Uplink Multi-User MIMO with SRS Channel Estimates in OpenAirInterface

Utku Uçak[1]

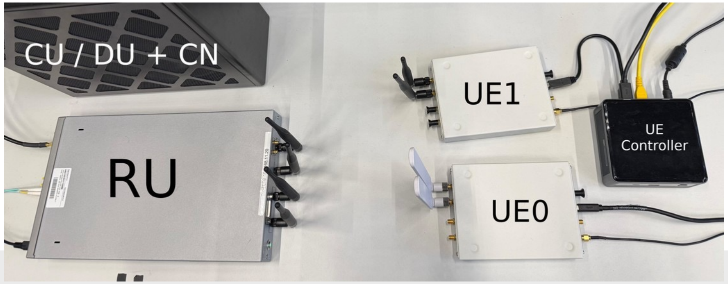
1: Fraunhofer Heinrich Hertz Institute, Berlin Germany

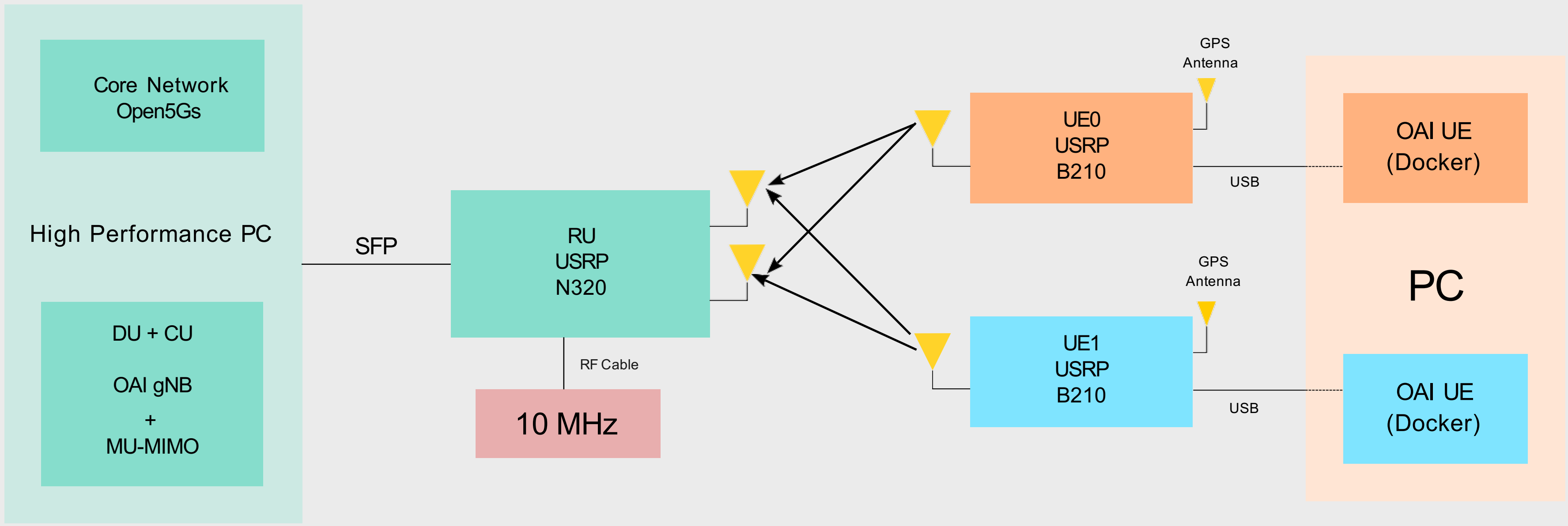
Fraunhofer HHI

Introduction & Motivation

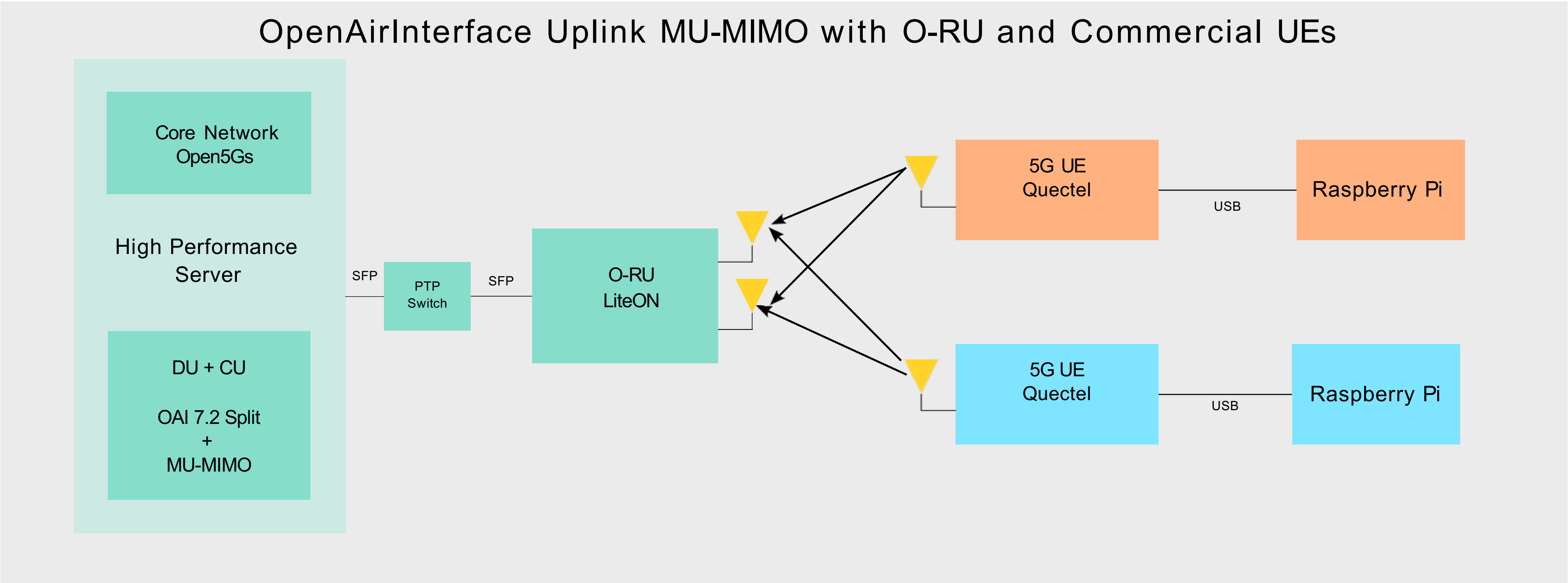
- A real time, end-to-end, 5G-NR compliant uplink MU-MIMO testbed with SDRs, based on OpenAirInterface
- By computing an uplink combiner matrix from SRS channel estimates and scheduling two user to non-orthogonal time-frequency resources
- Motivation
  - There is no 5G compliant open source project to experiment with MU-MIMO algorithms
  - MU-MIMO is considered a required feature for a cell-free system
  - Main operating mode of a cell free system is using TDD reciprocity to rely on uplink pilots for downlink precoder computation
  - Validate SRS as a piloting scheme for MIMO decoding for our Cell-Free testbed

System Block Diagram (USRP)





System Block Diagram (O-RU + COTS UE)



Theoretical Principles

OFDM MU-MIMO System Model (per subcarrier):

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}$$

Linear MIMO Detection:

$$\hat{\boldsymbol{x}} = \boldsymbol{V}^{\mathrm{H}}\boldsymbol{y}$$

where,

$\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{n} \in \mathbb{C}^{2}$ transmit, receive, and noise vectors

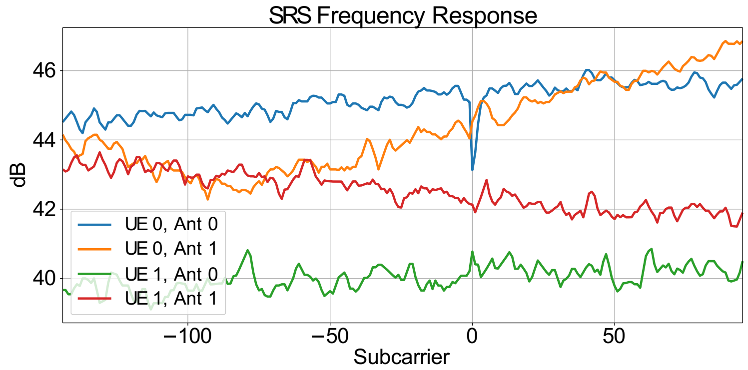
$\boldsymbol{H}, \boldsymbol{V} \in \mathbb{C}^{2\times 2}$ channel and combiner matrix

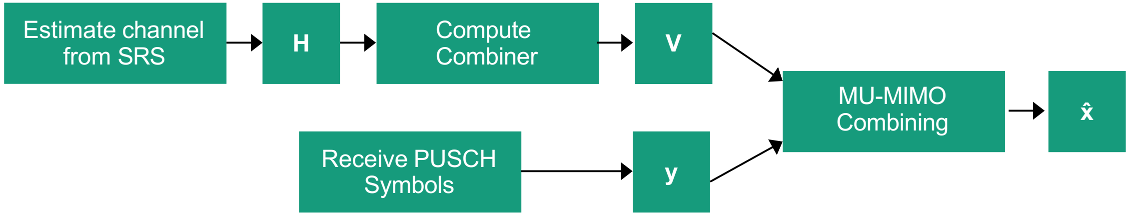
Maximum Ratio Combining (MRC):

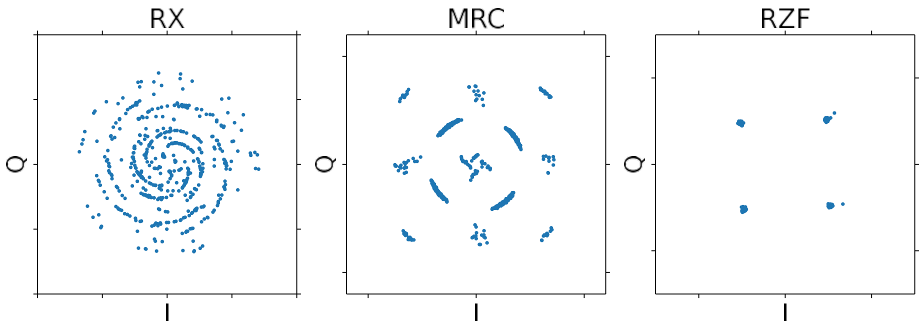
$$\boldsymbol{V}_{\mathrm{MRC}}^{\mathrm{H}} = \boldsymbol{H}^{\mathrm{H}}$$

Regularized Zero Forcing (RZF):

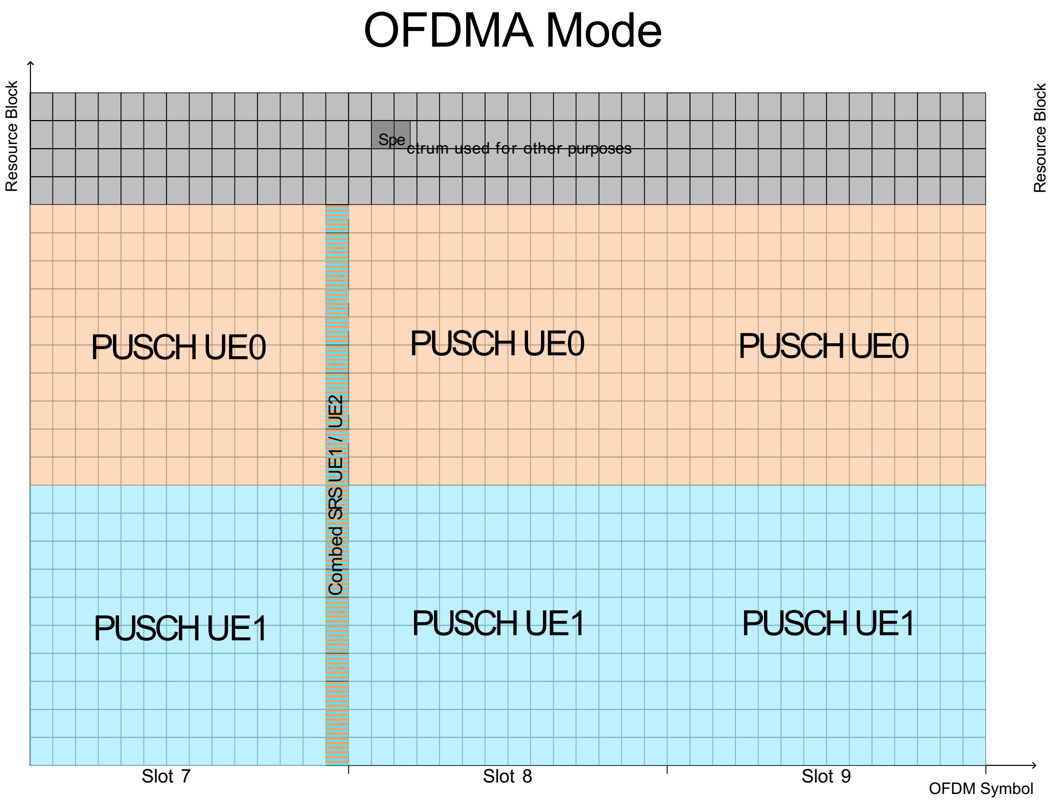
$$\boldsymbol{V}_{\mathrm{RZF}}^{\mathrm{H}} = \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H} + \lambda\boldsymbol{I}\right)^{-1}\boldsymbol{H}^{\mathrm{H}}$$

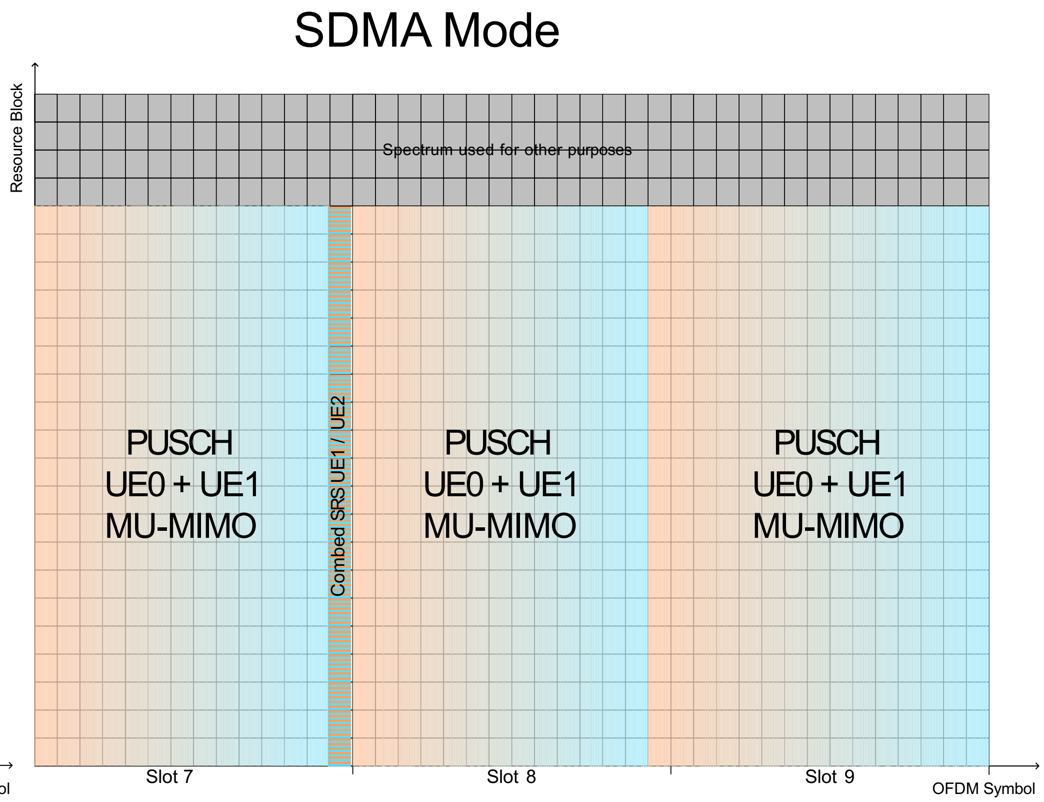






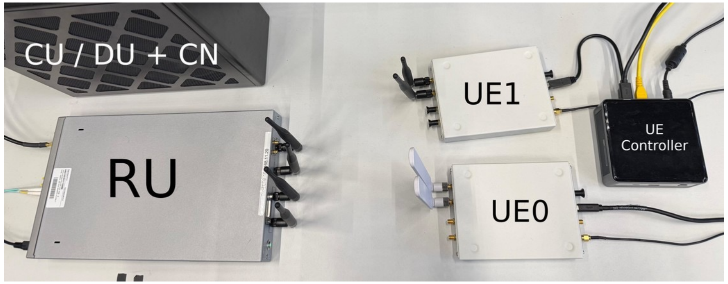
Uplink Scheduling Modes





Hardware Setup (USRP)

- Software Defined Radios
  - USRP N320 → RU
  - USRP B210 with GPSDO x 2 → UEs
- Computers
  - NUC Extreme for CU + DU + CN
  - NUC as a UE Controller, running two containerized OAI-UE instances
- RF Hardware
  - 10 MHz Signal source for gNB LO reference
  - Active GPS antennas for UE LO conditioning



OFDM System Parameters

No. Resource Blocks	24
No. Subcarriers	288
FFT Size	512
Sampling Rate	15.36 MSps
Subcarrier Spacing	30 kHz
Carrier Frequency	3319.68 MHz
Modulation	16-QAM
Code rate	.6

Hardware Setup (ORAN)

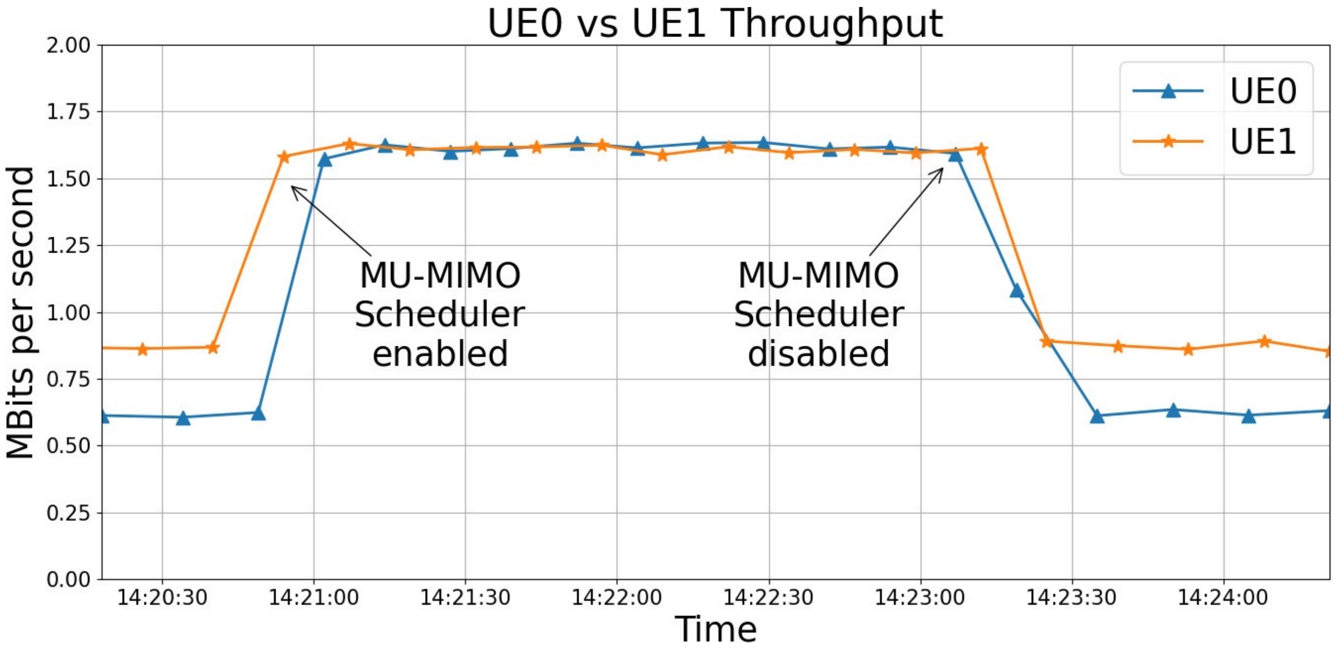
- O-RU
  - LiteOn
- UE
  - 2 x Quectel UE
- Computers
  - Server for CU + DU + CN
  - RasperryPi as a UE Controller
- Networking
  - PTP Switch

OFDM System Parameters

No. Resource Blocks	24
No. Subcarriers	288
FFT Size	512
Sampling Rate	15.36 MSps
Subcarrier Spacing	30 kHz
Carrier Frequency	3319.68 MHz
Modulation	16-QAM
Code rate	.6

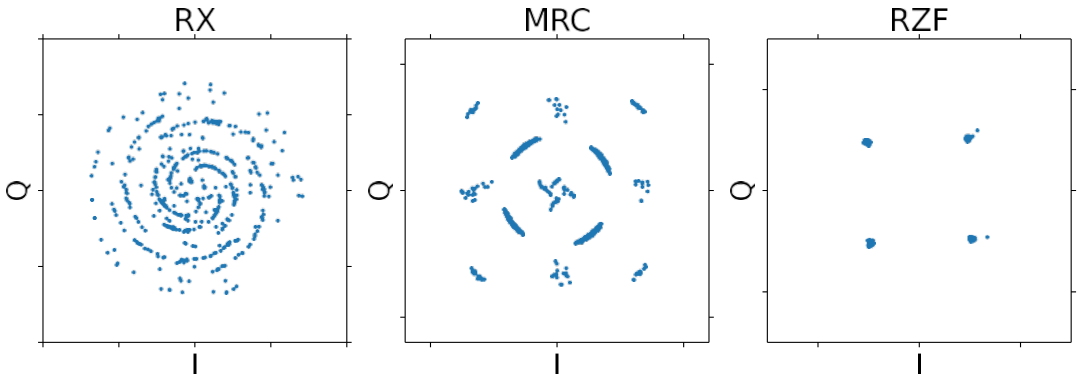
Results: Throughput Gains

- Clear increase in total throughput when schedule is switched to MU-MIMO mode.

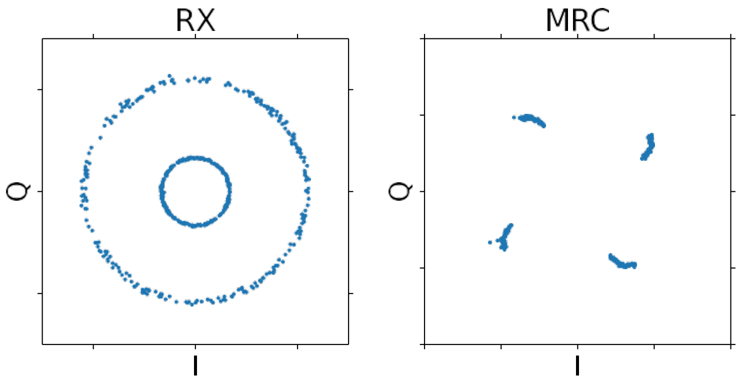


Results: Equalization with and without interference

- As expected, MRC is enough to equalize the signal when scheduling is orthogonal but channel inversion is necessary in SDMA mode.



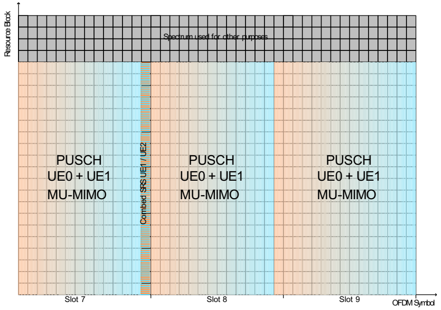
SDMA Scheduling



OFDMA Scheduling

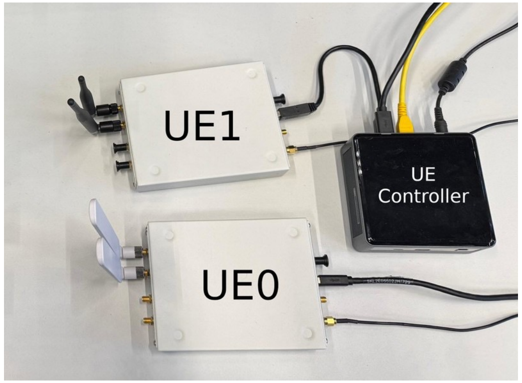
Practical Insight: SRS, DMRS, and two step channel equalization

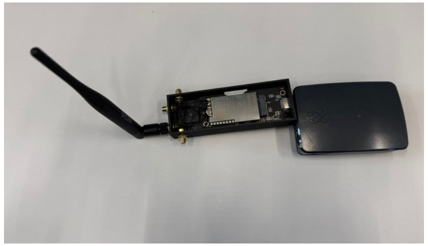
- Conventionally, PUSCH-DMRS pilots are used to compute MIMO combiners in an uplink MU-MIMO system.
- In this work, we chose to use SRS instead for acquiring the channel matrix for the two main reasons:
  - To decouple the channel estimation from users’ uplink data traffic.
    - The end goal is exploiting the TDD channel reciprocity and using uplink pilots to compute downlink precoders.
    - We would like to be able to do this even if user’s do not have uplink traffic.
  - To minimize the modifications necessary to the OAI code base.
    - PUSCH-DMRS channel estimation is tightly integrated with PUSCH decoding routine in OAI.
    - We can implement SRS based combining as a preprocessing step and leave OAI’s original PUSCH routine mainly untouched.



Practical Insight: OAI-UE, Commercial UEs, and Frequency Synchronization

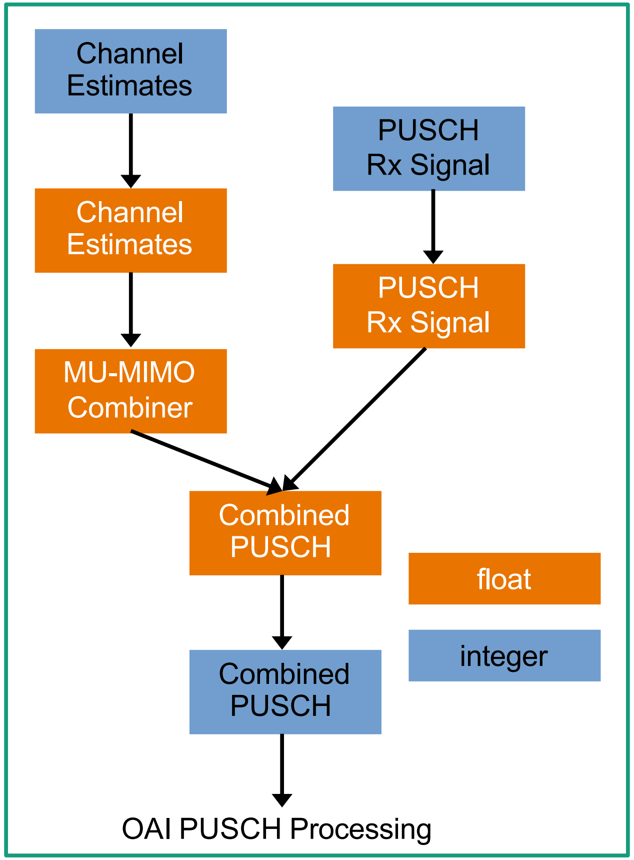
- We experimented with two types of UEs in this work:
  - Commercial 5G modules
  - USRPs controlled by OAI-UE software
- Both are theoretically possible as our gNB modifications are transparent to the UE
- In practice, USRPs were more stable because of their carrier frequency synchronization feature
- Using a 10 MHz reference signal or a GPSDO greatly increased the system stability.





Practical Insight: Integer vs Floating Point Representation

- For real-time performance reasons, OAI uses integer arithmetic in PHY signal processing
- This is fast but error prone due to overflows and underflows
- This is specially severe in matrix inversion for RZF
- Because of that, we implemented our functions using floating point arithmetic and converting the signals from integer to float and back
- This implementation was fast enough for our system parameters



Physical Layer Implementation

Original Function

Algorithm 1 OAI gNB Rx PHY Processing (simplified)

```
Require: frame_idx, slot_idx, PUCCH_set, PUSCH_set,
  SRS_set
  for all PUCCH in PUCCH_set do
    DecodePUCCH(PUCCH)
  end for
  for all PUSCH in PUSCH_set do
    DecodePUSCH(PUSCH)
  end for
  for all SRS in SRS_set do
    SRSChannelEstimation(SRS)
  end for
```

Our Implementation

Algorithm 2 PHY receiver with MU-MIMO support (simplified)

```
Require: frame_idx, slot_idx, PUCCH_set, PUSCH_set,
  SRS_set
  for all PUCCH in PUCCH_set do
    DecodePUCCH(PUCCH)
  end for
  for all SRS in SRS_set do
    H ← SRSChannelEstimation(SRS)
    V ← ComputeRZFCombiner(H)
  end for
  for all PUSCH in PUSCH_set do
    if is_mu_mimo_active then
      MUMIMOPreprocessing(PUSCH, V)
    end if
    DecodePUSCH(PUSCH)
  end for
```

Conclusion & Future Work

- We have extended OpenAirInterface to build a real time, end-to-end MU-MIMO testbed.
- Periodic uplink pilots can be used to compute uplink MU-MIMO combiners. This paves the way for reciprocity based downlink MU-MIMO in Cell-Free systems.
- User grouping based on channel (dis)similarity, SRS scheduling schemes, and more sophisticated combiner algorithms are interesting areas for future work.
- The system is under further development to improve robustness, increase MIMO dimensions, and investigating the topics listed above.

References

- Utku Uçak, Fariba Armandoust, Matthias Mehlhose, Daniel Schäufele, Jochen Fink, Renato L. G. Cavalcante, Slawomir Stanczak *Uplink Multi-User MIMO Testbed Implementation in OpenAirInterface*, European Conference on Networks and Communications (euCNC) 2026, Malaga, Spain, May 2026, arXiv: https://arxiv.org/abs/2601.09384