Massive MIMO in Practice

-from proof-of-concept to implementation efficiency

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Massive MIMO

"Technology to handle orders of magnitude more data traffic!"

"Focus energy into ever smaller regions of space to bring huge improvements in throughput and radiated energy efficiency!"

"Simplifies the multiple access layer!"

"Linear processing is able to provide near-optimal performance!"

...

How does it perform in real-life scenarios?
what are realistic performance gains?
where are the bottlenecks in the technology?
How to implement such big systems with resonable cost?
...

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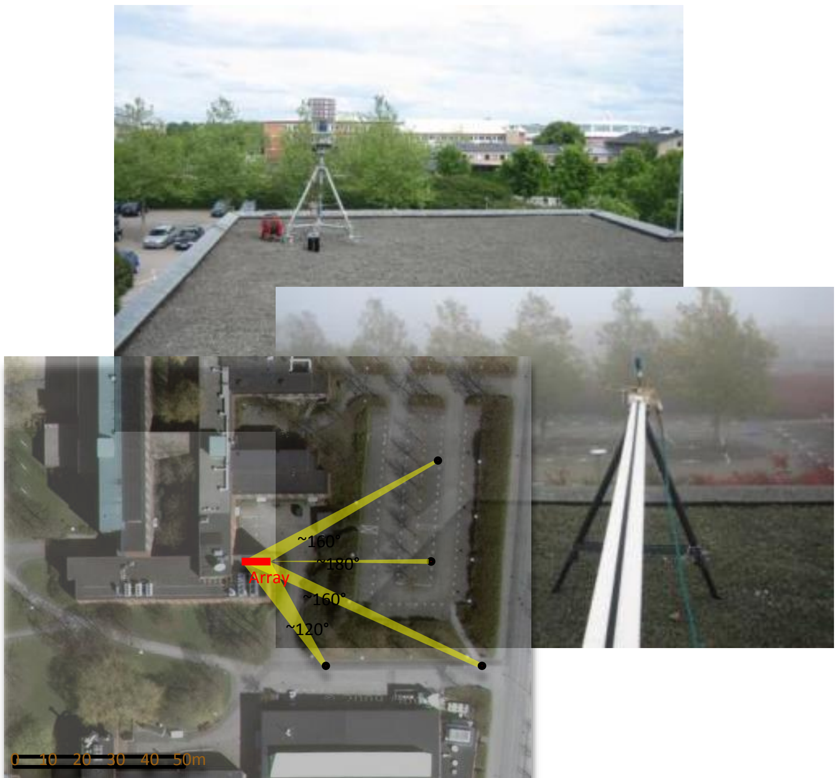
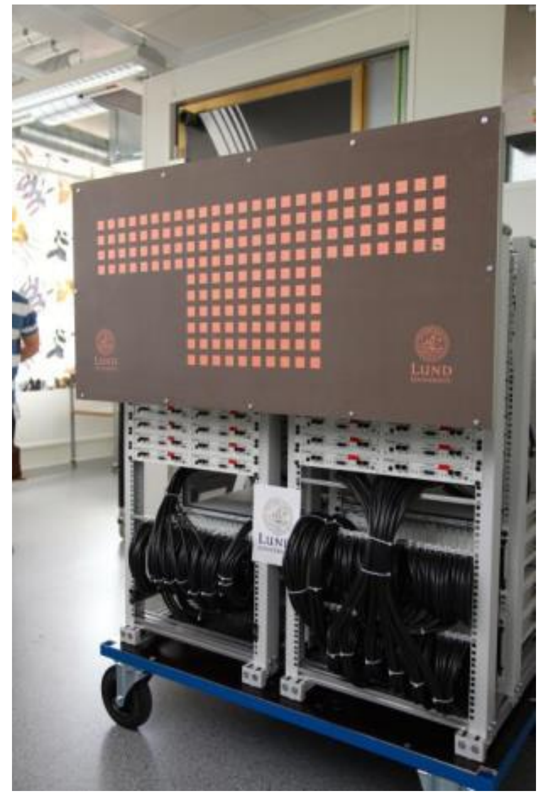
Massive MIMO research in Lund



Channel measurement & model



LuMaMi testbed with 100 basestation antennas

RUSK channel sounder

128-port cylindrical antenna array


Xiang Gao


Ghassan Dahman


Jose Flordelis


Carl Gustafson


Ove Edfors


Fredrik Tufvesson

- Multiplexed array channel sounders
- Optical fibers for synchronization
- 2.6 GHz carrier and 40 MHz bandwidth

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Open exhibition

- Out-door BS serves out-door UEs
- UEs are randomly distributed with high density and low mobility

9 users were moving inside a circle with a diameter of 5 m

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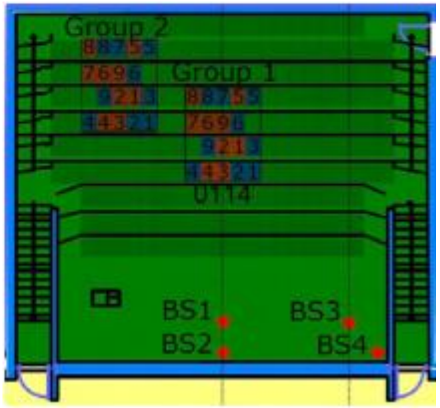
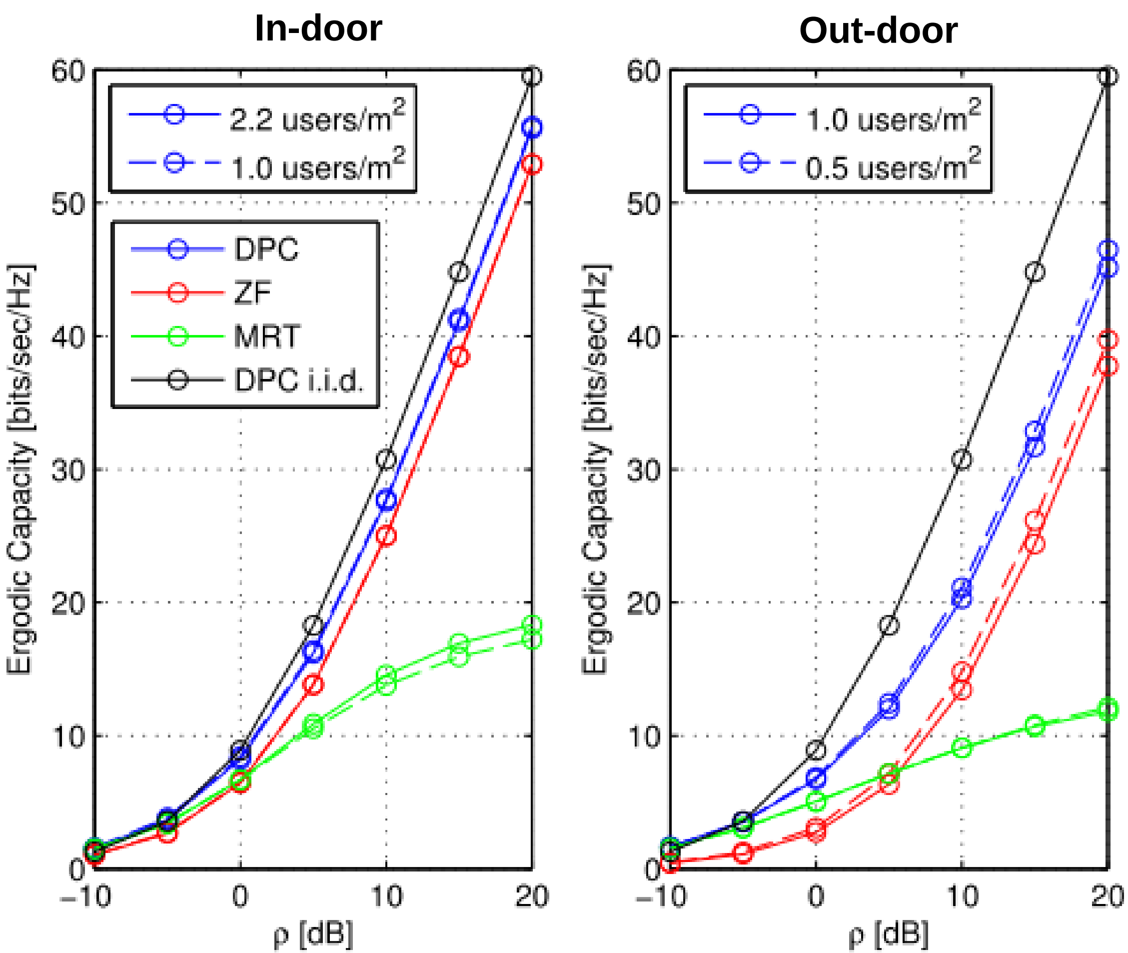
Crowed auditorium



- In-door BS serves in-door UEs
- UEs are seated regulaly with very limited movement

A measurement run with 9 active users surrounded with 11 non-active users

Sum-rate capacity



LuMaMi:
Lund Massive MIMO TestBed


Steffen Malkowsky


Joao Vieira


Hemanth Prabhu


Erik Bengtsson

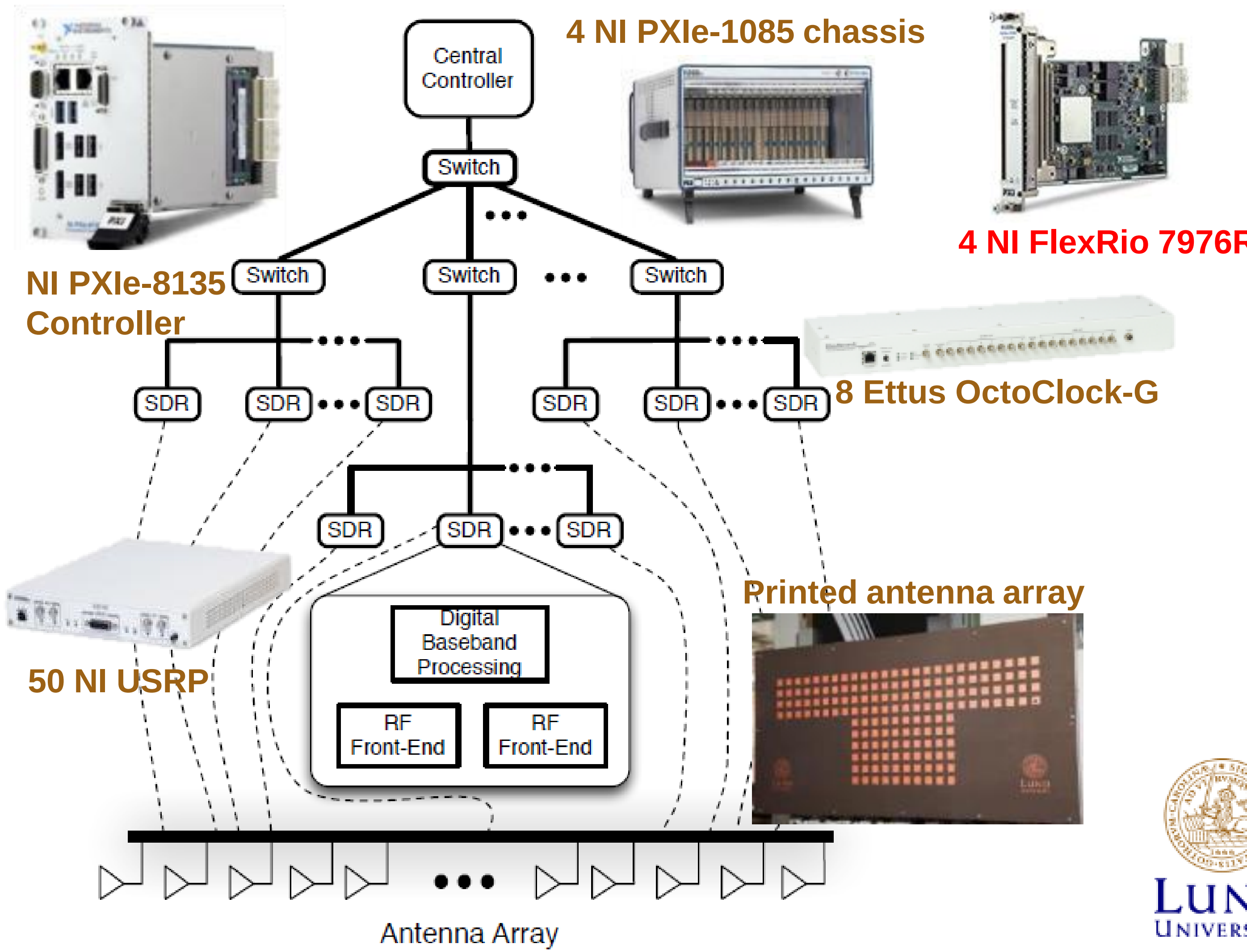

Ove Edfors


Fredrik Tufvesson

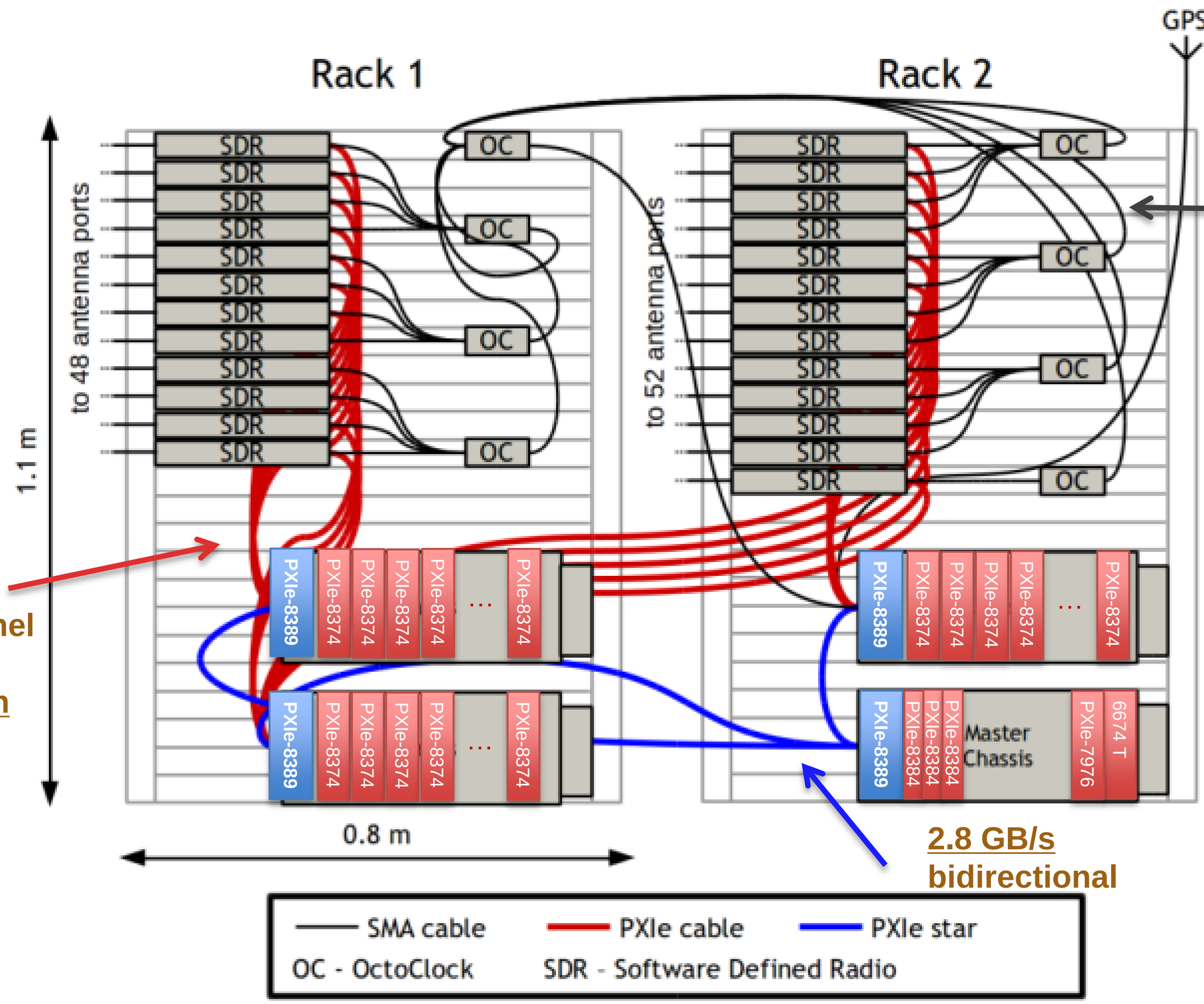

Liang Liu


Viktor Öwall

System component & architecture



BS hardware setup: side-view



Clock/PPS Distribution network

10 DMA channel
Up to 800 MB/s/direction

2.8 GB/s bidirectional

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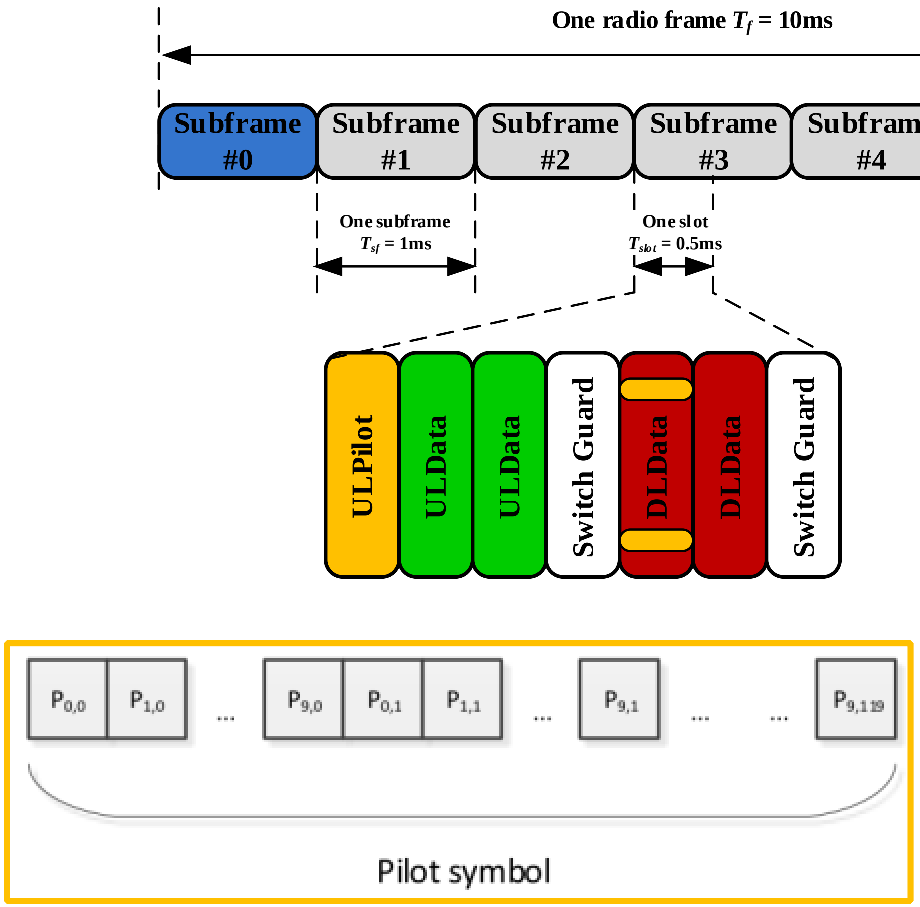
User-equipment

Proof-of-Concept

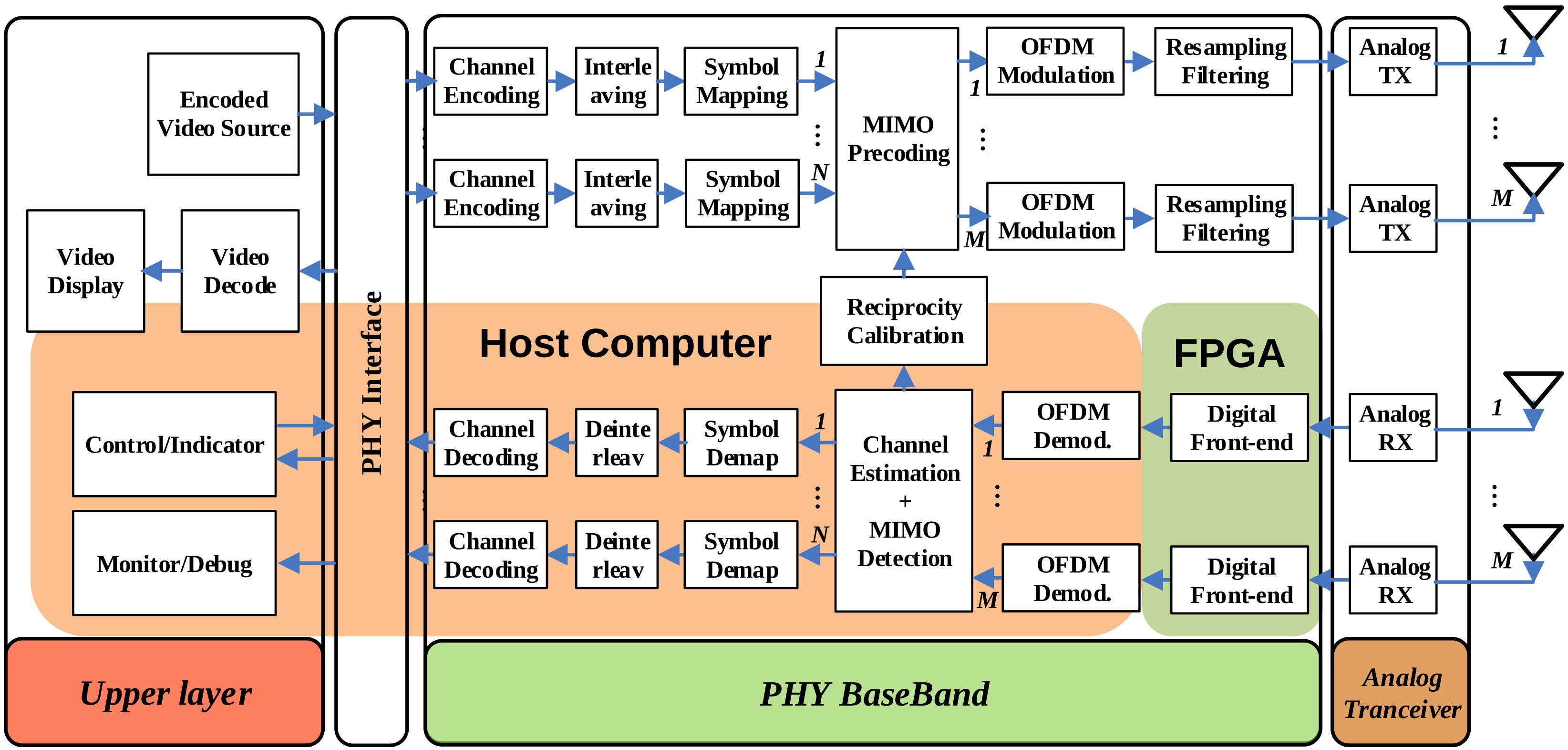
LTE-like OFDM TDD Massive MIMO

Parameter	**Variable**	**Value**
Bandwidth	W	20 MHz
Carrier frequency	f_c	3.7 GHz
Sampling Rate	F_s	30.72 MS/s
FFT Size	N_{FFT}	2048
# Used subcarriers	N_{used}	1200
Slot time	T_S	0.5 ms
Sub-Frame time	T_{sf}	1 ms
Frame time	T_f	10 ms
# UEs	K	10
# BS antennas	M	100

LTE-like OFDM TDD Massive MIMO



Step1: Uplink with host processing

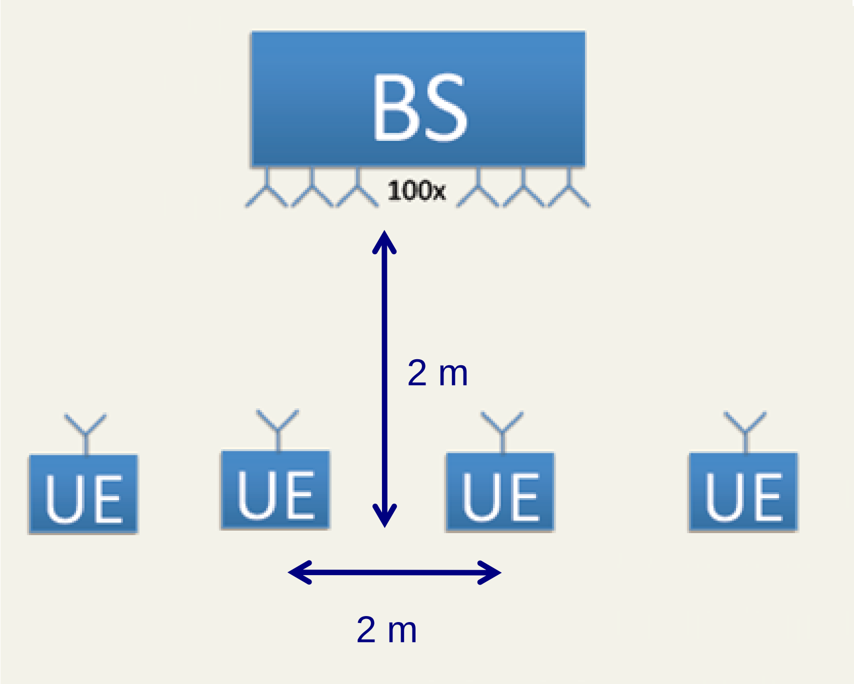


Quick Verification

- *Easy Coding*
- *Convenient Debug*
- *Quick Compile*

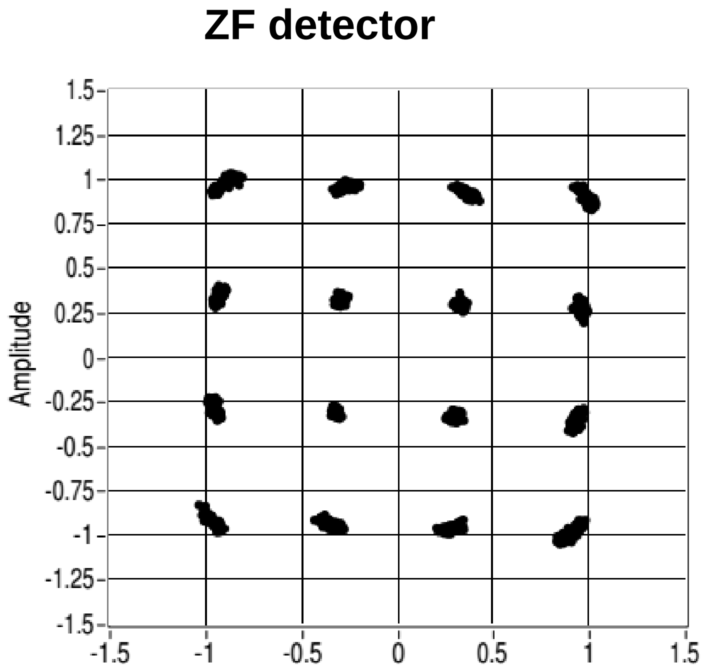
Initial results

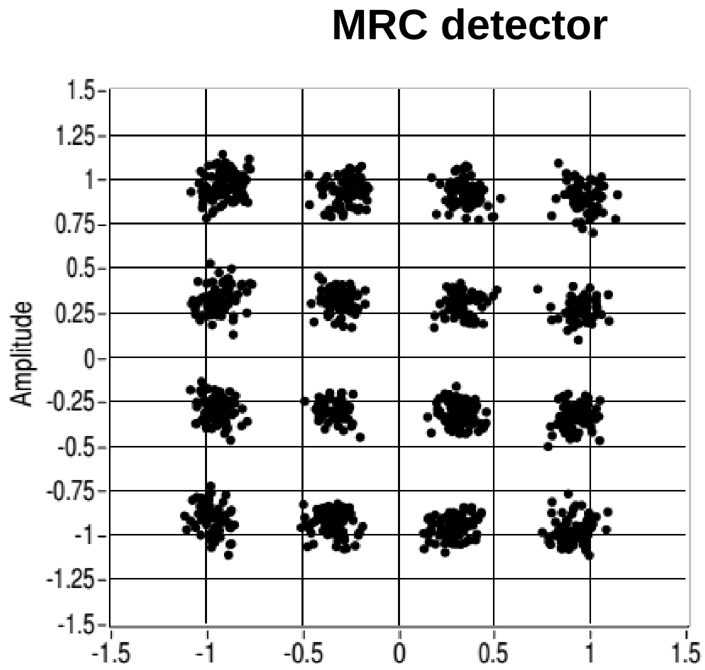
Received signal constellations – LOS & four users 2 m separation



Initial results (floating-point)

Received signal constellations – LOS & four users 2 m separation





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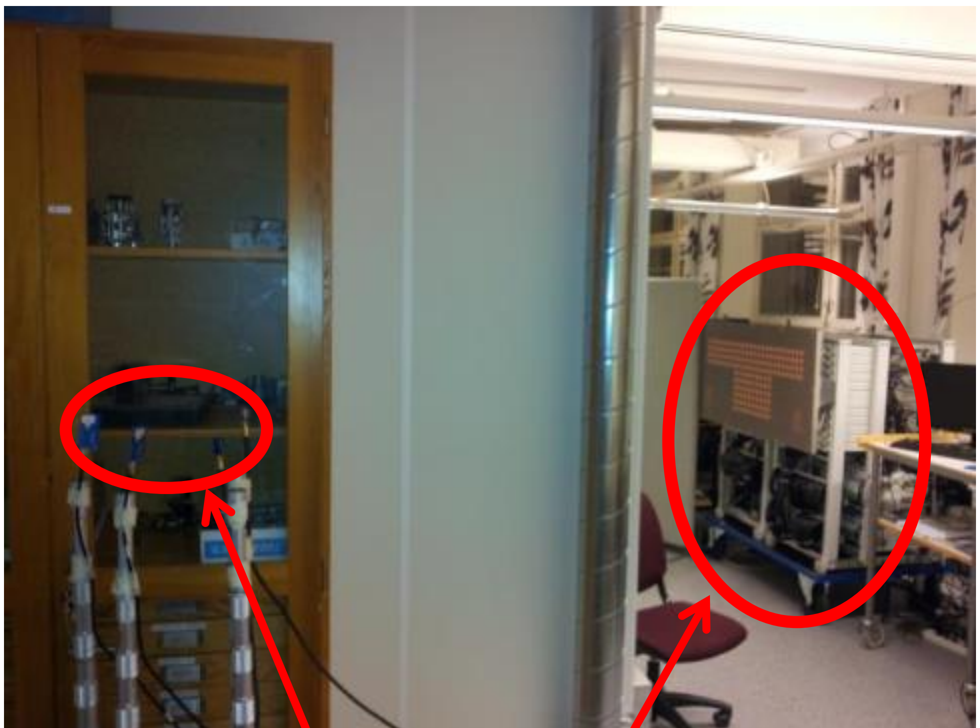
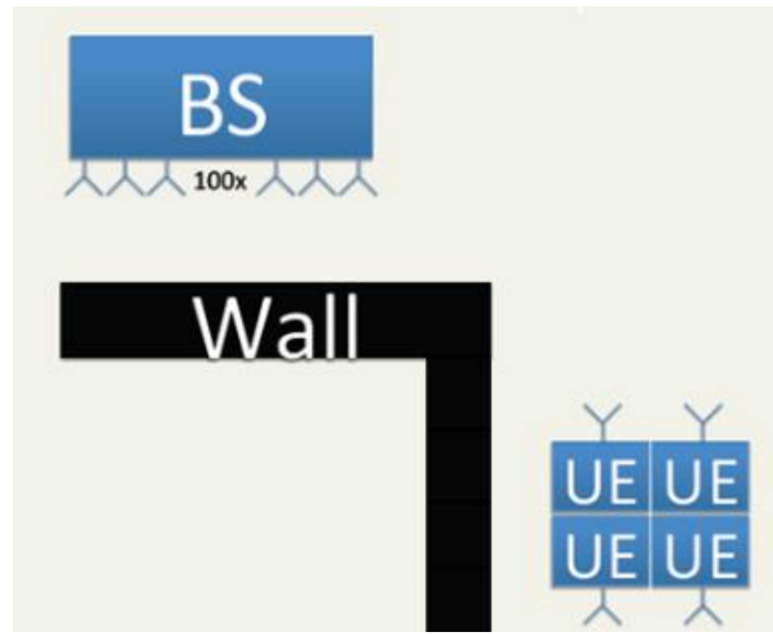
Initial results

Received signal constellations – NLOS & four users in 15 cm radius



Base station

Four terminal antennas



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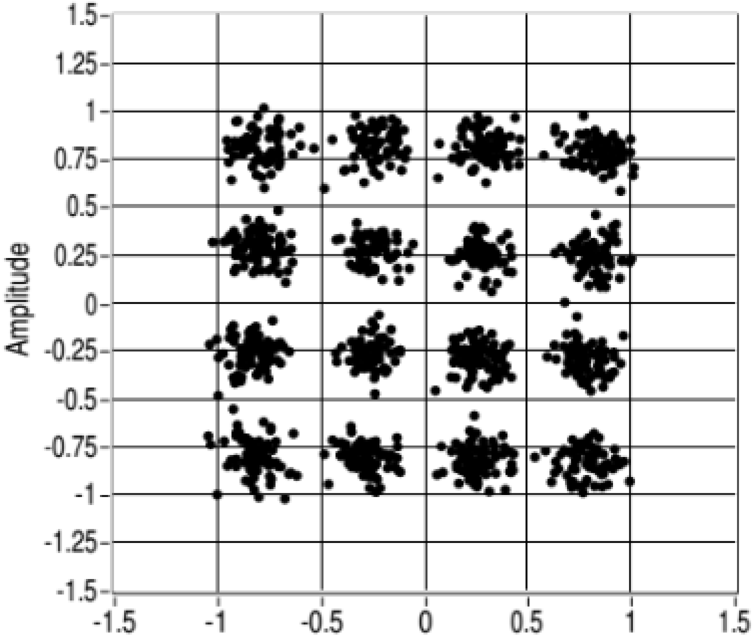
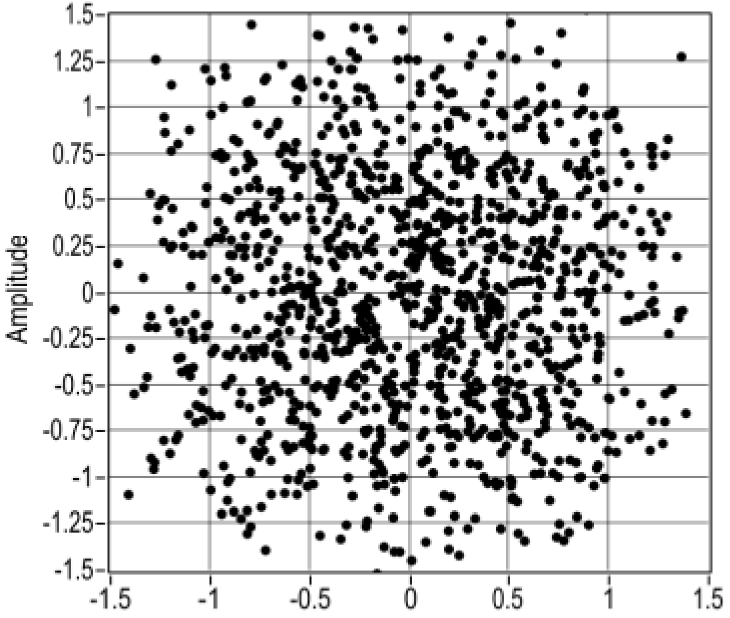
Initial results (floating-point)

Received signal constellations – NLOS & four users in 15 cm radius

User 1 – ZF detector



User 1 – MRC detector



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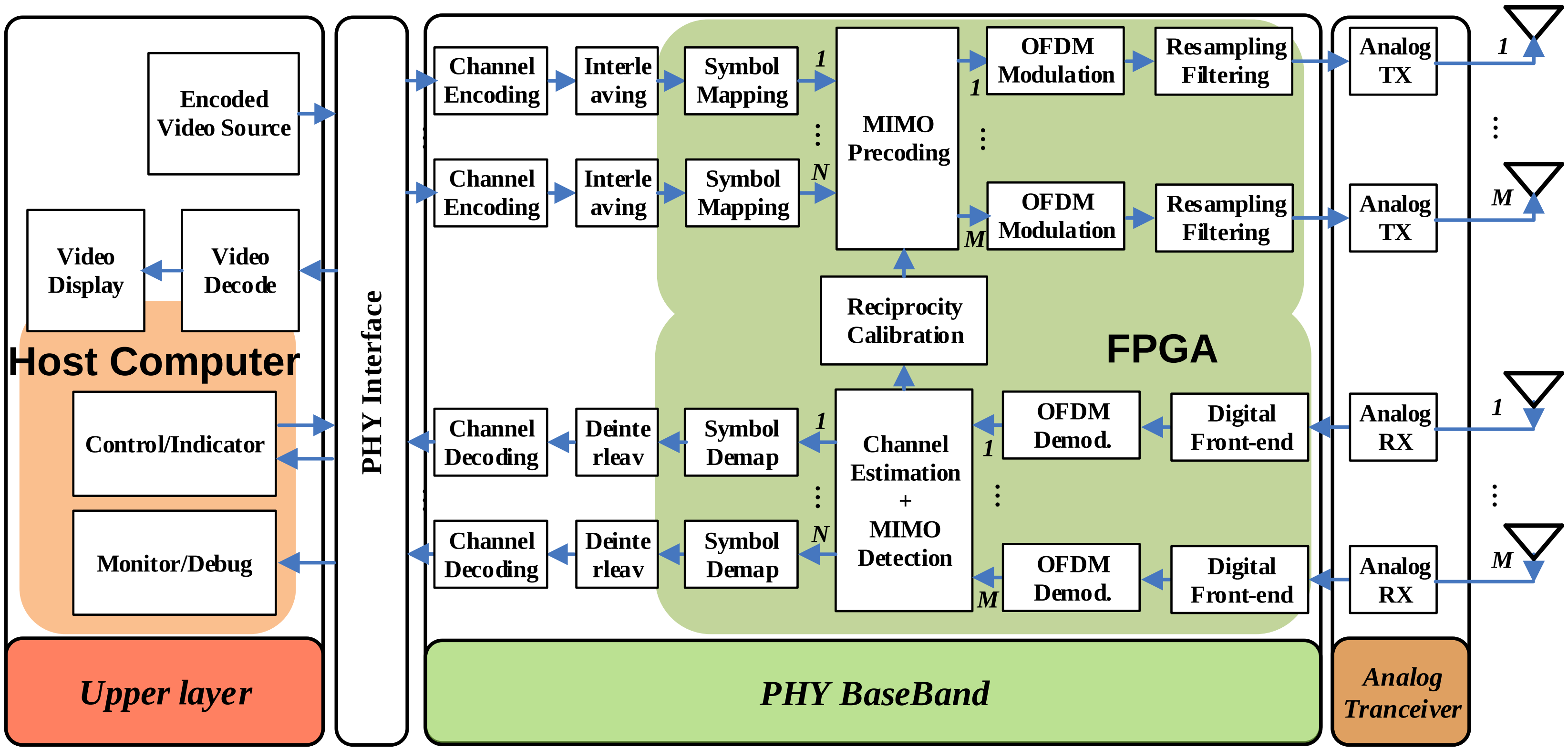
FPGA Implementation

Step2: Real-time FPGA processing



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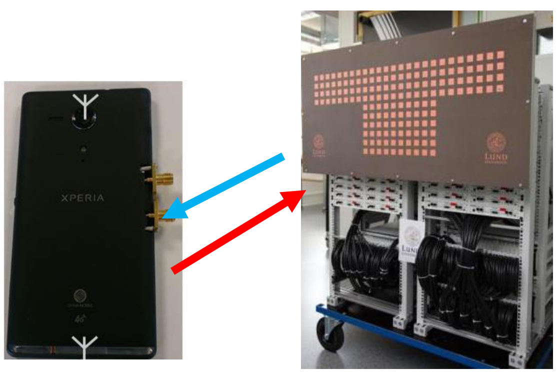
Challenges

Coherence

Data Shuffling



Reciprocity

Baseband Proces.

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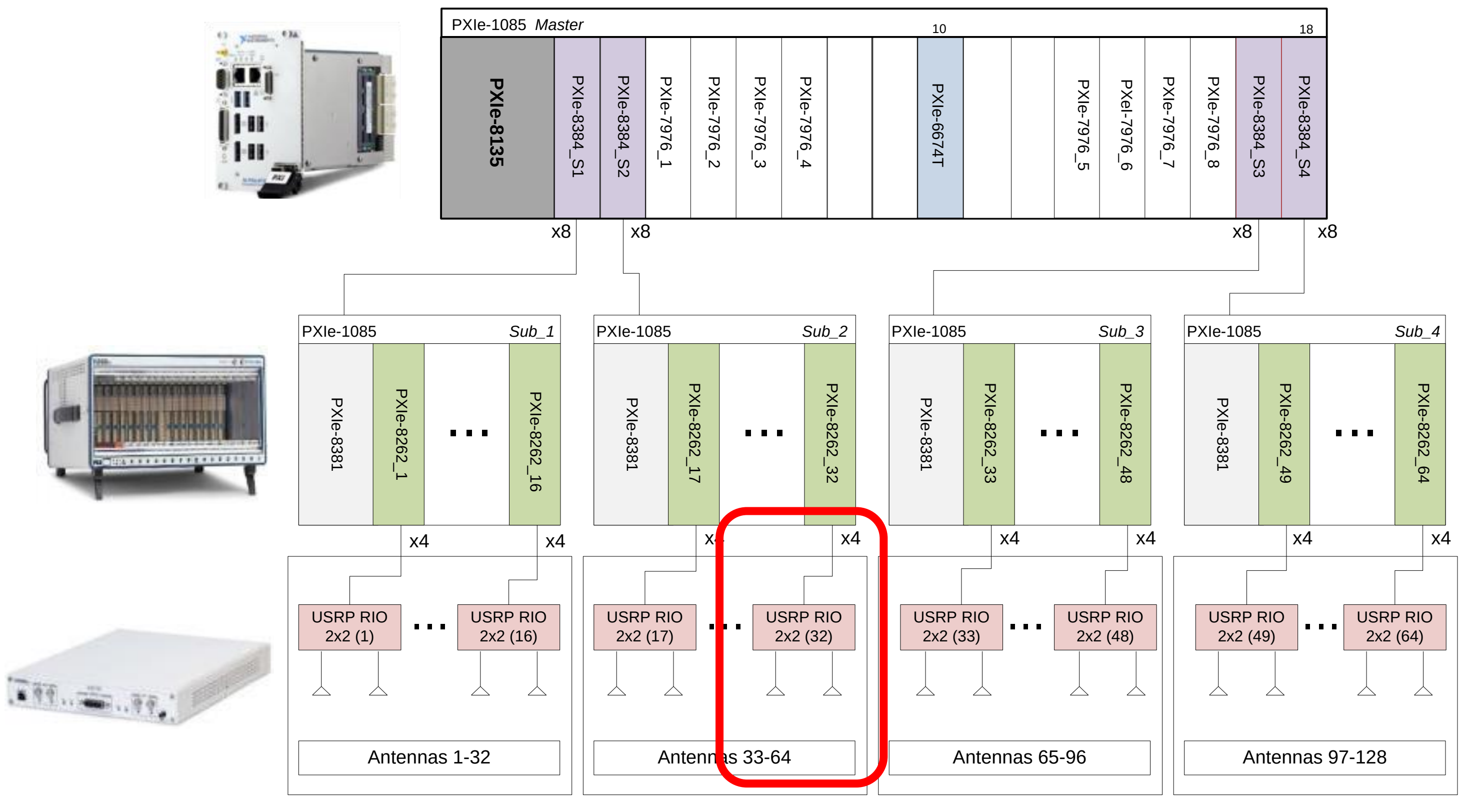
Processing distribution (over 50 FPGAs)

- **Data-level parallelism among antennas and subcarriers**
  - **<u>8 USRP</u> per subsystem, 7 subsystems**
  - **<u>150 subcarrier</u> per MIMO processing, 8 MIMO processors**



Let's focus on one of these sub systems ...

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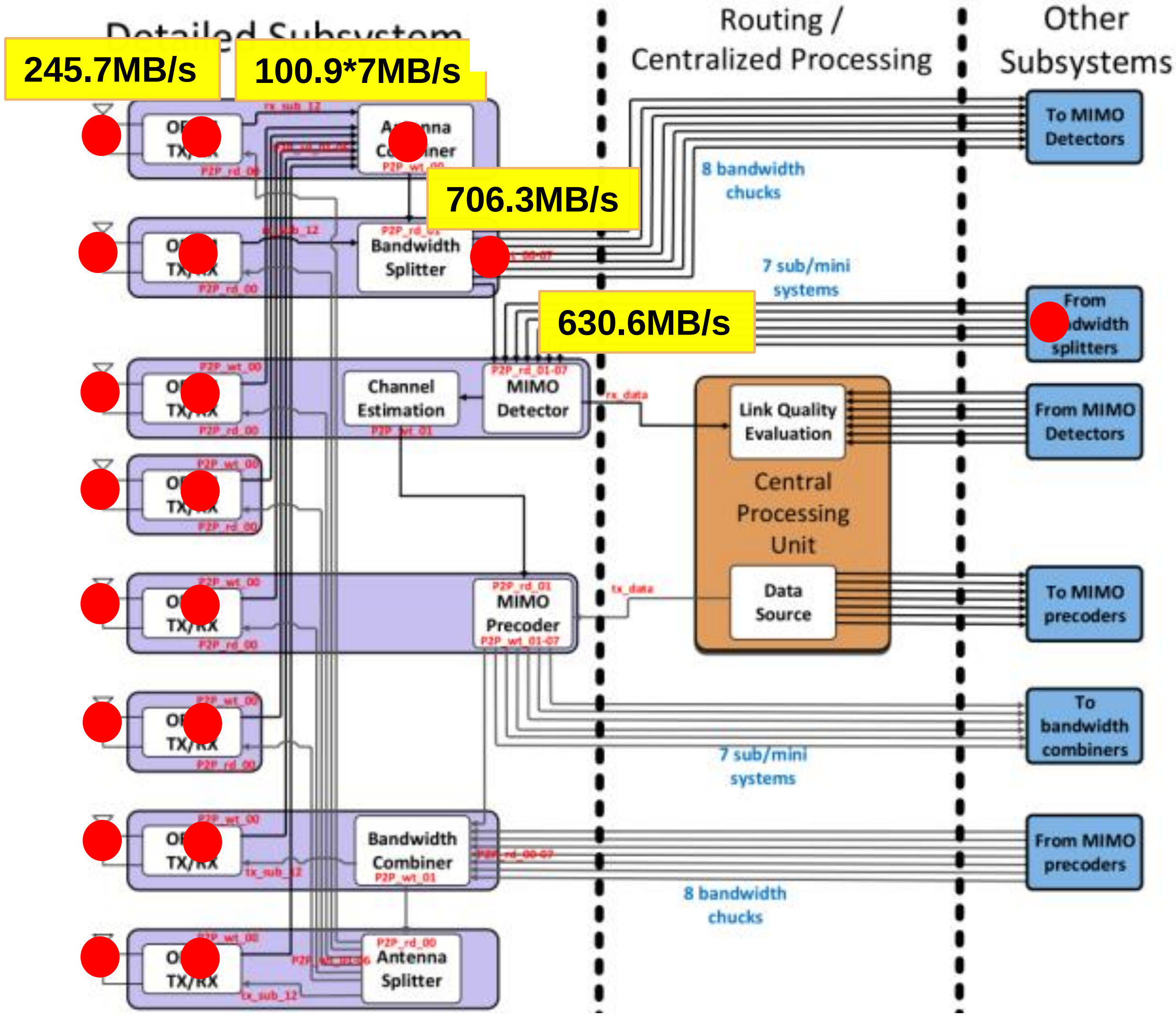
Data Shuffling



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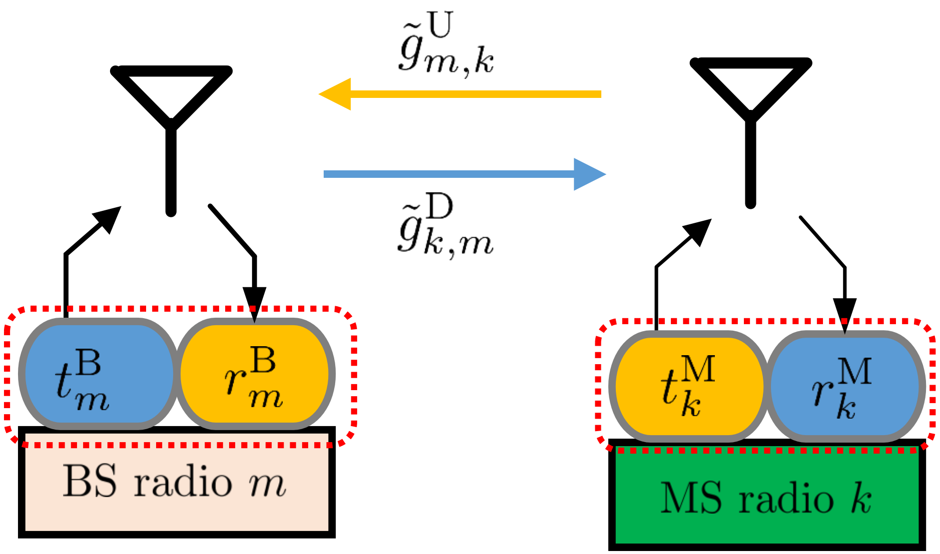
Reciprocity calibration

- Channel reciprocity is used to realize efficient TDD Massive MIMO



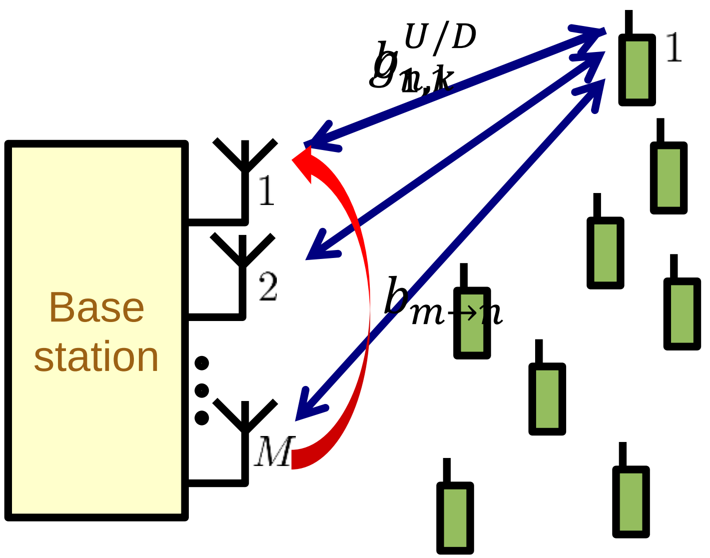
$$g^{\mathrm{U}}_{m,k} = r^{\mathrm{B}}_{m}\,\tilde{g}^{\mathrm{U}}_{m,k}\,t^{\mathrm{M}}_{k}$$

$$g^{\mathrm{D}}_{k,m} = r^{\mathrm{M}}_{k}\,\tilde{g}^{\mathrm{D}}_{k,m}\,t^{\mathrm{B}}_{m},$$

$$b_{m,k} = \frac{t^{\mathrm{B}}_{m}}{r^{\mathrm{B}}_{m}}\,\frac{r^{\mathrm{M}}_{k}}{t^{\mathrm{M}}_{k}}$$

Reciprocity calibration: solution

- Calibrate by referering to the same base-station antenna
  - Calibration within base-station

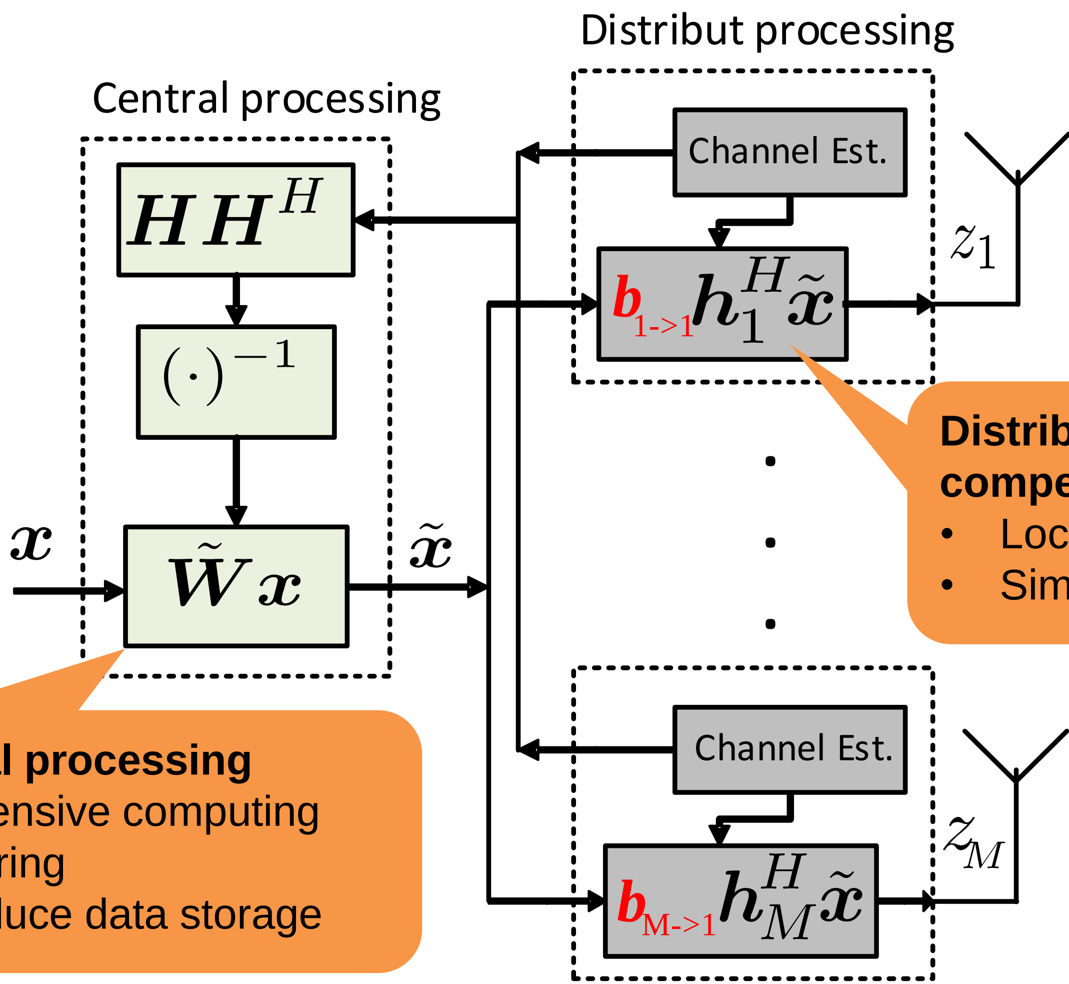


$$b_{m,k} = \frac{t_m^{\mathrm{B}}}{r_m^{\mathrm{B}}} \frac{r_k^{\mathrm{M}}}{t_k^{\mathrm{M}}} = \frac{r_n^{\mathrm{B}}\, t_m^{\mathrm{B}}}{r_m^{\mathrm{B}}\, t_n^{\mathrm{B}}} \frac{r_k^{\mathrm{M}}\, t_n^{\mathrm{B}}}{r_n^{\mathrm{B}}\, t_k^{\mathrm{M}}} = b_{m\to n} b_{n,k}$$

Calibration between reference ante. and UE: **down-link pilot**

Calibration with in base station: **slow changes**

Reciprocity calibration: processing distribution

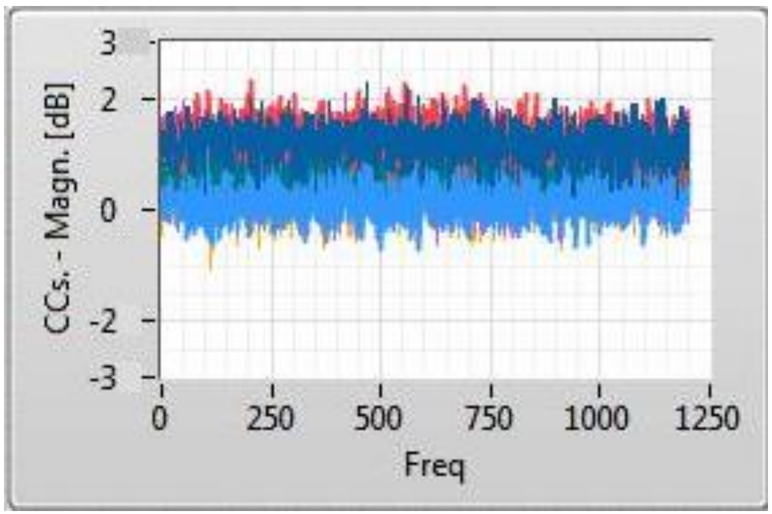


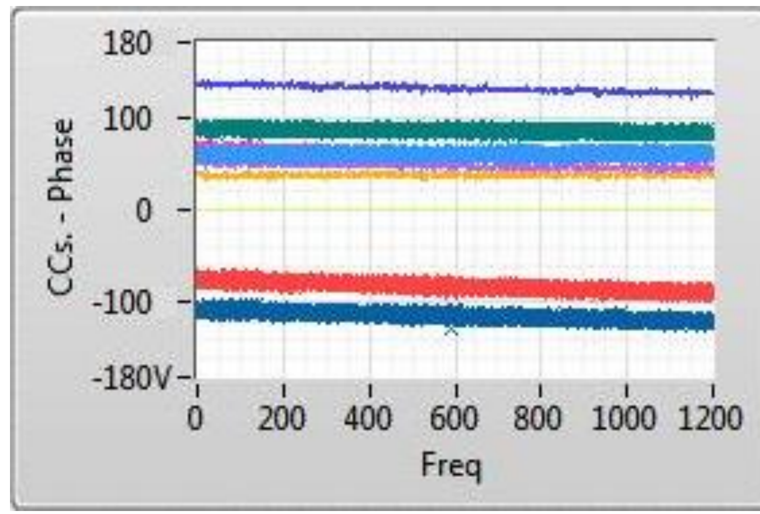
Distributed compensation
- Localize data transfer
- Simplify memory access

Central processing
- Extensive computing sharing
- Reduce data storage

Reciprocity calibration: initla results

- Calibration process within base station (**$b_{m->n}$**)
  - transmit successively
  - use antenna coupling and listen with all other antennas

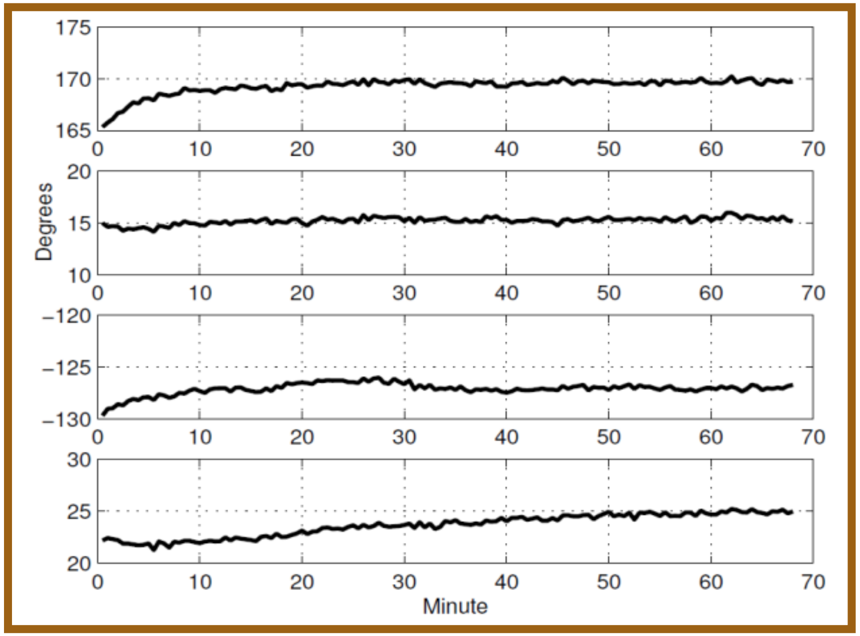




Changes with frequency

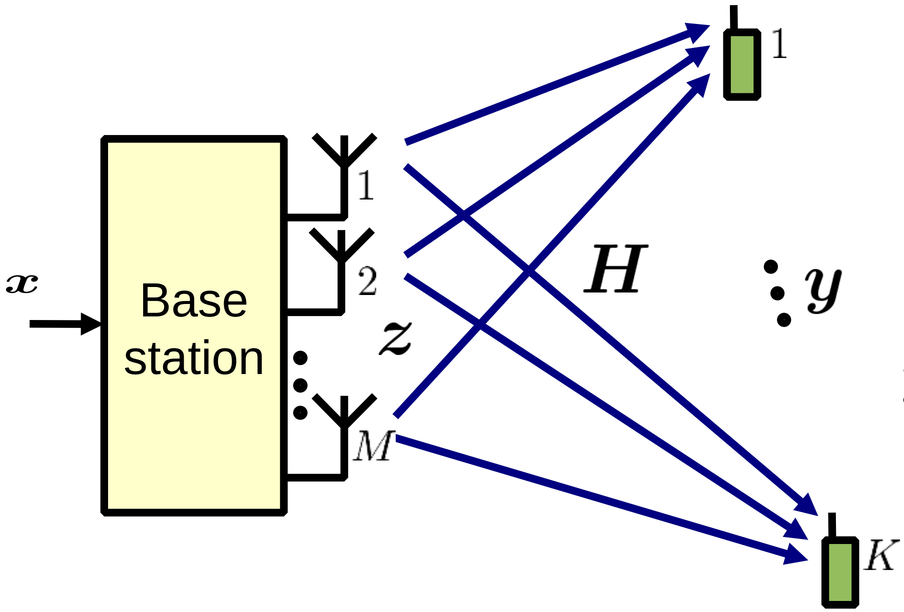
Reciprocity calibration: initla results

- Calibration process within base station (**$b_{m->n}$**)
  - transmit successively
  - use antenna coupling and listen with all other antennas



Changes with time

High Speed DSP: Pre-coding & detection



Maximum-ratio transmission (MRT)

$$\boldsymbol{z} = \boldsymbol{H}^H \boldsymbol{x}$$

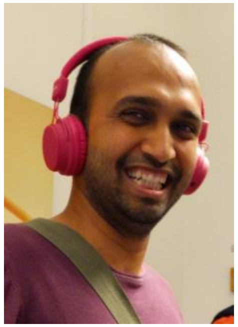
Hermitian transpose of channel

Zero-forcing (ZF)

$$\boldsymbol{z} = \boldsymbol{H}^+ \boldsymbol{x}$$

Pseudo-inverse of channel

- Matrix inversion with Neumann-series approximation
- Zero-forcing with QR-decomposition
- Zero-forcing with Cholesky-decompostion
- Constant-envelop pre-coding



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Demo (video)

https://www.dropbox.com/s/pid54pd1w6rn7y0/lumami2.mp4?dl=0

Research partners

Thanks!