{j\to i} - \mathsf{Y}_{i\to j}^T \mathsf{F}_j \mathsf{P}_j = \widetilde{\mathsf{N}}_{ij}.$$

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

$$\mathbf{F}_i = \mathbf{R}_i^{-T}\mathbf{T}_i \text{ and } \mathbf{F}_j = \mathbf{R}_j^{-T}\mathbf{T}_j \qquad \mathbf{F}_i = \text{diag}\{\mathbf{f}_i\}$$

Estimation of Calibration Matrix

- **Collect all measurements in** $\mathcal{Y}(\mathbf{P})\mathbf{f} = \tilde{\mathbf{n}},$

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

- **Solve least squares problem**

$$\hat{\mathrm{f}} = \arg\min_{\mathrm{f}} \|\mathcal{Y}(\mathrm{P})\,\mathrm{f}\|^2$$

  - Different solutions based on constraints on f (to avoid trivial solution f=0)

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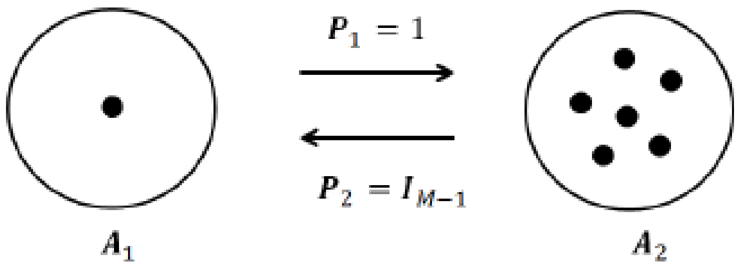
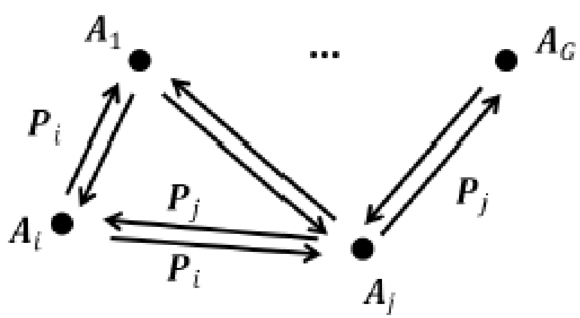
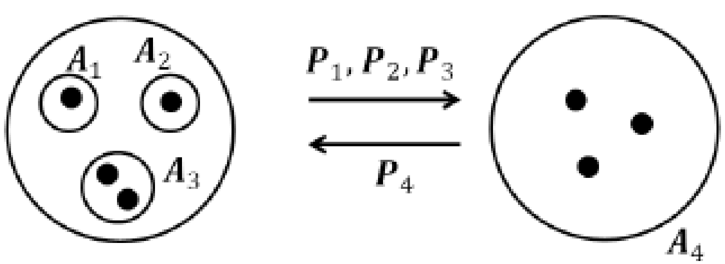
Existing Calibration methods



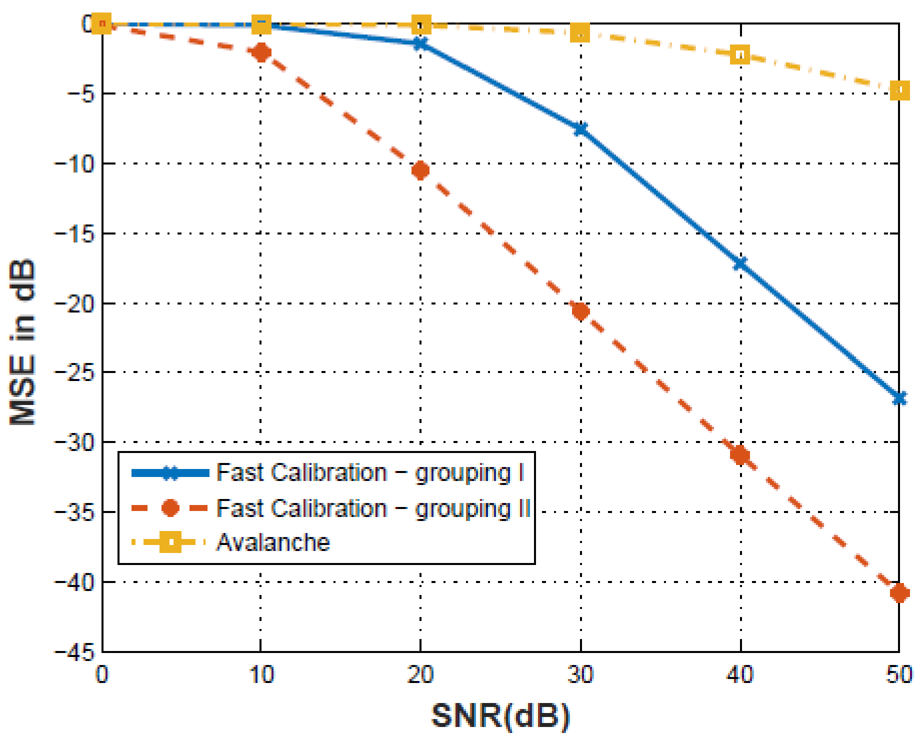




- Argos [Argos, 2012]: Bidirectional transmission between the reference antenna and the other antennas;
- Method in [Rog, 2014]: Perform bi-directional transmission between each pair of antenna elements;
- Avalanche [Avalanche, 2014]: Use calibrated antenna array to calibrate uncalibrated array.

Calibration methods	Number of channel uses
Argos	M
Rogalin	M
Avalanche	$\lceil \sqrt{2M - \frac{7}{4}} + \frac{1}{2} \rceil$
Optimal antenna grouping	$\lceil \sqrt{2M - \frac{7}{4}} + \frac{1}{2} \rceil$

Better Fast Calibration methods



- Simulation results based on Co-located array with M=64
- → min. channel uses = 12
- Other groupings have better MSE than Avalanche

Scheme	Antennas transmitting per channel use. $M = 64$										
Avalanche	1	1	2	3	4	5	6	7	8	9	10	8
FC-I	1	1	2	3	4	5	6	7	8	9	10	8
FC- II	5	5	5	5	5	5	5	5	6	6	6	6

Calibration for distributed MIMO

- **Optimal grouping depends on scenario and antenna geometry**
- **Not all antennas might hear each other**
  - Not an issue as long as Y(P) has full rank, i.e., if

$$\sum_{1\leq i<j\leq G} L_j L_i \geq M-1$$

- **Different rows in Y(P) can also be collected in non-coherent time slots**
  - At the cost of the number of channel uses

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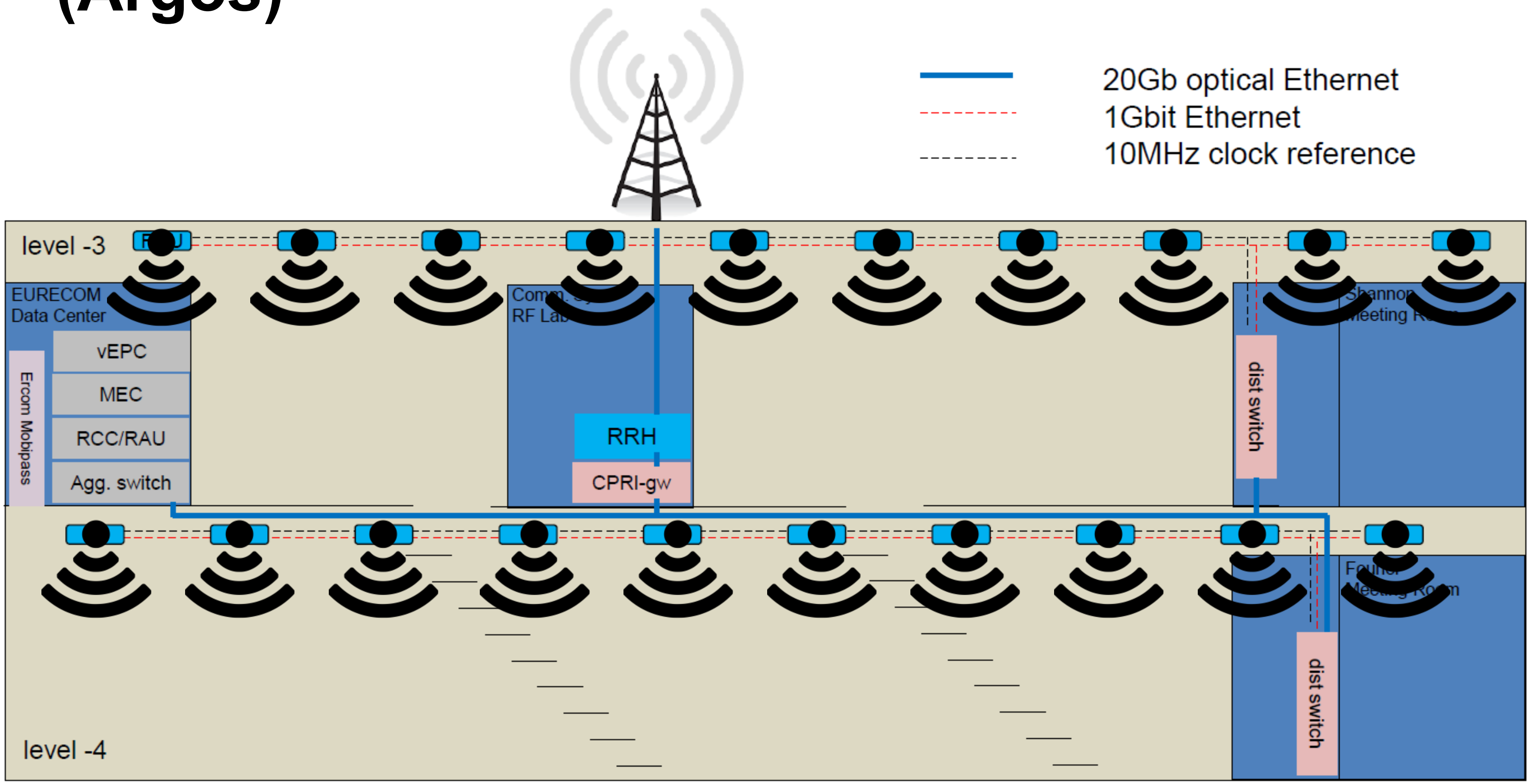
Option 1: Long Channel Coherence Time

- **One node broadcasts at a time, all others listen (Argos)**



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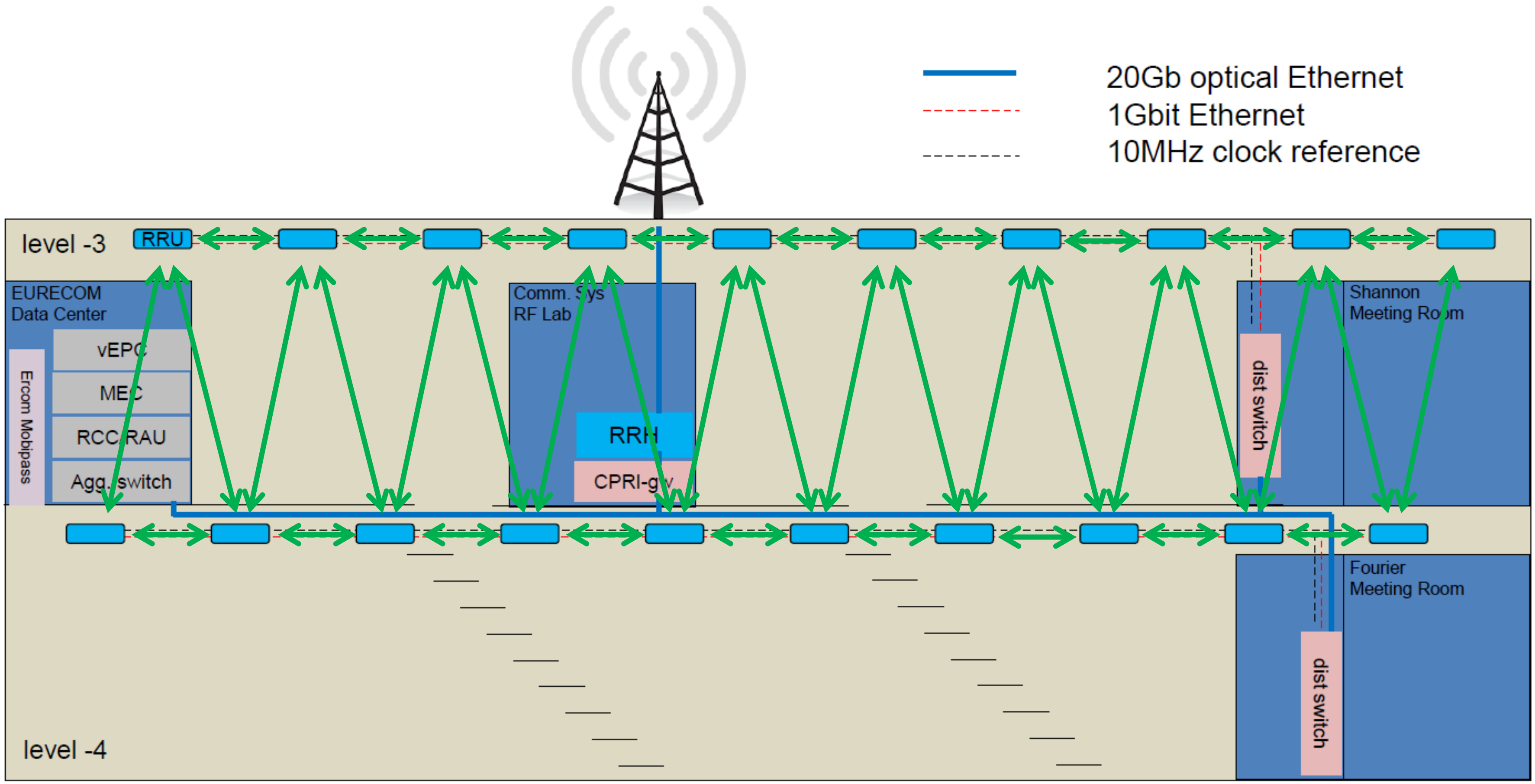
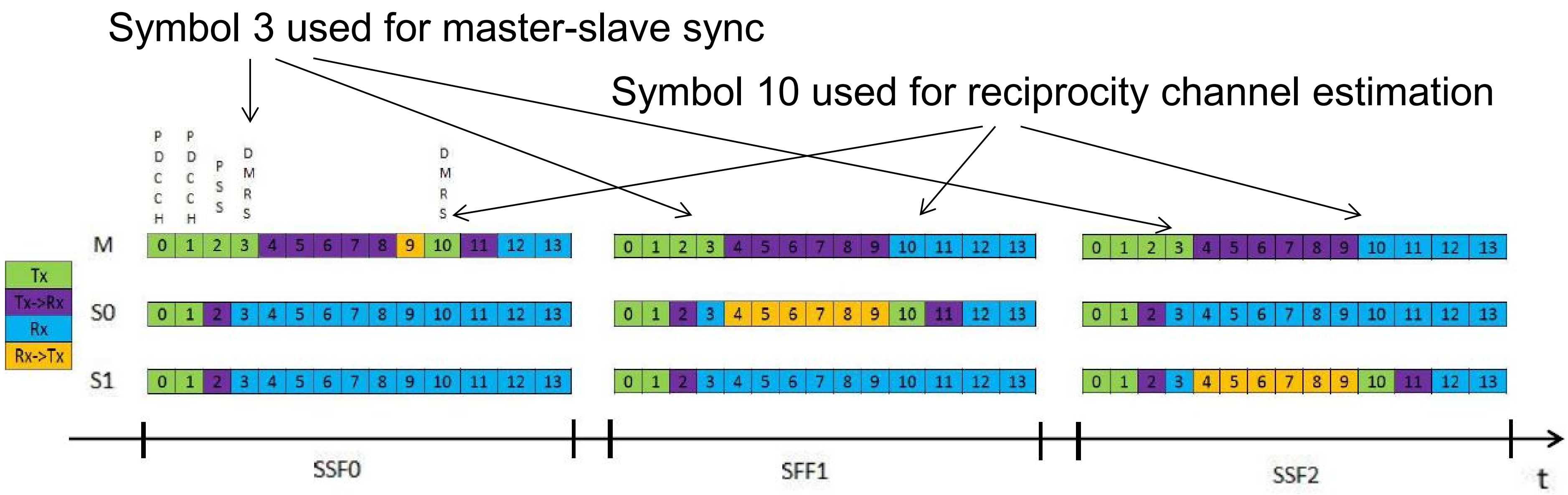
Option 2: Short Channel Coherence Time

- **Multiple bi-directional measurements**



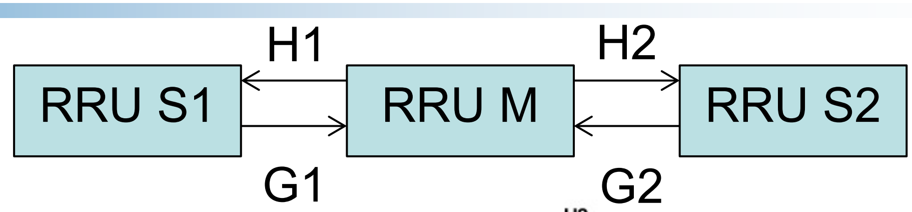
Integration into LTE

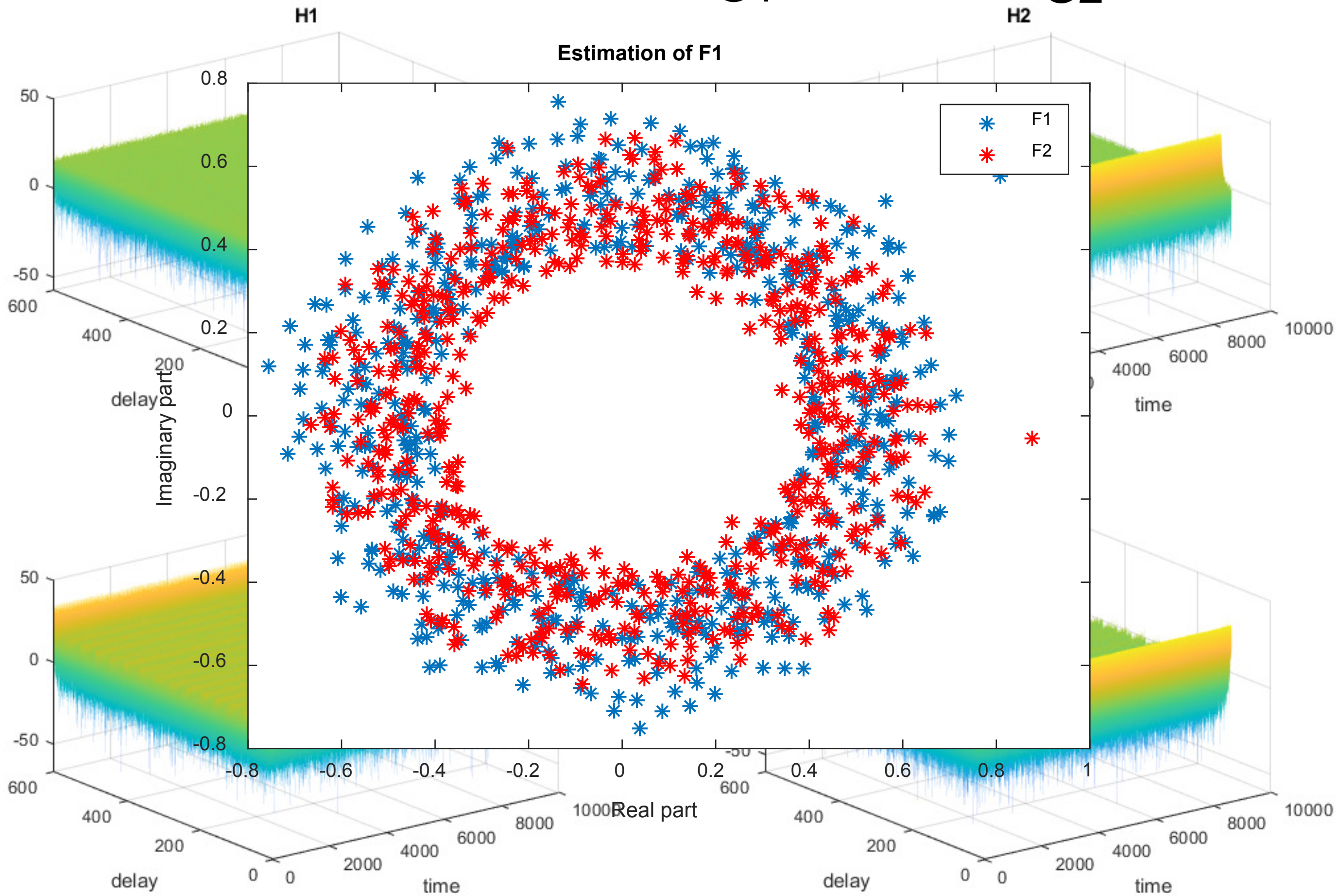
- **Calibration can be integrated in live operation using dynamic configuration of special subframe**
- **Example: 3 RRUs**



Some preliminary results

- **3RRUs, Argos**





Conclusions

- **Building a distributed MIMO system is hard**
- **Synchronization on 3 levels: time, frequency, phase**
- **New reciprocity calibration scheme**
  - Flexible grouping of RRUs to account for
    - Channel coherence time
    - Topology (RRU connectivity)
    - MSE
- **Future work**
  - Validation of reciprocity calibration using real UEs
  - Play with different groupings and calibration algorithms

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THANK YOU!

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