Real-Time Experimentation Platform for sub-6GHz and Millimeter-Wave MIMO Systems.

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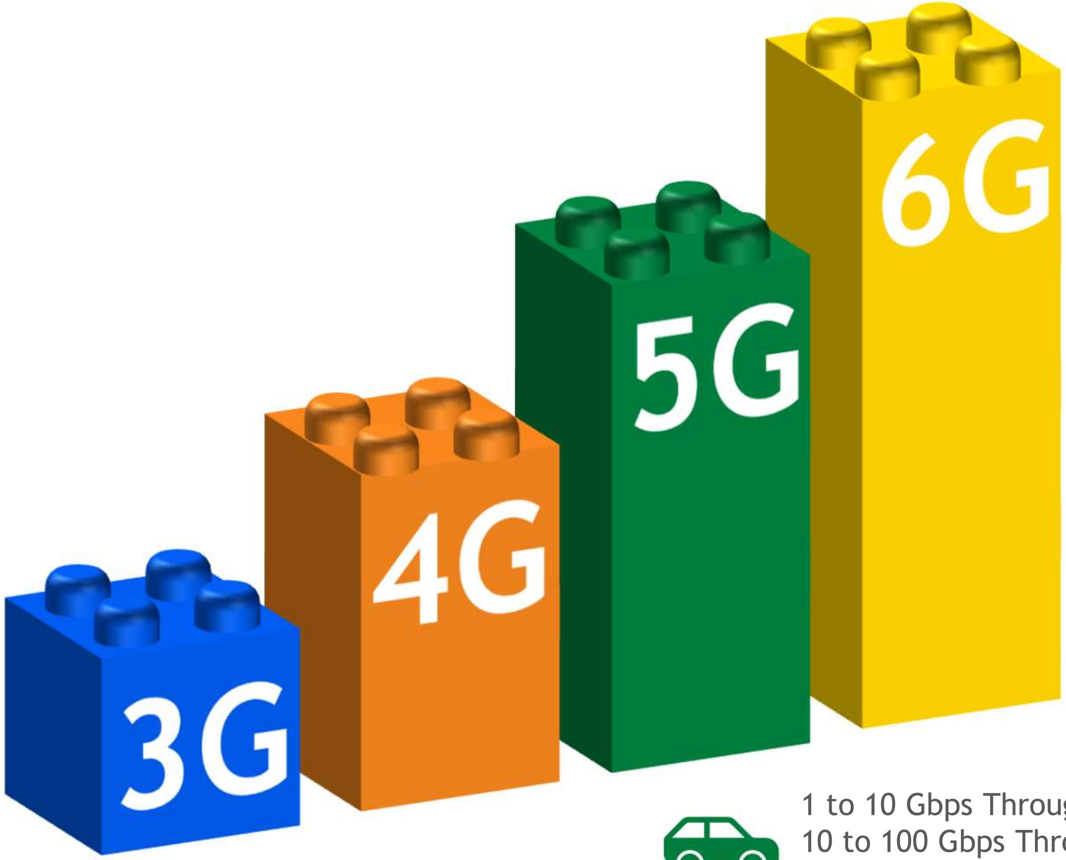
Developing the Science of Networks

The endless road to higher performance



2 Mbps Throughput
100-500 ms Latency

0.3 to 1 Gbps Throughput
10-50 ms Latency

1 to 10 Gbps Throughput (sub-6GHz)
10 to 100 Gbps Throughput (mmWave)
1 ms Latency ?

1 Tbps Throughput
100 us Latency ?

16x16 MIMO
256QAM
~400MHz BW
FR2 Freq.

} ~37Gbps

The endless road to higher performance

- Similarly for WLAN systems:
  - IEEE 802.11a/g → 54Mbps
  - IEEE 802.11n → 600 Mbps
  - IEEE 802.11ac → 6.9 Gbps
  - IEEE 802.11ax → 14 Gbps

  - IEEE 802.11ad → 7 Gbps
  - IEEE 802.11ay → >100 Gbps

} mmWave

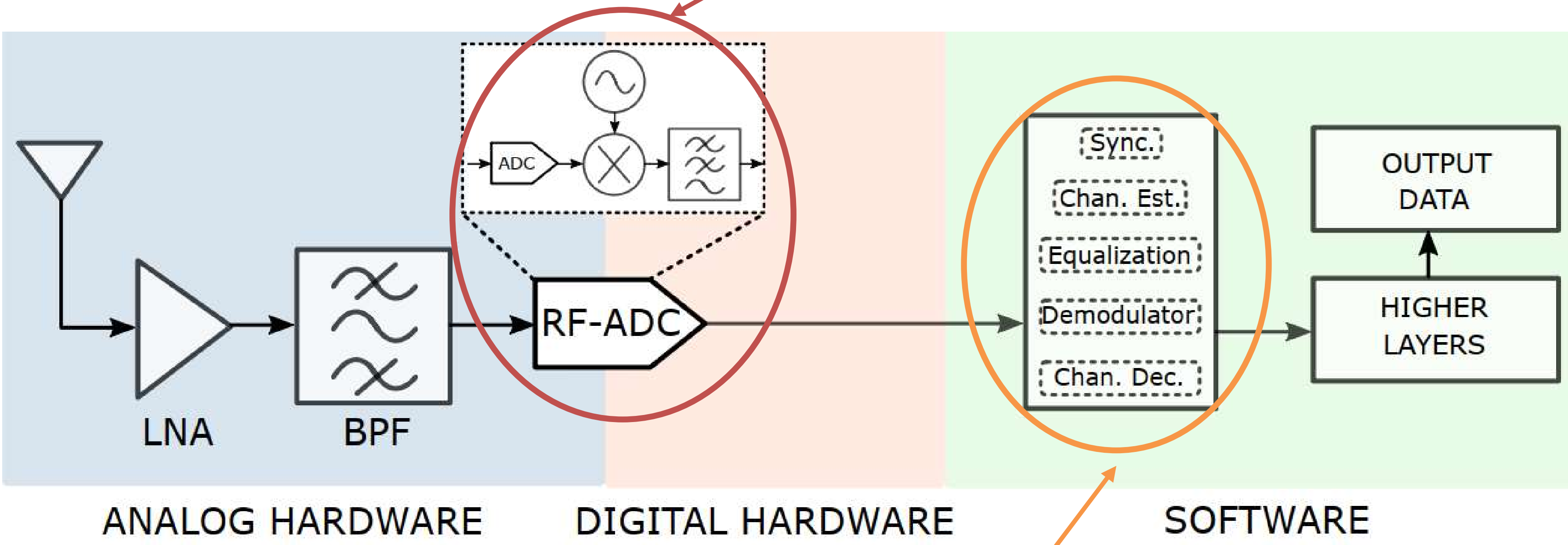
4x4 MIMO
64 QAM
>8 GHz BW
} 90 Gbps

What about experimentation?

- mmWave WLAN:
  - COTS devices, some (limited) FPGA-based testbeds
- THz communications:
  - Highly complex, some interesting preliminary work at Northeastern
- Mobile networks: 5G-NR and beyond (6G…)
  - COTS devices
  - srsRAN, OAI → all software (limited bandwidth, only FR1)
    - Now also LDPC offloading, targeting FR2 next year
  - No solutions for FR2 frequencies
    - Let alone mm-wave MIMO with multi-GHz bandwidth, etc. → future 6G

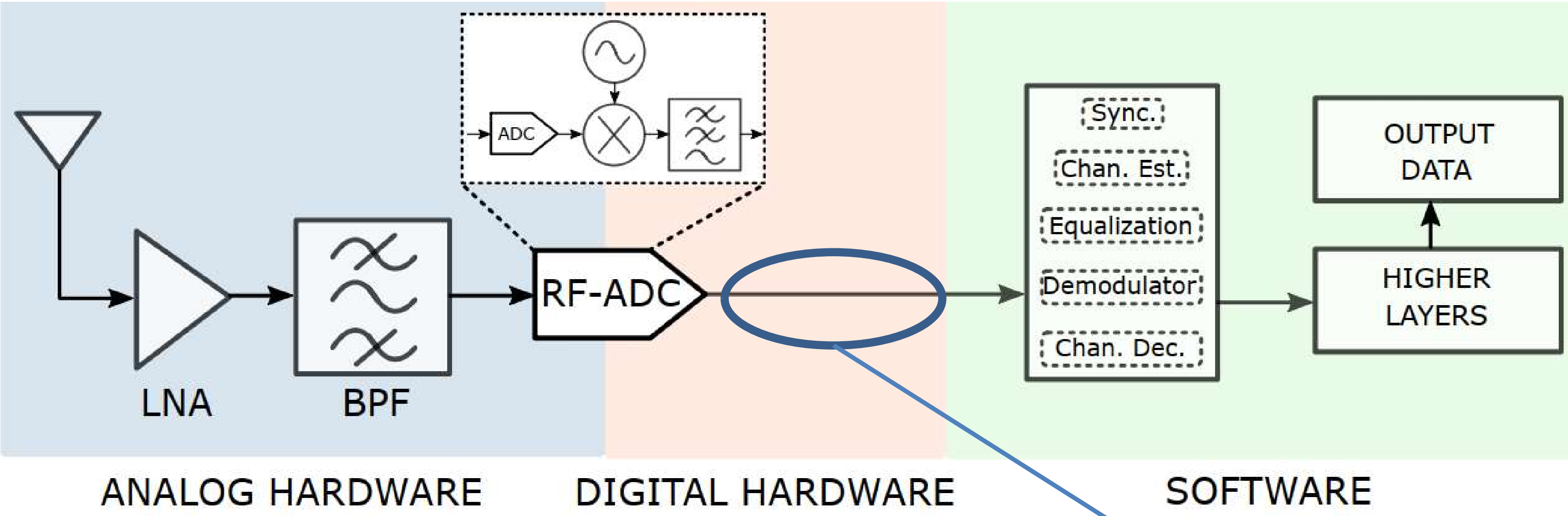
What about experimentation?

- ADCs with Giga-sampling rates capabilities become easily available → Direct RF sampling!



- High speed multicore processors become popular → Move functionality to software!

What about experimentation?



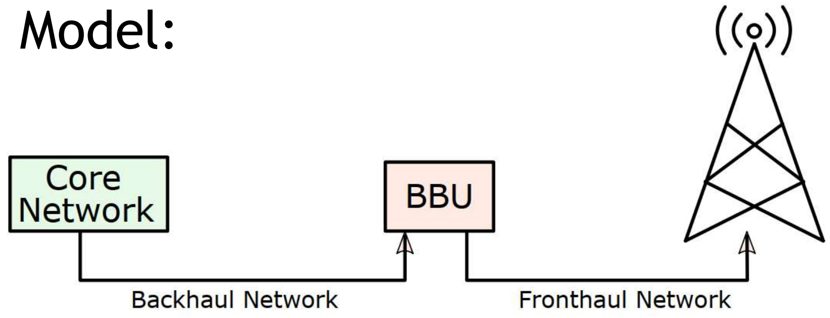
Digital hardware is "reduced" to *packetizers* and high-speed interfaces to send IQ samples to powerful processors (servers).

Only works for low to moderate bandwidth!

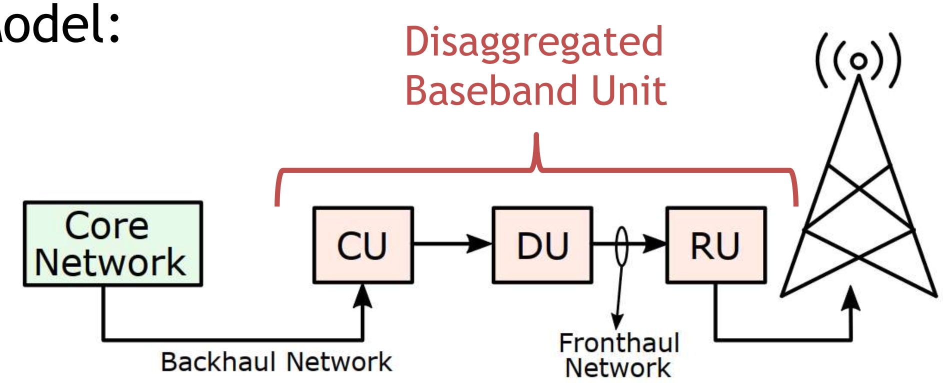
5G-NR functional splits

- Standardization committees are aware of the need of changing the architecture to support the envisioned capabilities of 5G/6G networks:

From 4G C-RAN Model:



To 5G RAN Model:

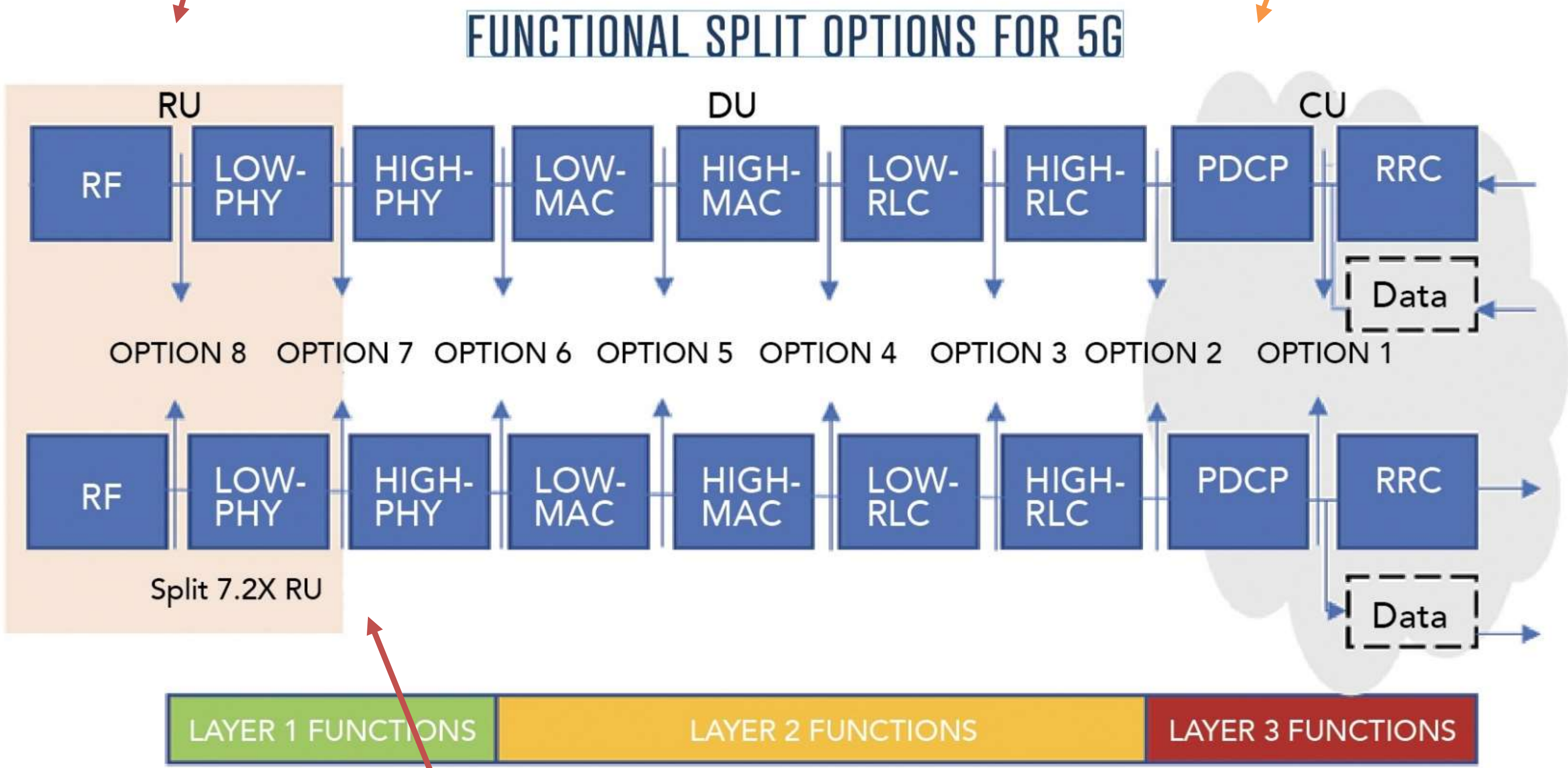


https://www.5gtechnologyworld.com/functional-splits-the-foundation-of-an-open-5g-ran/

5G-NR functional splits

More functions implemented in SW

More functions implemented in HW



7.1: remove CP / FFT
7.2: RE demapper
7.3: Equalization / Layer Demapper / Demodulation

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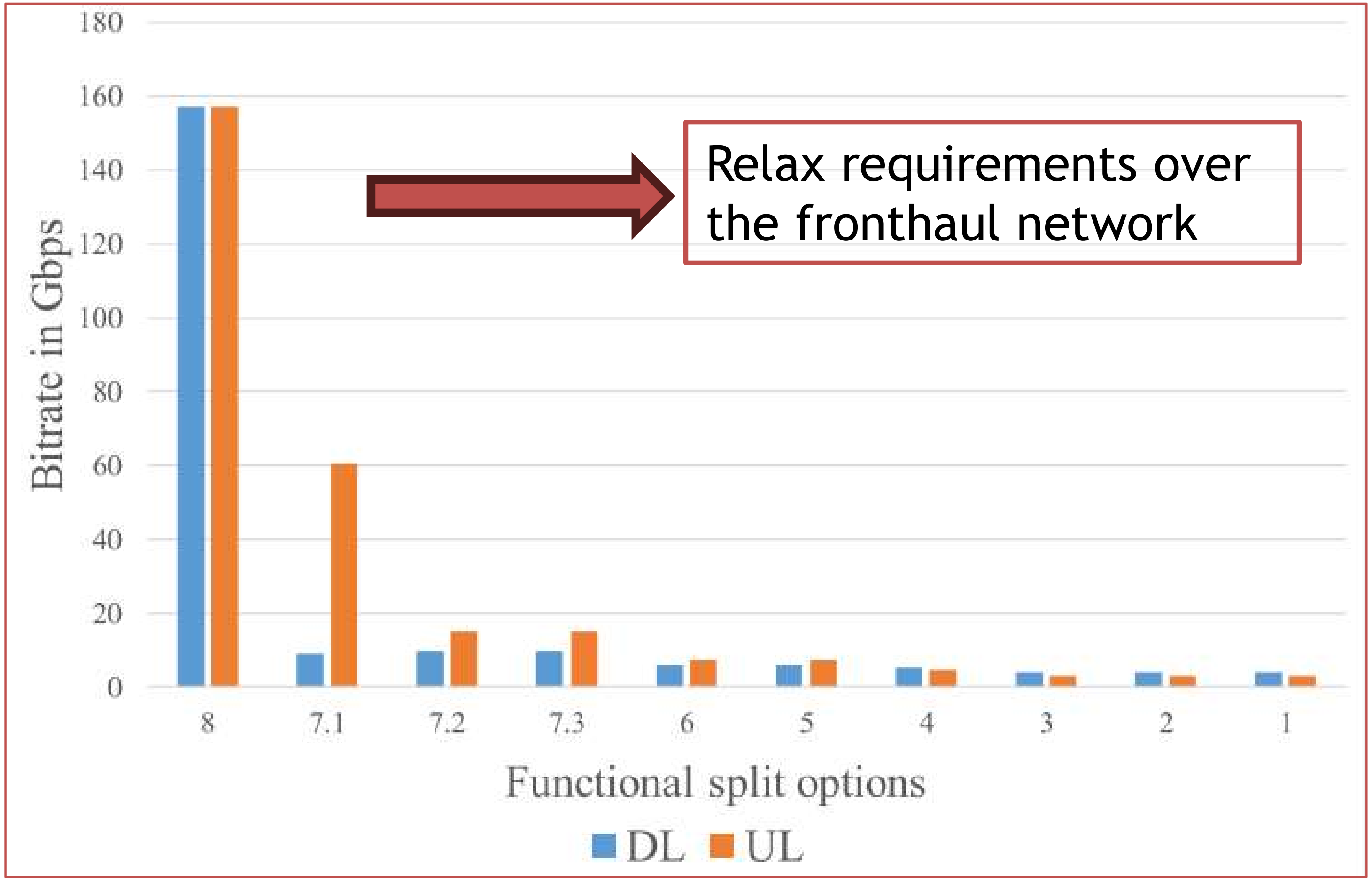
5G-NR functional splits

- Fronthaul bit rates:

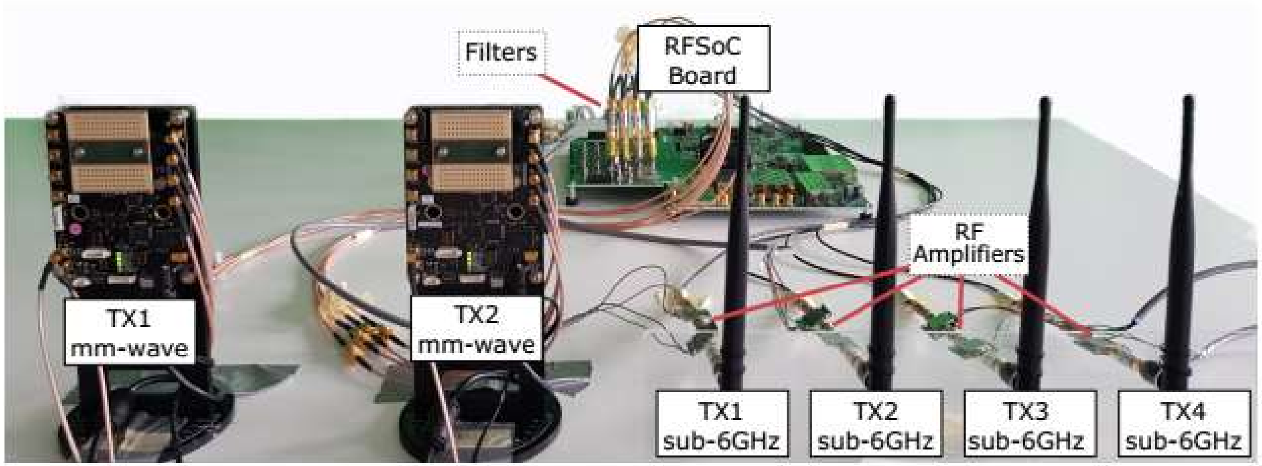


https://www.5gtechnologyworld.com/functional-splits-the-foundation-of-an-open-5g-ran/

MIMORPH platform[1]

Open-source system based on Xilinx RFSoC board

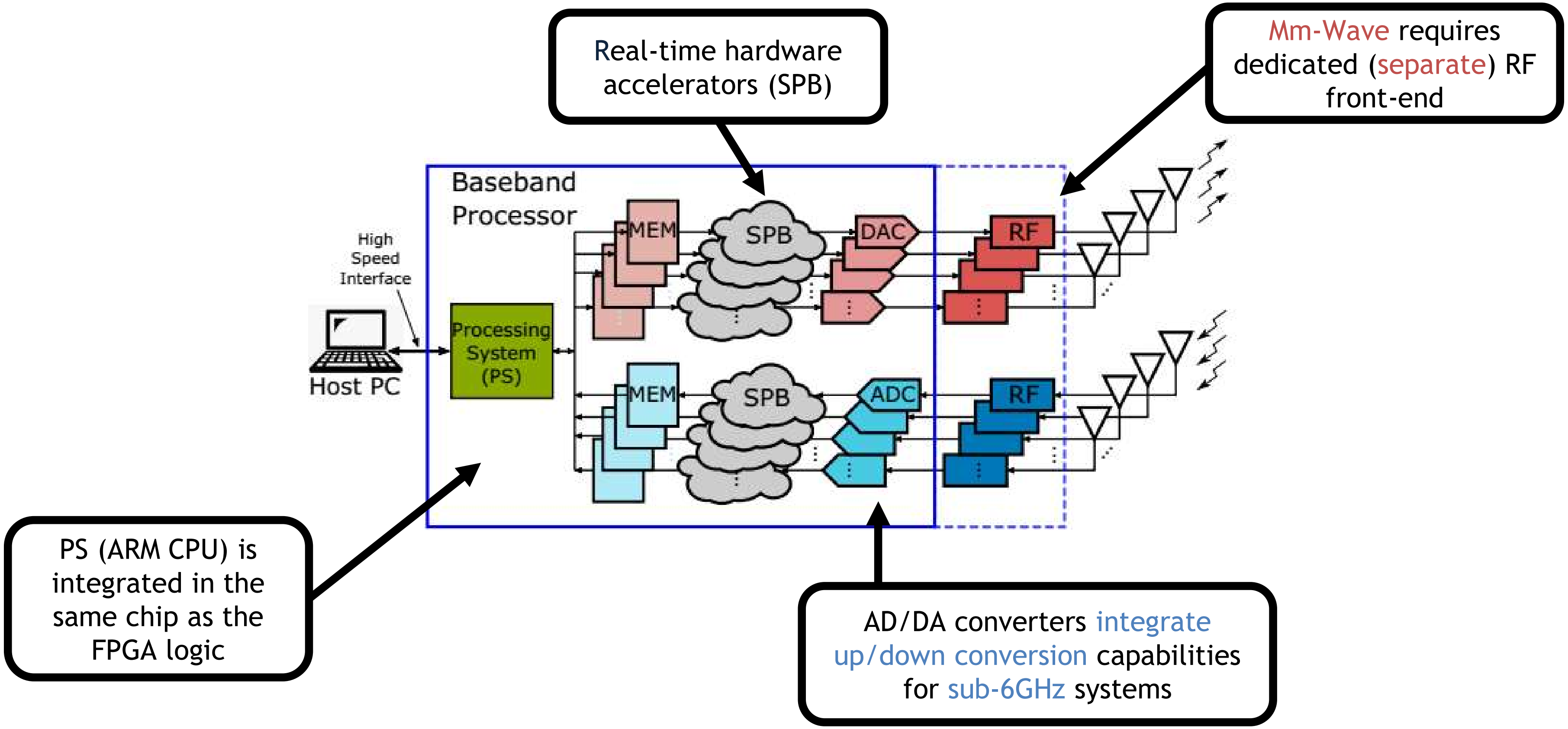
- Memory-based design with hardware accelerators for time-critical functions (full DDR memory to store IQ samples)
- Main focus: ultra-high performance
- Three basic operation modes:
  - 8x8 MIMO at any sub-6 GHz frequency
  - 4x4 MIMO at mmWave via exchangeable RF frontends (e.g., 24-30 GHz or 57-71 GHz) with up to 2 GHz of bandwidth per channel! (Limited by the mmWave front-end)
  - Mixed configurations → multiple mmWave + sub-6 GHz interfaces



[1] J. O. Lacruz, R. Ruiz, and J. Widmer. 2021. "**A real-time experimentation platform for sub-6 GHz and millimeter-wave MIMO systems**". In ACM *MobiSys '21*. pp. 427-439. DOI:https://doi.org/10.1145/3458864.3466868

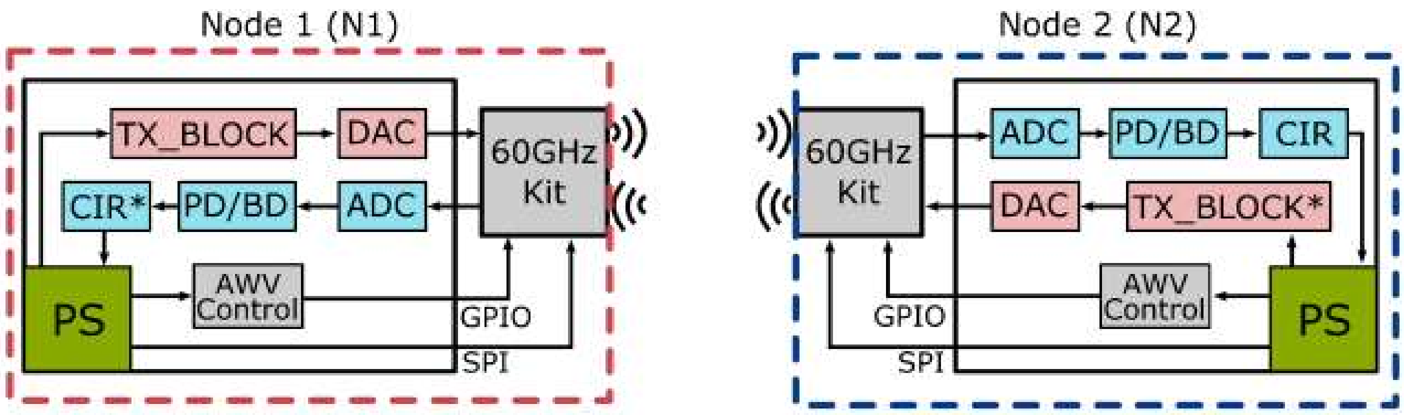
MIMORPH platform

- Memory-based design
  - Stream samples to/from on-board DRAM, offloading via Ethernet
  - Easy experimentation → send & capture frames and process in software (e.g., Matlab)
  - HW accelerators on the FPGA for time-critical functions
  - Efficient channelizer to work with different number of RF chains and bandwidth



MIMORPH platform

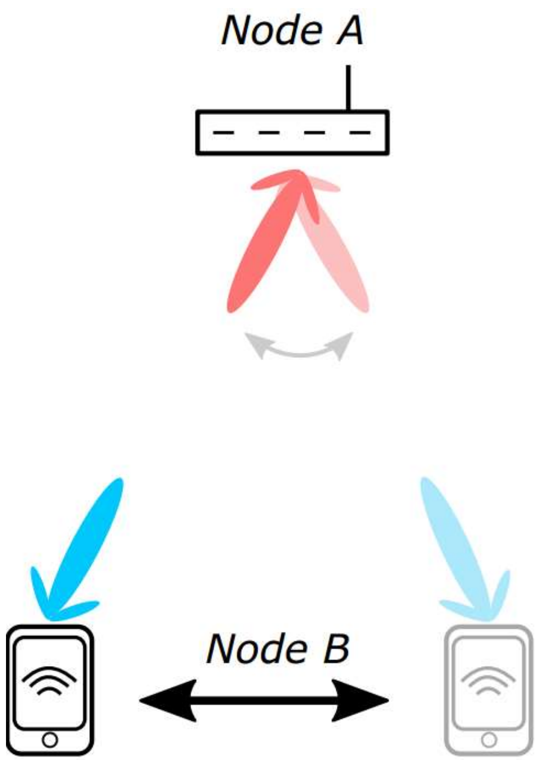
- Closed-loop operation
  - First of its kind for open mmWave experimentation
  - Several hardware accelerators to enable functionality
    - Packet detection / synchronization (currently for IEEE 802.11ay)
    - 4x4 MIMO channel estimation and beam tracking → ~100us Tx-Rx latency of the control loop
    - Nanosecond-level antenna reconfiguration → using GPIO / SPI functionality on the RFSoC and RF front-ends

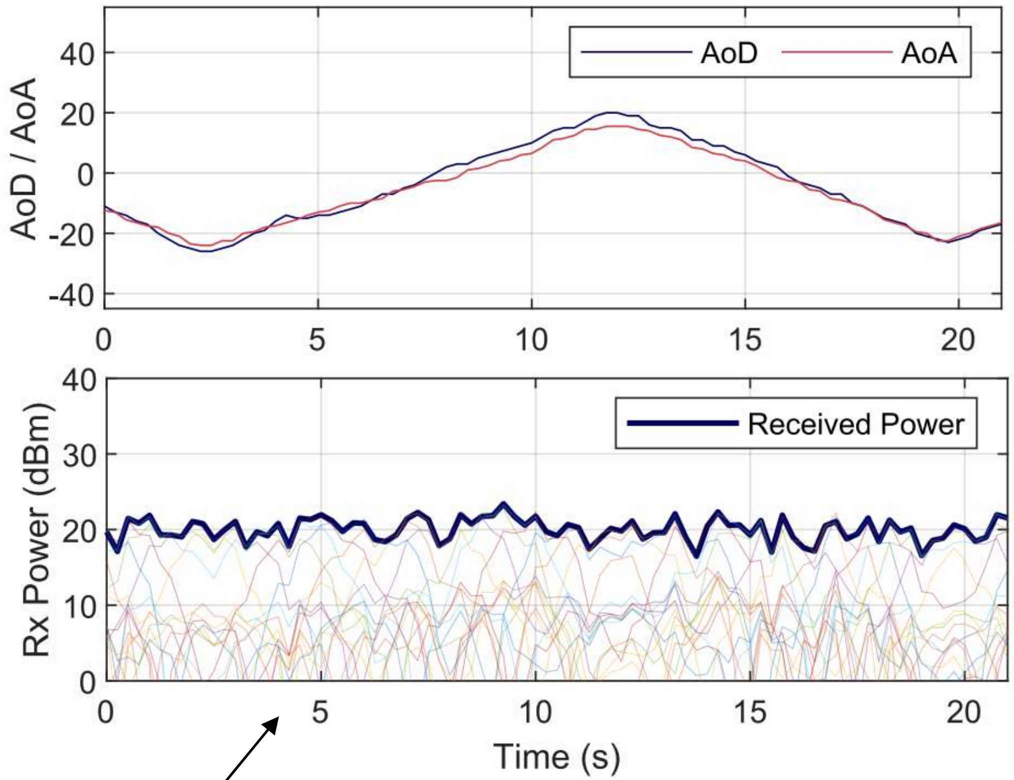


MIMORPH platform

- Real-time beam tracking

Receive power for the different beam patterns allows to locate the devices!





Always selects the best beam pattern combination for communication

5G → 6G platform

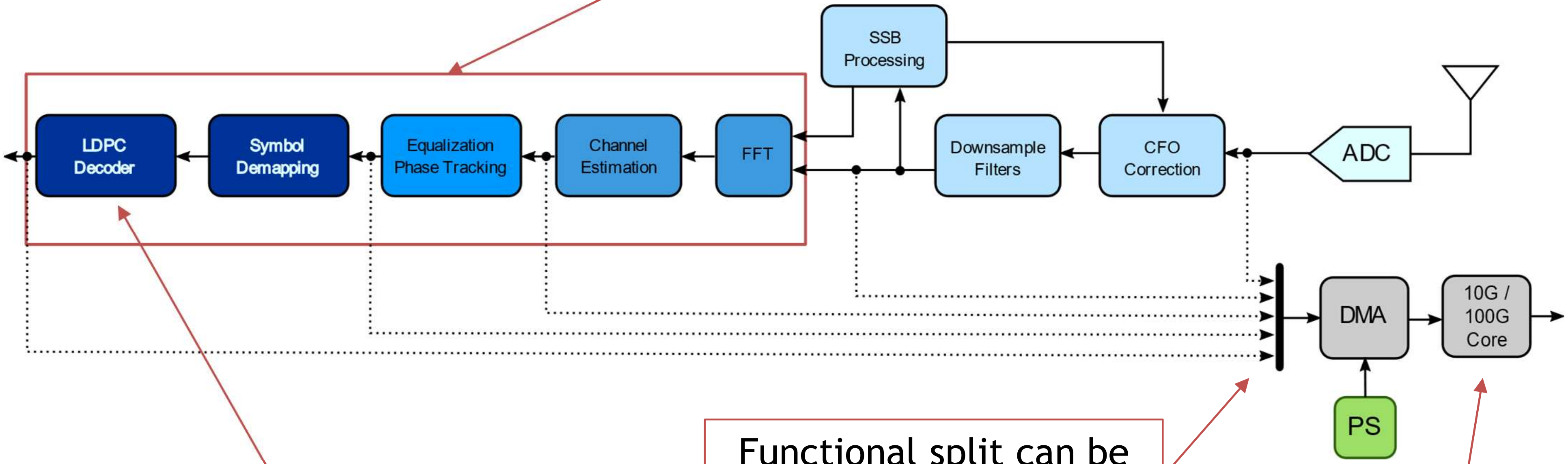
Use MIMORPH as baseline design:

- 5G-NR PHY platform (flexible functional splitting)
  - Multiple 5G-NR numerologies
    - 30KHz sub-carrier spacing (FR1) → sub-6GHz frequencies
    - 240KHz sub-carrier spacing (FR2) → mmWave frequencies
  - ~40MHz BW (FR1) and 400MHz BW (FR2)
  - Design can be extended to support higher bandwidths

5G → 6G platform

- 5G PHY receiver:

Implemented in HW or SW depending on the functional split



Functional split can be changed on real time!

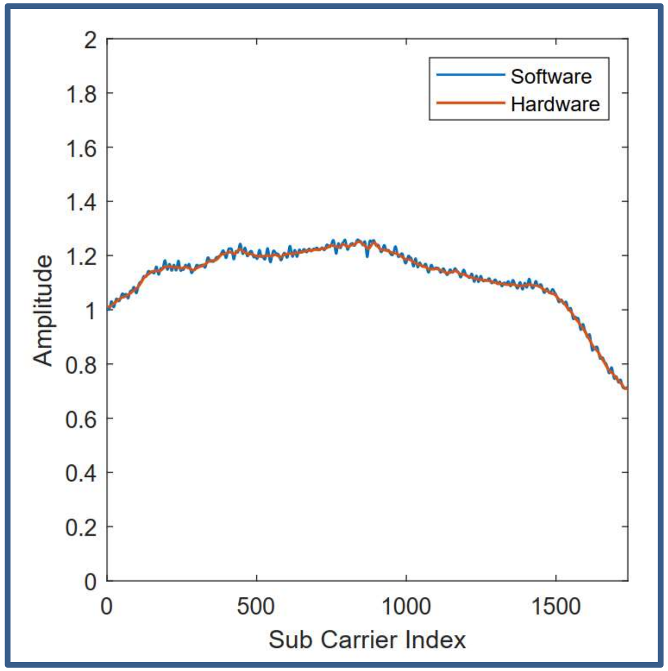
-Heavy computational complexity
-Take advantage of hardware on the RFSoC

10G interface was added to stream information faster!

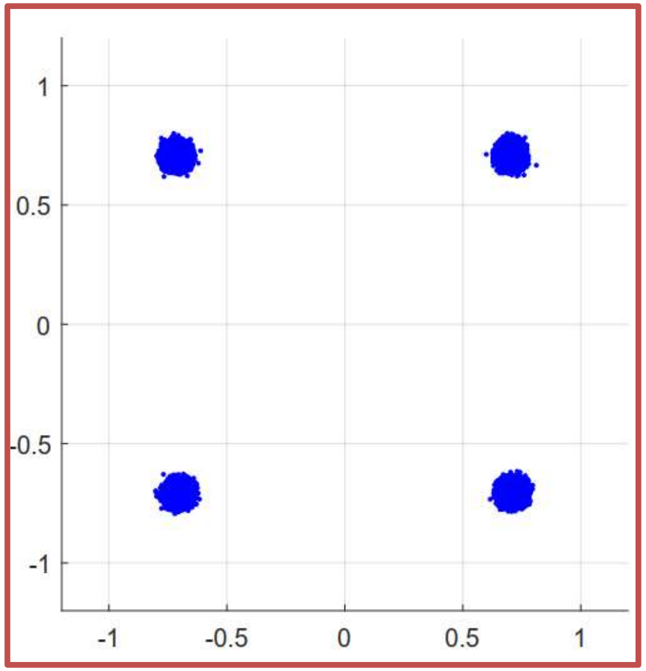
5G → 6G platform

- Some results....

417MHz BW



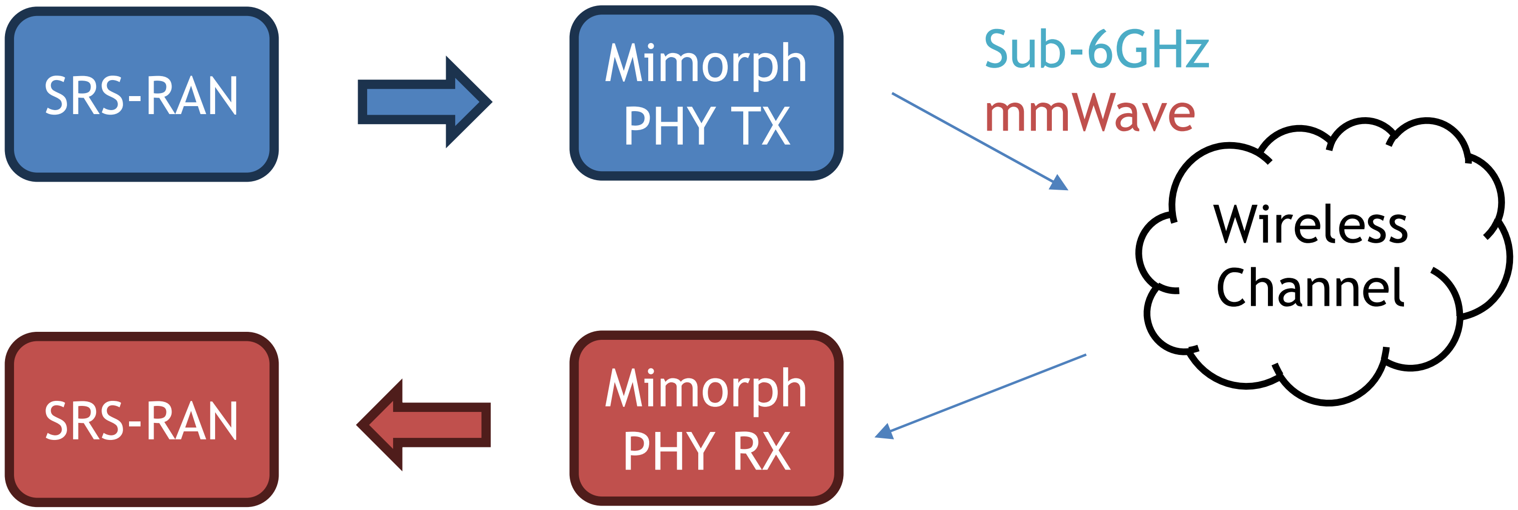
Measured Channel



IQ constellation

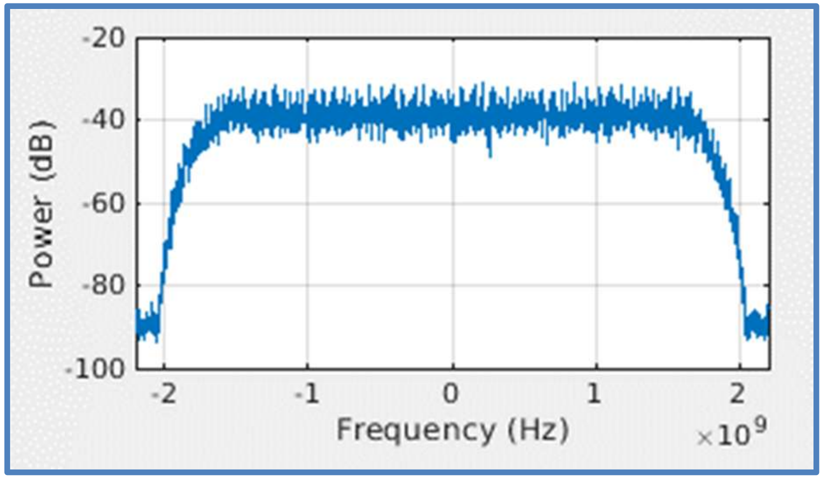
5G → 6G platform

- Short-term goals
  - 5G PHY transmitter:
    - Same capabilities as the designed 5G PHY receiver.
    - Implemented on the same device → allowing for full-duplex operation (Ideal for Integrated Sensing and Comm. Systems)
  - Integration with SRS-RAN:
    - Configurable numerology, flexible on-demand capabilities.



MIMORPH Platform: What is next?

- Increase bandwidth to fit the requirements of future WLAN standards
  - Preliminary tests with single carrier IEEE 802.11ay generation / decoding with 4 GHz of bandwidth → First of its kind!



  - Enable new frontiers on JCS applications

MIMORPH Platform: What is next?

- THz communications
  - Gained a lot of attention recently!
  - Extremely challenging to have 8-10 GHz of BW!
  - Beyond capabilities of current RFSoC devices

  - Possible solutions:
    - Multi-ADC sample interleaving*
    - MIMO THz communications → Multi-RFSoC synchronization
      - Huge amount of data → Requires real-time processing
      - Limited FPGA logic

* https://www.xilinx.com/video/events/a-prototype-example-of-a-10gsps-rf-adc.html

MIMORPH Platform: What is next?

- Joint Communication & Sensing:
  - IEEE 802.11ay WLAN → higher bandwidth:
    - Higher Resolution
    - Frequency selective channels
  - 5G-NR JCS
    - MIMORPH is ready for this
    - Real-time channel measurements → more data in memory
    - Cooperation between FR1 and FR2 → best of both worlds
  - Impact of the position (angle) of the person on activity recognition
    - Micro Doppler changes!

MIMORPH Platform: What is next?

- Joint Communication & Sensing:

RAPID: Retrofitting IEEE 802.11ay Access Points for Indoor Human Detection and Sensing

SPARCS: A Sparse Recovery Approach for Integrated Communication and Human Sensing in mmWave Systems

JUMP: Joint communication and sensing with Unsynchronized transceivers Made Practical

MIMORPH Platform: What is next?

- Real-time Machine Learning assisted communication systems:
  - ML can help to improve communication performance
    - Cope with hardware imperfections, adapt to changing conditions
    - First results that we can outperform common baselines (MMSE, …)
  - Move ML engine to the FPGA logic
    - Not trivial: area is limited
      - Low-resolution ML engines
      - Sparse (not fully connected) architectures
  - JCAS: do sensing (like person identification & activity recognition) in real-time!

THANK YOU !