Institute for the Wireless Internet of Things at Northeastern University

Toward Open, Programmable, and Virtualized 5G Networks

Michele Polese

Institute for the Wireless Internet of Things

Northeastern University

m.polese@northeastern.edu

Toward Open, Programmable, and Virtualized 5G Networks

Contributions from

Institute for the Wireless Internet of Things, Northeastern University

- L. Bonati, M. Polese, S. D'Oro, S. Basagni, and T. Melodia, "Open, Programmable, and Virtualized 5G Networks: State-of-the-Art and the Road Ahead," Computer Networks, vol. 182, December 2020.
- L. Bonati, S. D'Oro, M. Polese, S. Basagni, and T. Melodia, "Intelligence and Learning in O-RAN for Data-driven NextG Cellular Networks", arXiv:2012.01263 [cs.NI], December 2020

University of Padova and AT&T Labs

- M. Polese, R. Jana, V. Kounev, K. Zhang, S. Deb, M. Zorzi, "Machine Learning at the Edge: a Data-Driven Architecture with Applications to 5G Cellular Networks", IEEE Transactions on Mobile Computing, June 2020

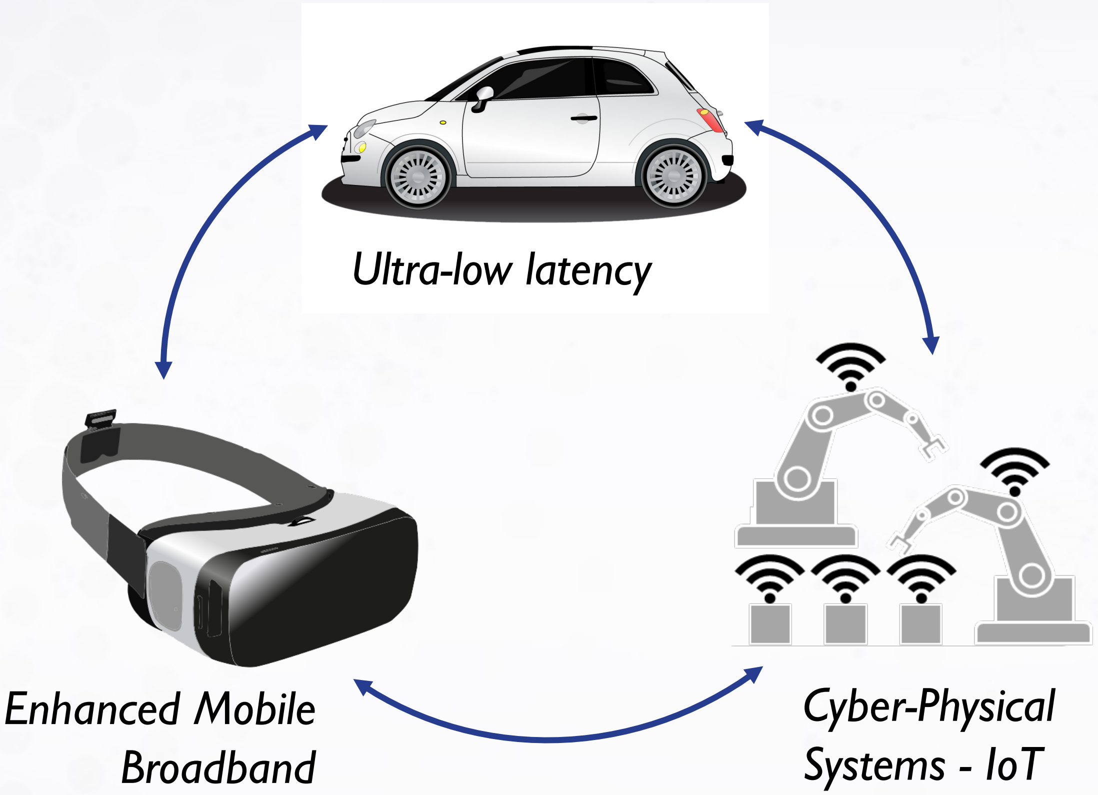
Institute for the Wireless Internet of Things at Northeastern University

Outline

- Openness and programmability
- 5G open, programmable, and virtualized architectures
- Intelligent control through O-RAN
- Use cases:
  - Self-clustering and load prediction
  - Scheduler selection with DRL
- Conclusions
- Useful resources

Institute for the Wireless Internet of Things at Northeastern

Why do we need a new architecture? - 1



5G supports a **diverse** and **heterogeneous** set of use cases

Need a **flexible** and **programmable** network architecture

Institute for the Wireless Internet of Things at Northeastern

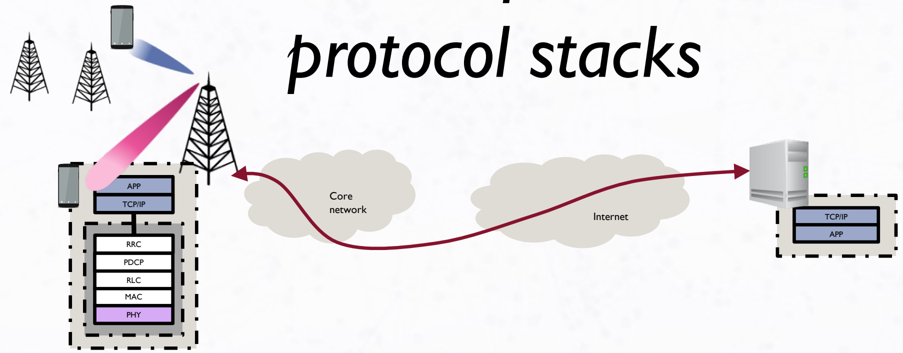
Why do we need a new architecture? - 2

Network complexity is increasing

More devices

More spectrum

Complex protocol stacks



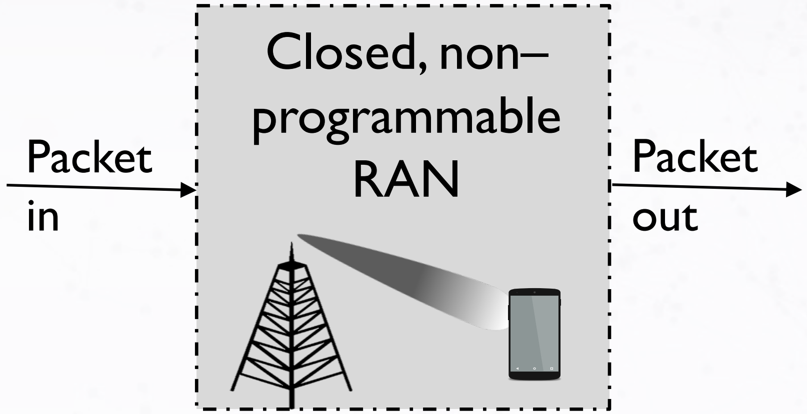
| 5G RAN | 5G Core | Internet | Applications |

Need an **automated** and **intelligent** network architecture

Institute for the Wireless Internet of Things at Northeastern

Toward open, programmable cellular architectures

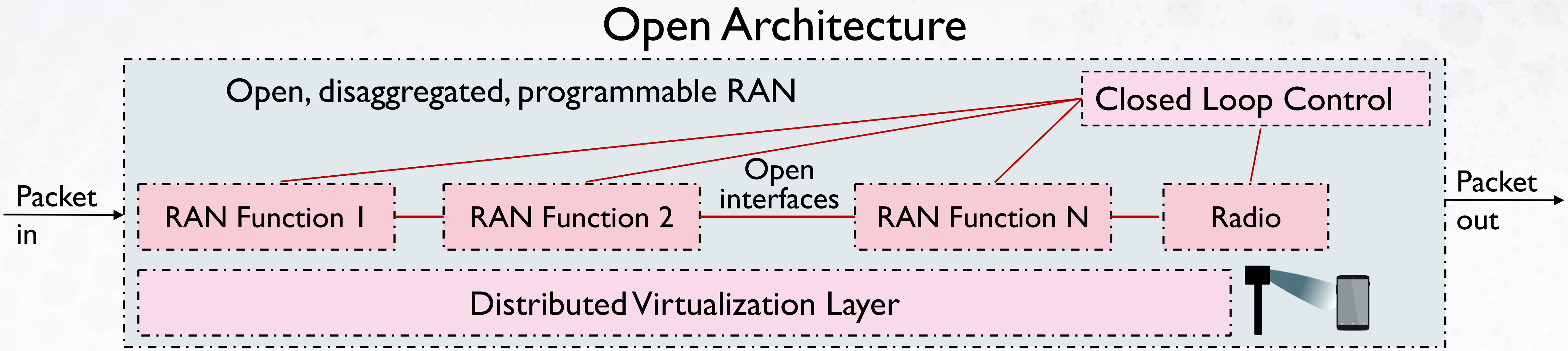
Black box Architecture



- Limited re-configurability and adaptability
- Limited coordination among network nodes
- Vendor lock-in

Institute for the Wireless Internet of Things at Northeastern

Toward open, programmable cellular architectures

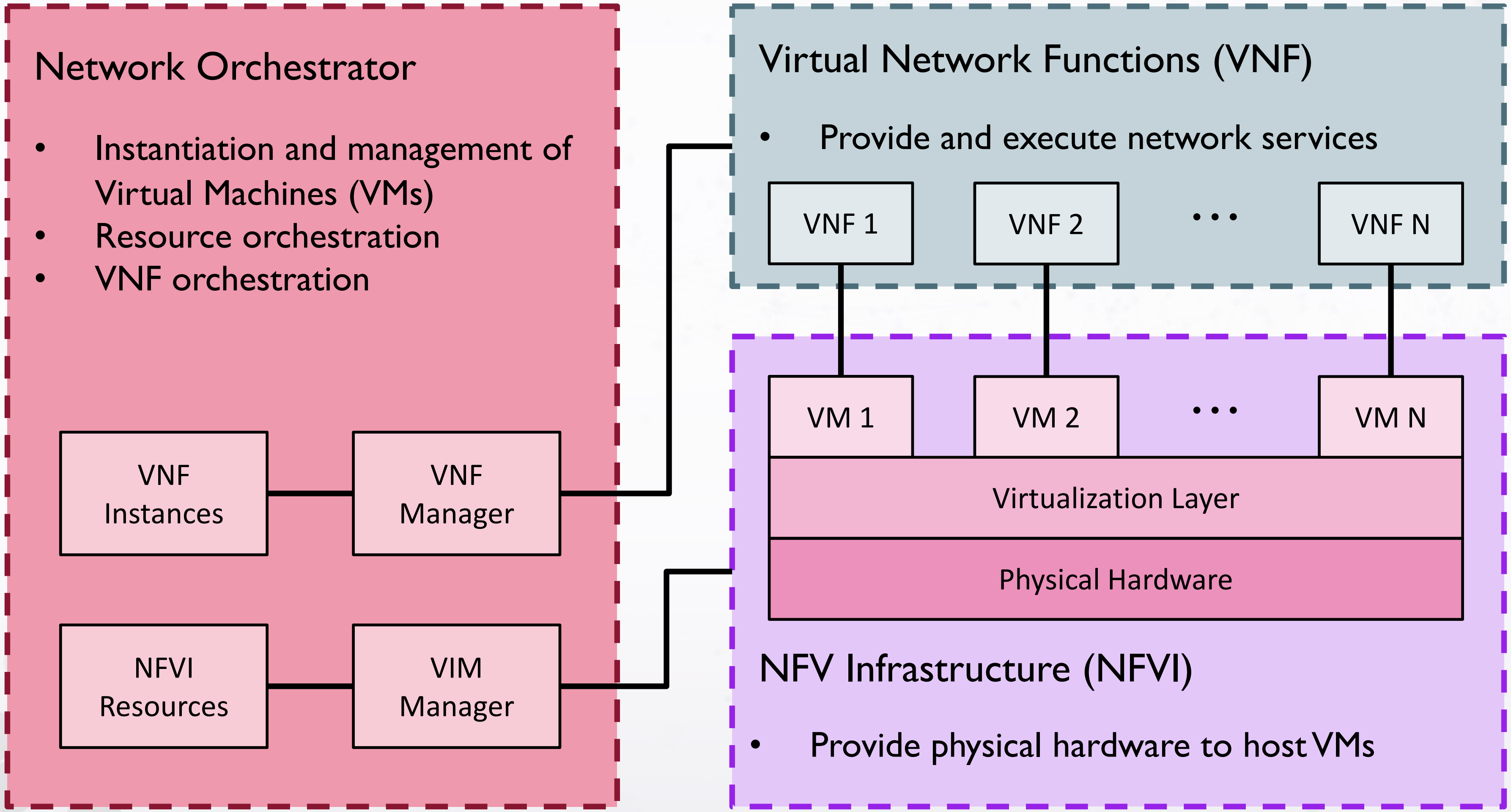


Based on

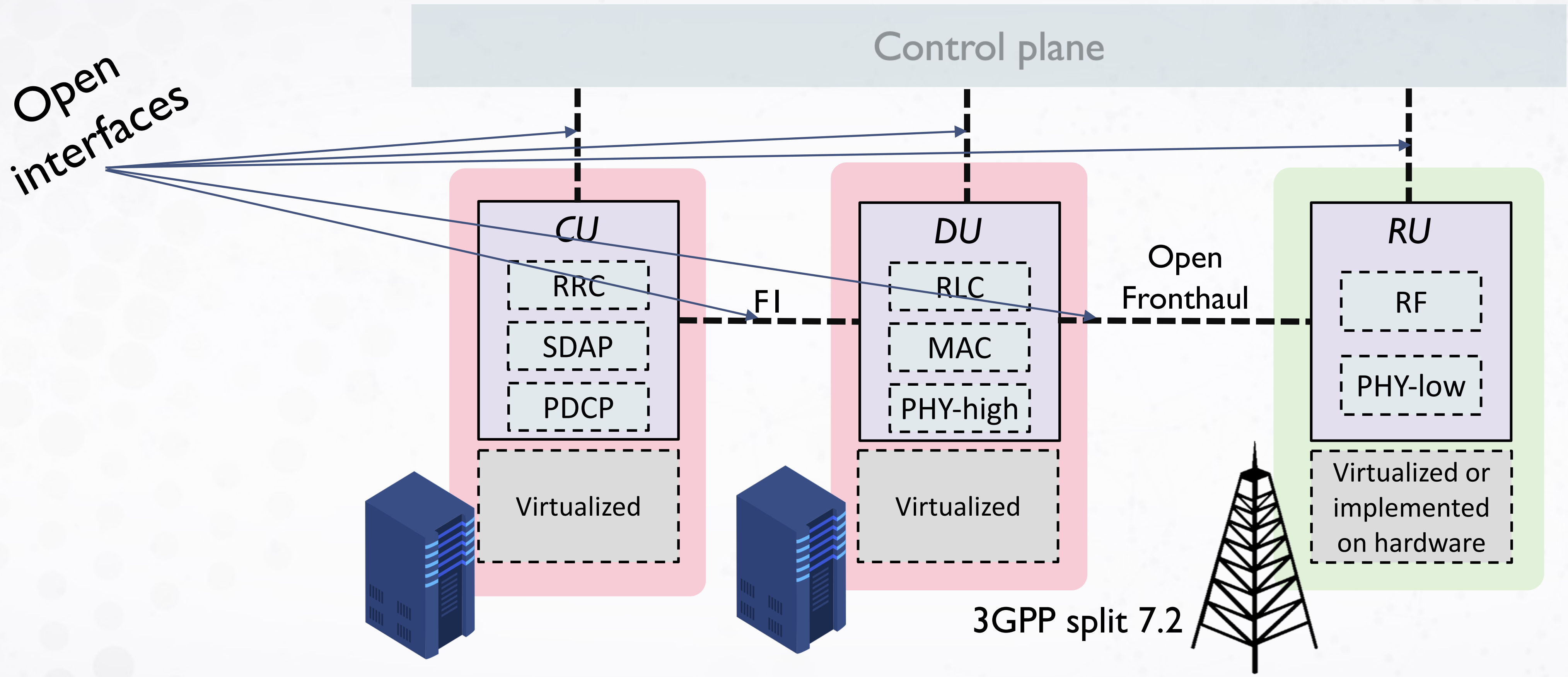
1. Virtualization
2. Disaggregation and open interfaces
3. Programmable network nodes and control loops

Virtualization

Networking functionalities are implemented in **software**, and run on **white-box** hardware

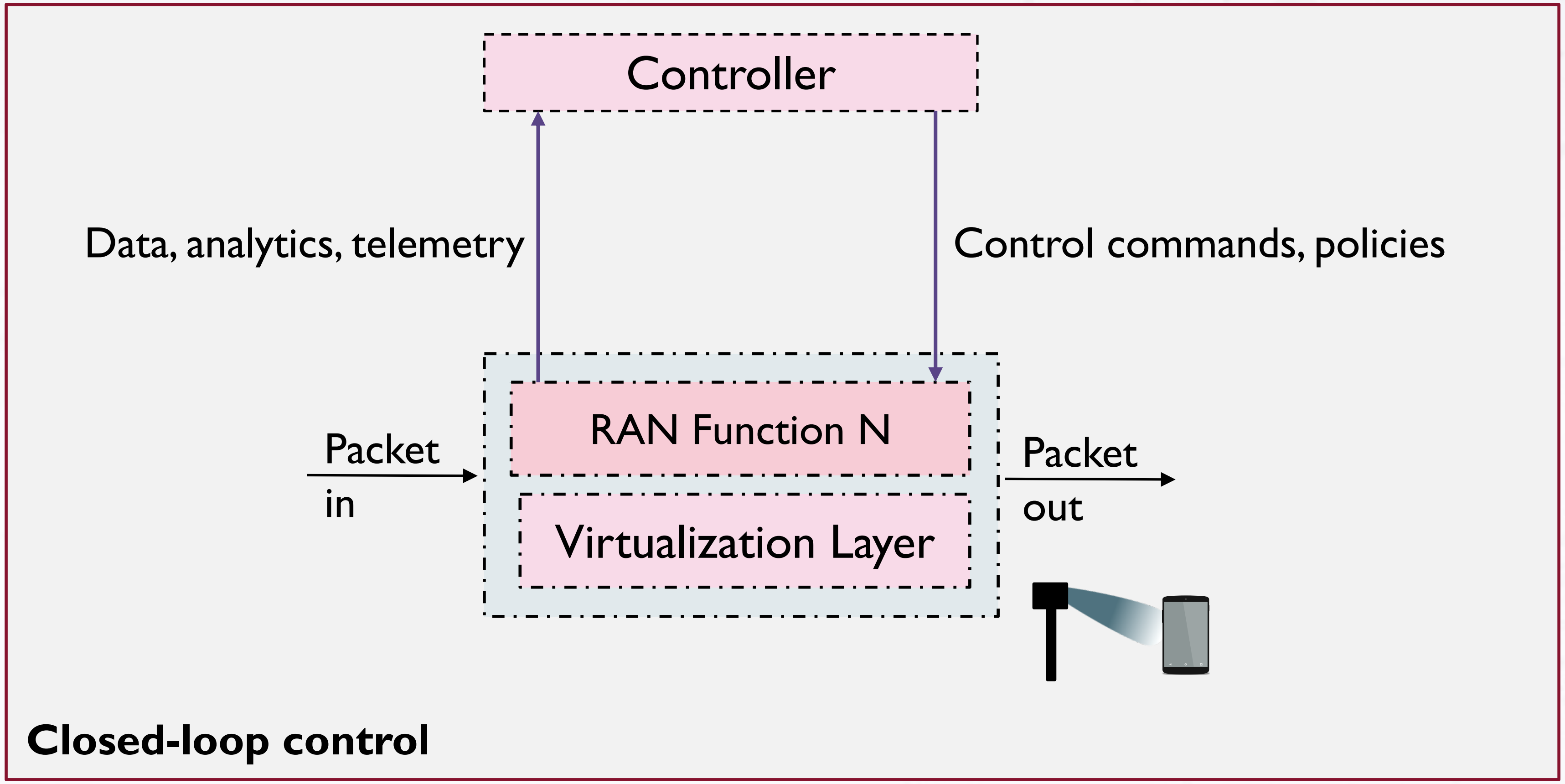


Disaggregation and open interfaces



The RAN and Core network nodes are split into multiple **network functions**, connected through **standardized** interfaces

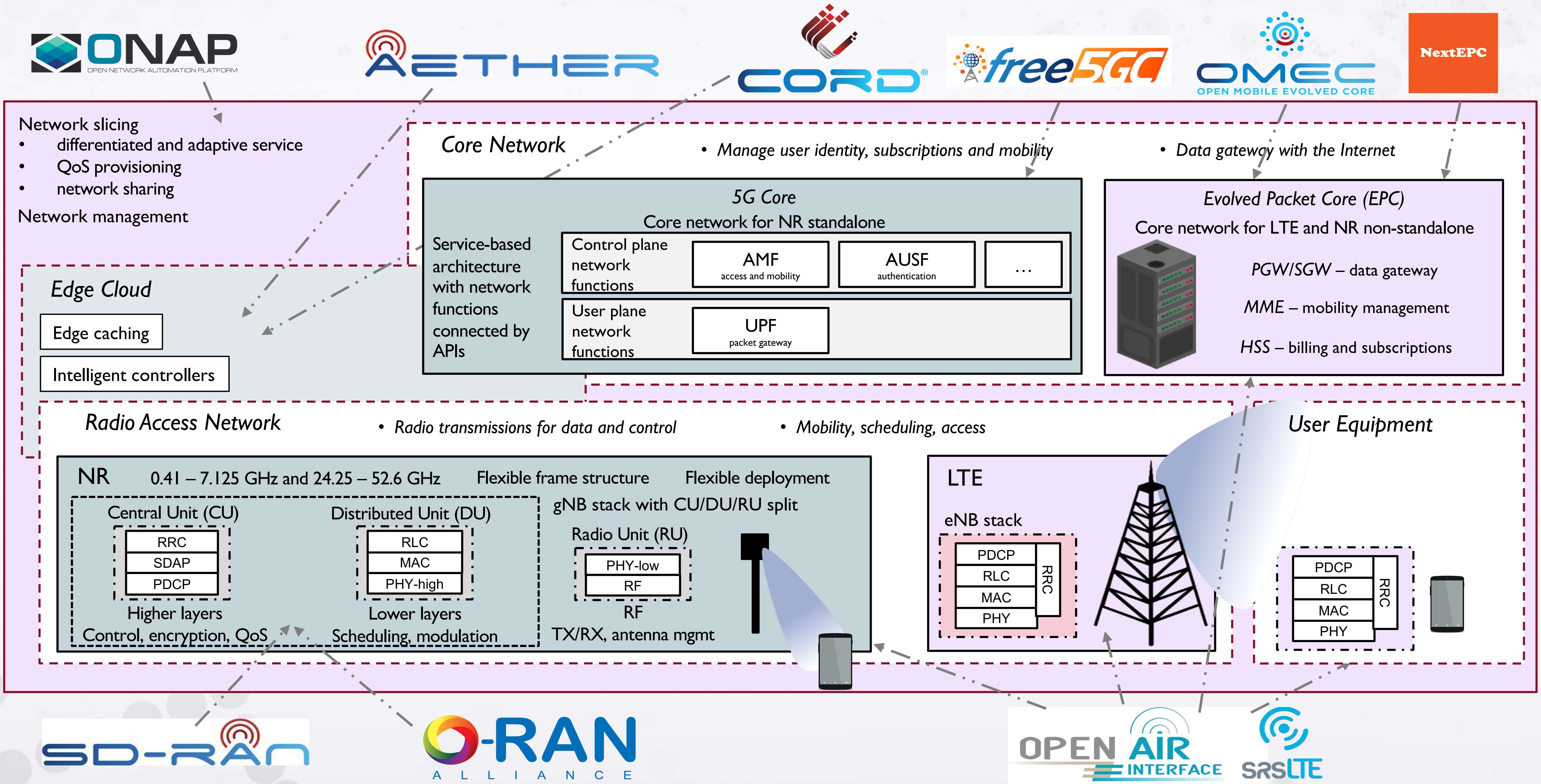
Programmable network nodes and control loops



1. Implement programmable control logic
2. Embed intelligence in the network

Institute for the Wireless Internet of Things at Northeastern

5G open, programmable, and virtualized architecture



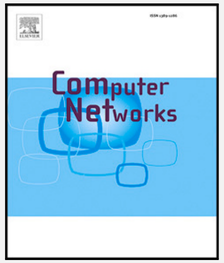
Resources on 5G open source software

Computer Networks 182 (2020) 107516

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet



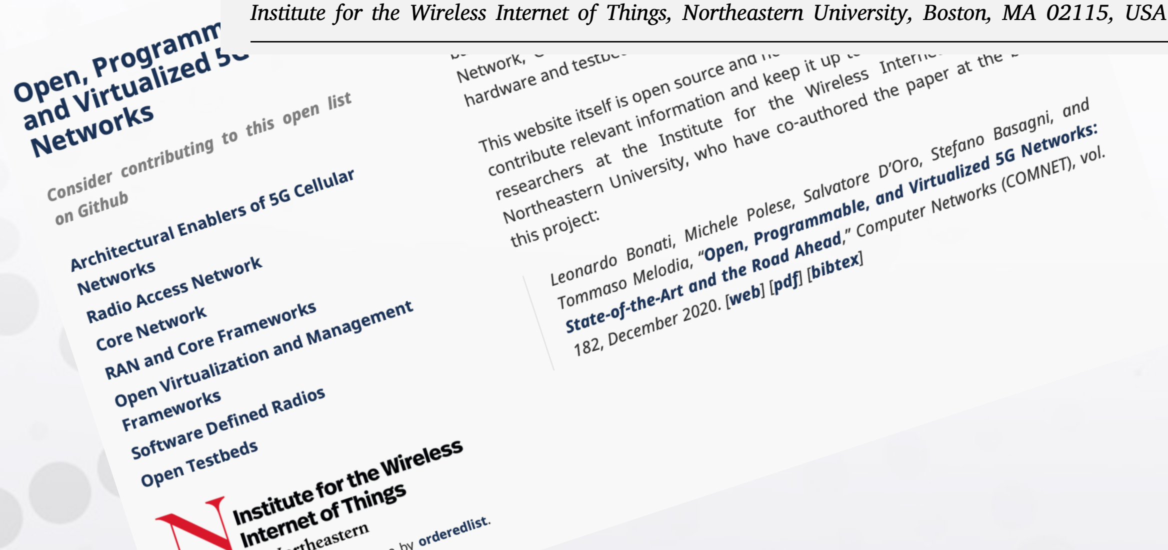
Survey paper

Check for updates

Open, Programmable, and Virtualized 5G Networks: State-of-the-Art and the Road Ahead☆

Leonardo Bonati *, Michele Polese, Salvatore D'Oro, Stefano Basagni, Tommaso Melodia

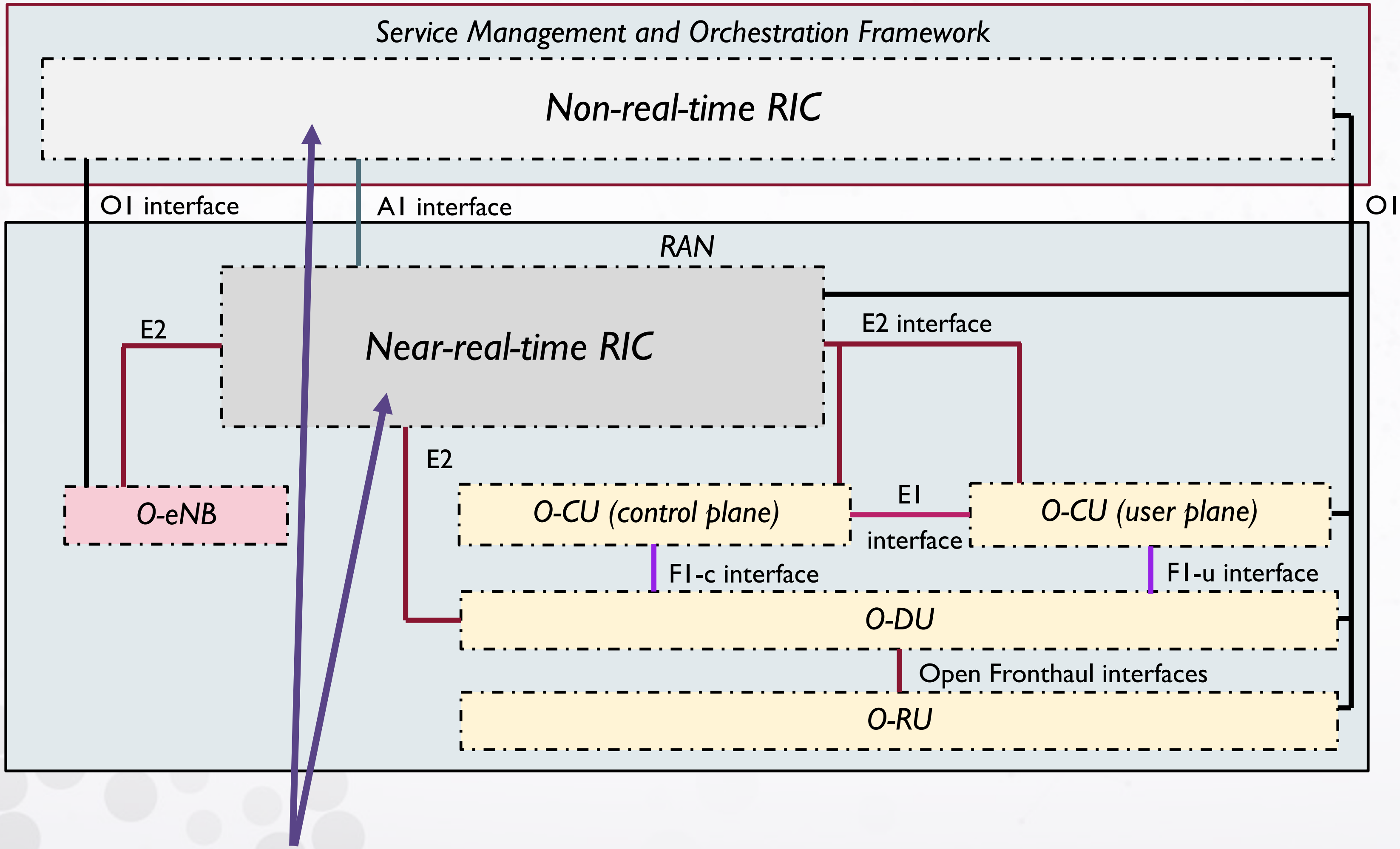
Institute for the Wireless Internet of Things, Northeastern University, Boston, MA 02115, USA



Website: open5g.info

Institute for the Wireless Internet of Things at Northeastern

O-RAN ALLIANCE - a reference architecture for programmable 5G



1. Open, standardized interfaces
2. Disaggregated RAN
3. Open-source contributions
4. RAN Intelligent Controllers

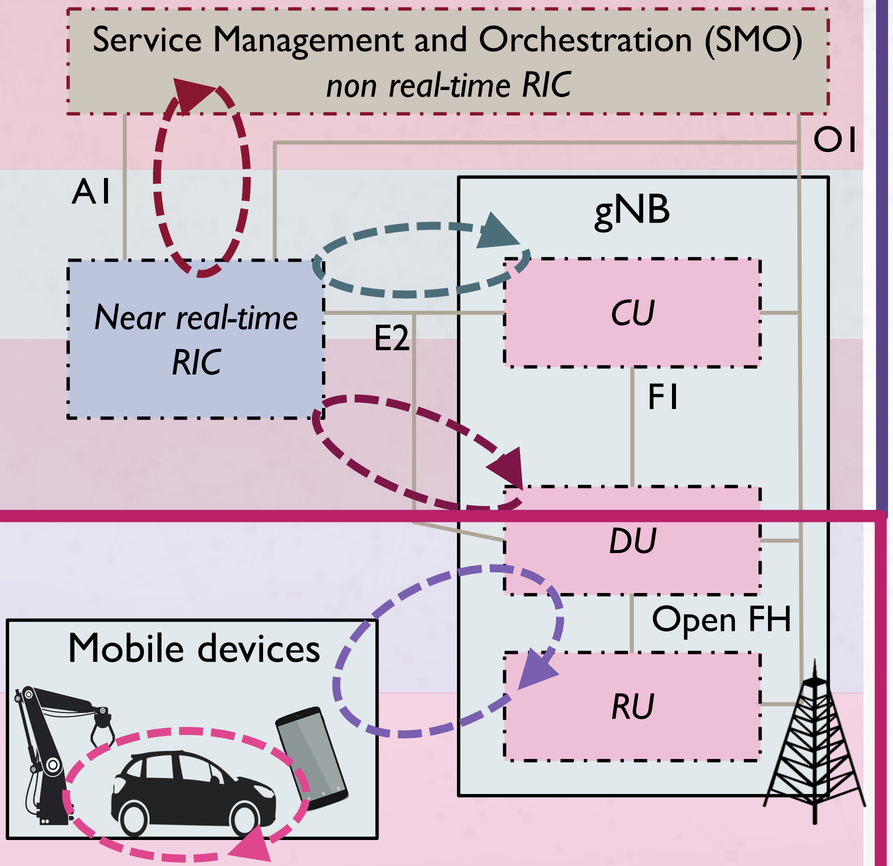
Institute for the Wireless Internet of Things at Northeastern

Intelligent Control Loops

Currently supported by O-RAN

Control and learning objective	Scale	Input data	Timescale
Policies, models, slicing	> 1000 devices	Infrastructure-level KPIs	Non real-time > 1 s
User Session Management e.g., load balancing, handover	> 100 devices	CU-level KPIs e.g., number of sessions, PDCP traffic	Near real-time 10-1000 ms
Medium Access Management e.g., scheduling policy, RAN slicing	> 100 devices	MAC-level KPIs e.g., PRB utilization, buffering	Near real-time 10-1000 ms
Radio Management e.g., resource scheduling, beamforming	~10 devices	MAC/PHY-level KPIs e.g., PRB utilization, channel estimation	Real-time < 10 ms
Device DL/UL Management e.g., modulation, interference, blockage detection	1 device	I/Q samples	Real-time < 1 ms

Architecture



For further study or not supported

Use cases for intelligent and programmable 5G networks

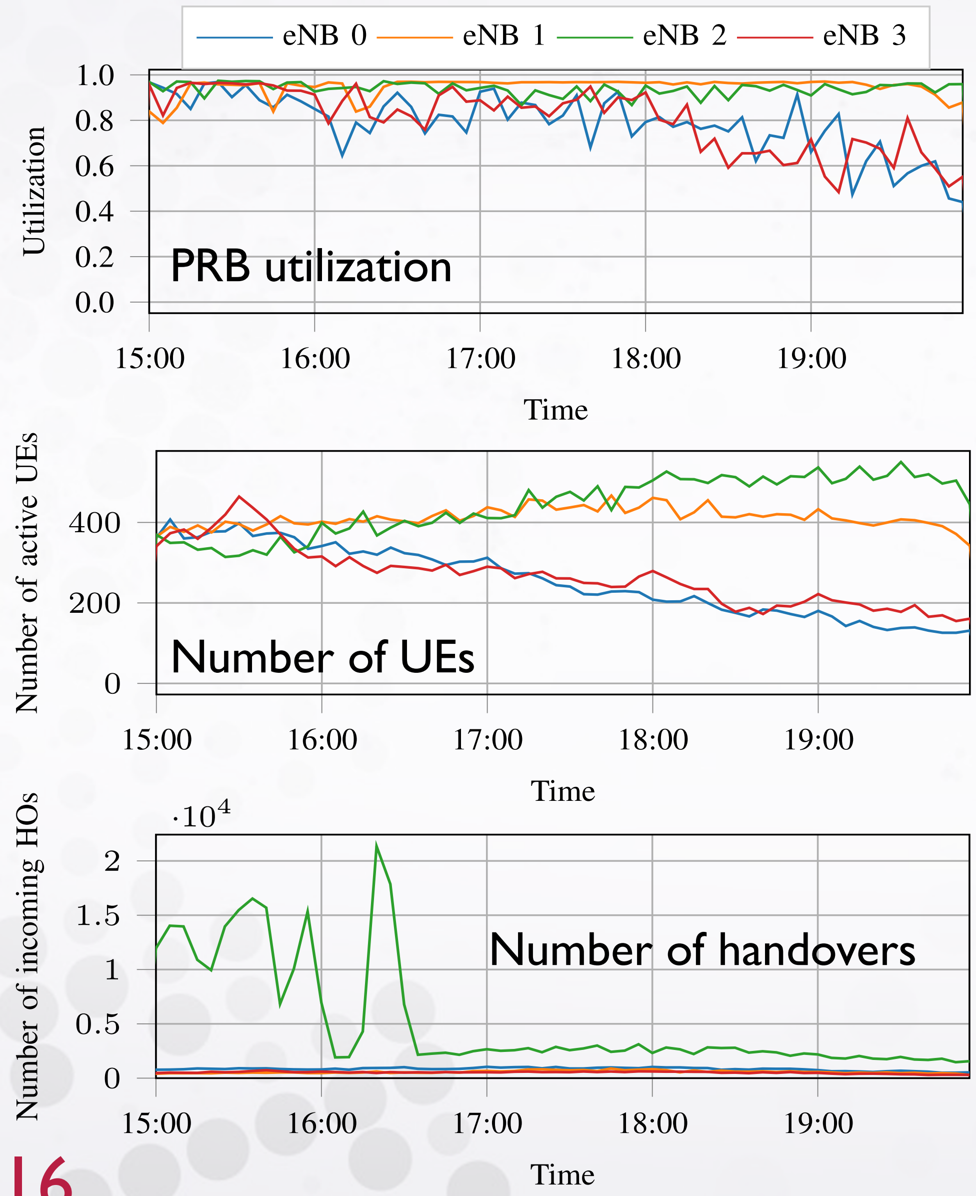
Data-driven clustering and load prediction

Real-world dataset from AT&T with >600 base stations

Scheduling selection with deep reinforcement learning

First O-RAN demonstration with white-box real-time RAN control Colosseum

Data-driven clustering and prediction



The dataset:

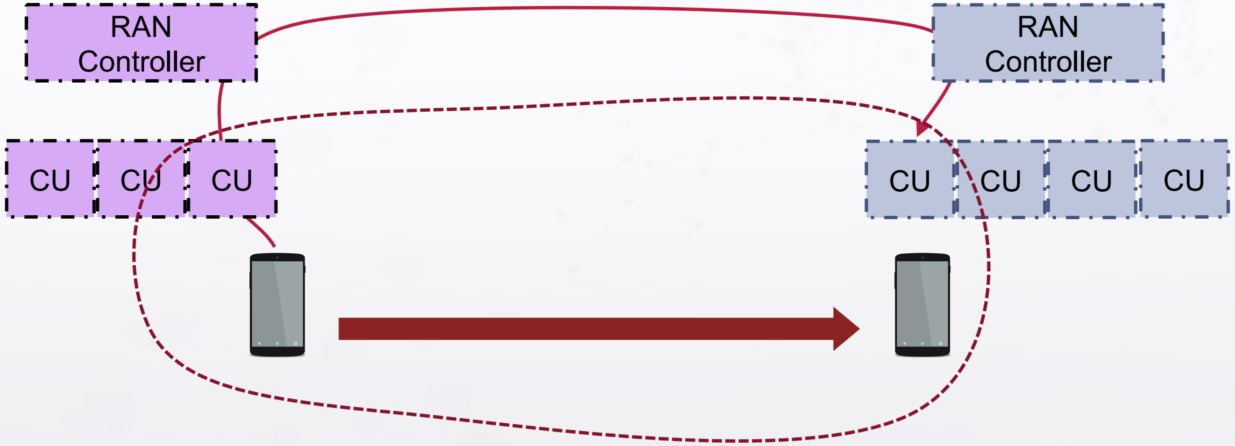
- 472 eNBs in San Francisco
  - February 2017, every day, 3 P.M. to 8 P.M.
- 178 eNBs in Palo Alto
  - June-July 2018, 24h
- 4G LTE deployment
- Data collected:
  - Resource utilization
  - Number of incoming and outgoing handovers
  - Number of active UEs

Institute for the Wireless Internet of Things at Northeastern

Data-driven operations: RAN clustering

- How can the network automatically match the CU and controllers?
- Goal: minimize the interaction among different controllers
  - Avoid inter-controller sync-up
  - Avoid the exchange of inter-controller messages

Minimize the control plane latency

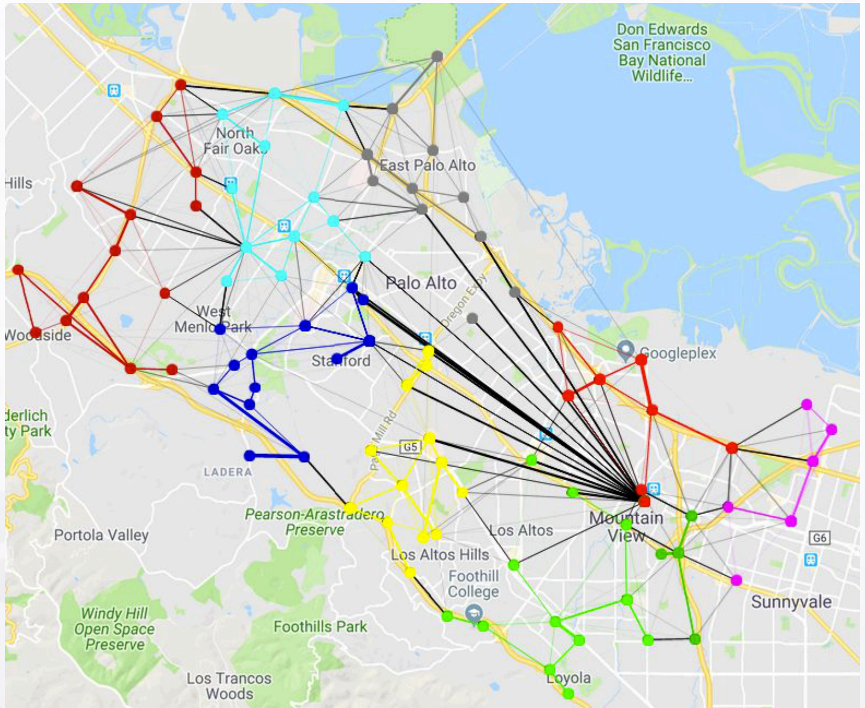


Institute for the Wireless Internet of Things at Northeastern

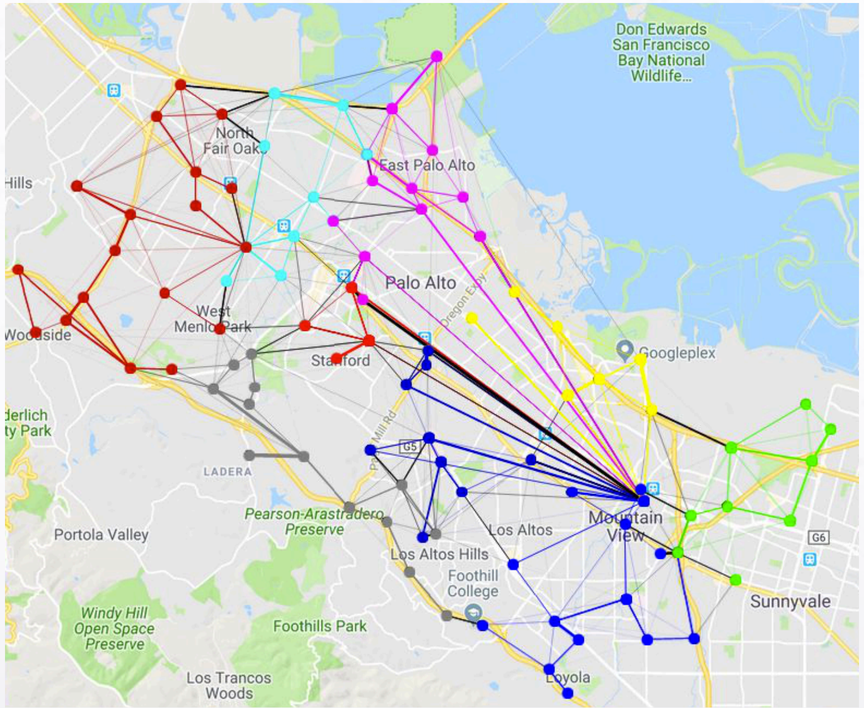
Data-driven operations: RAN clustering

Goal: minimize inter-controller interactions
(impact on control plane latency)

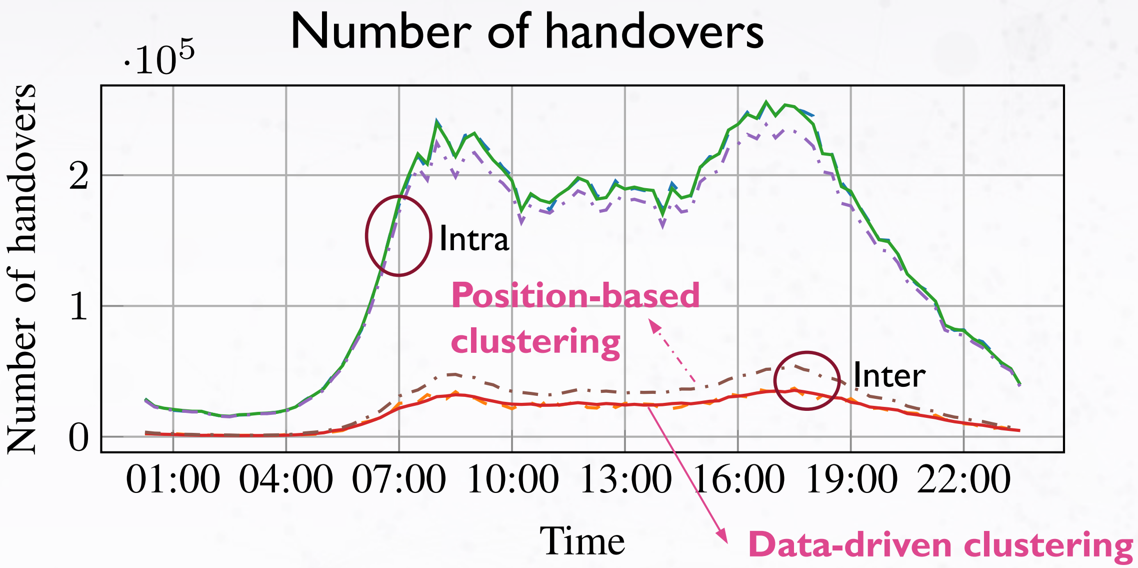
Clustering based on base station positions (fixed, no dynamic data)

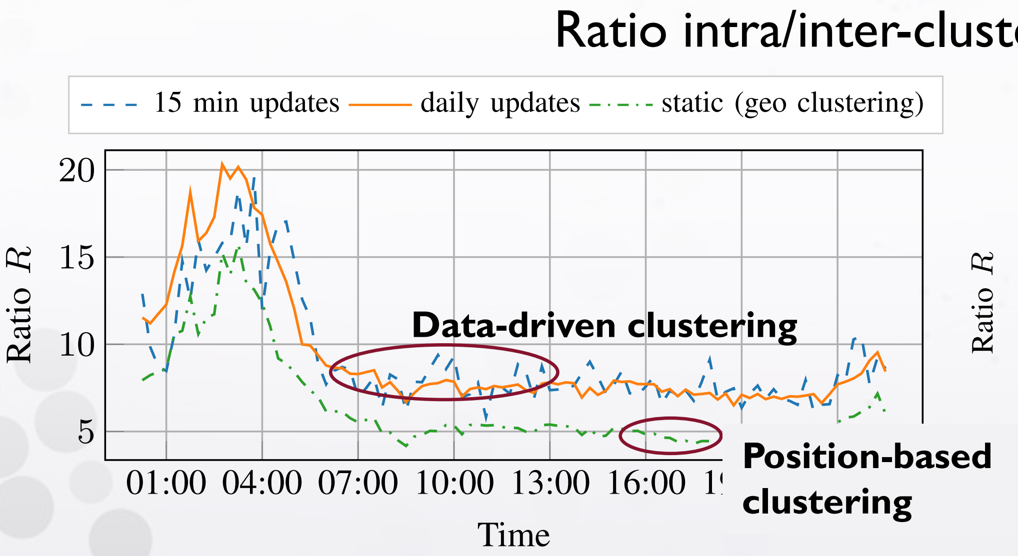


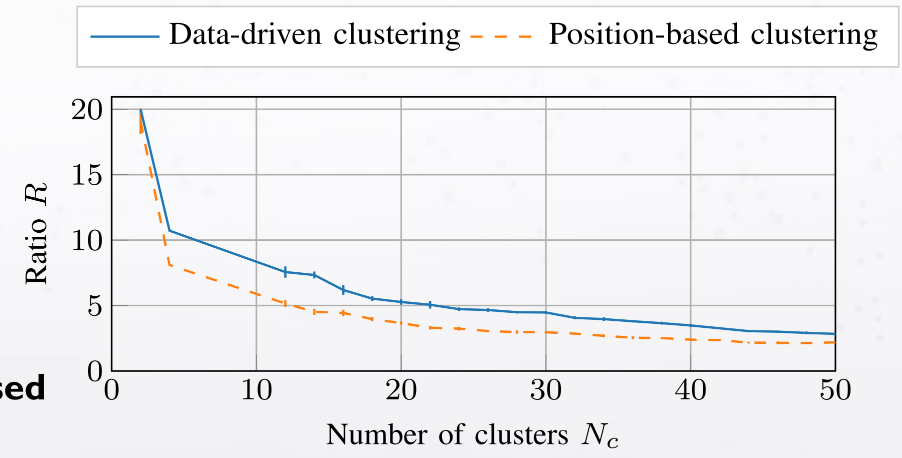
Clustering based on handover transitions (dynamic, based on network data)



Data-driven operations: RAN clustering







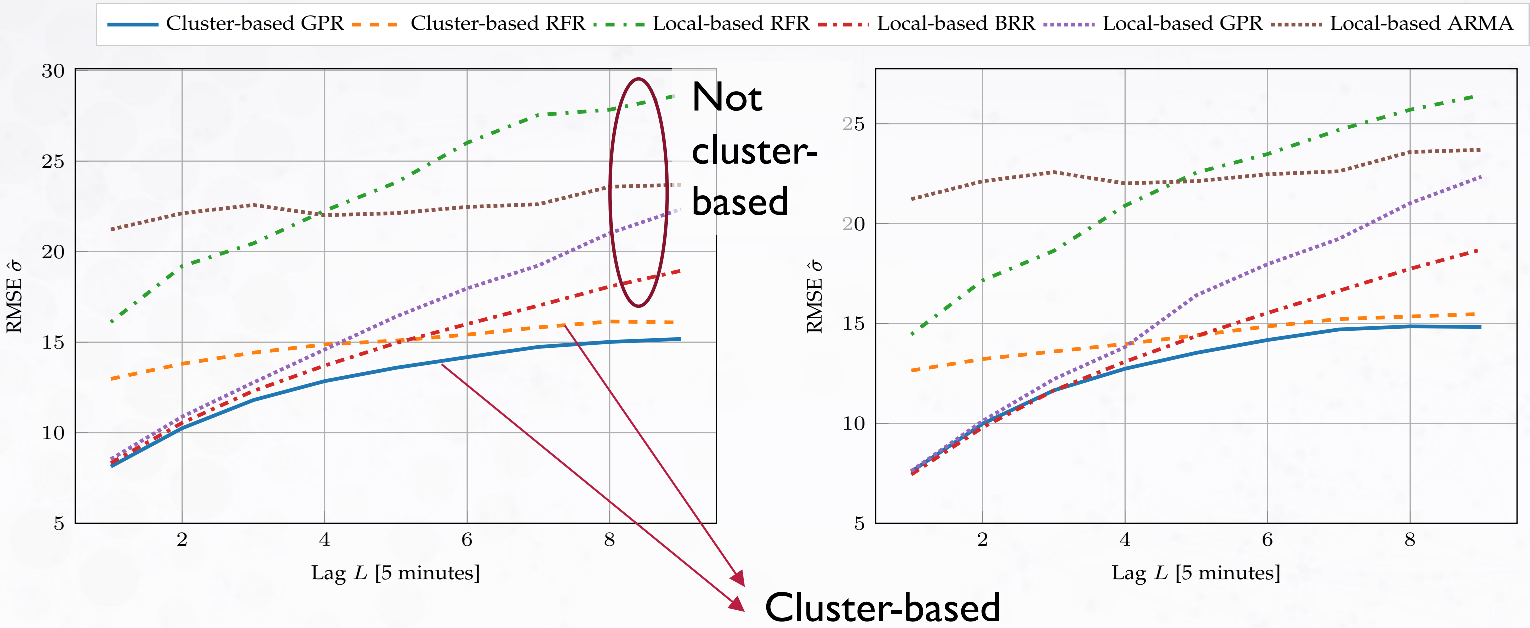
Data-driven operations: prediction

Goal: predict the number of active UEs

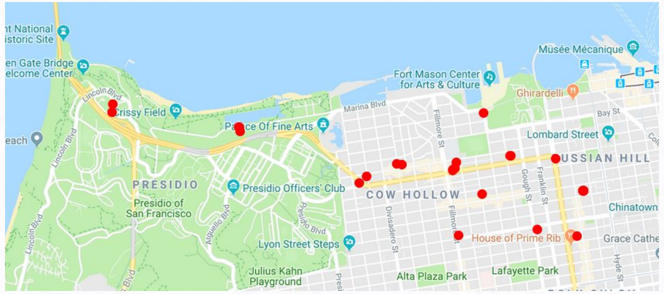
- Local-based method: train a different model in each BS to predict the number of UEs in each single BS
  - This is what is possible in 4G LTE networks
- Cluster-based method: train a model per cluster, predict a vector with the number of UEs in each BS of the cluster
  - **Enabled by RAN controllers**
  - **Exploit spatial correlation to improve the prediction**

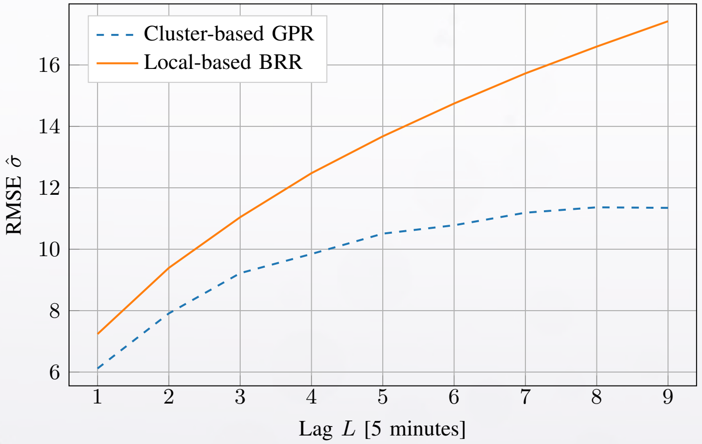
Please check the paper for details on data processing, training, testing
M. Polese, R. Jana, V. Kounev, K. Zhang, S. Deb, M. Zorzi, "Machine Learning at the Edge: a Data-Driven Architecture with Applications to 5G Cellular Networks", IEEE Transactions on Mobile Computing, June 2020

Data-driven operations: prediction



Results on a sample cluster

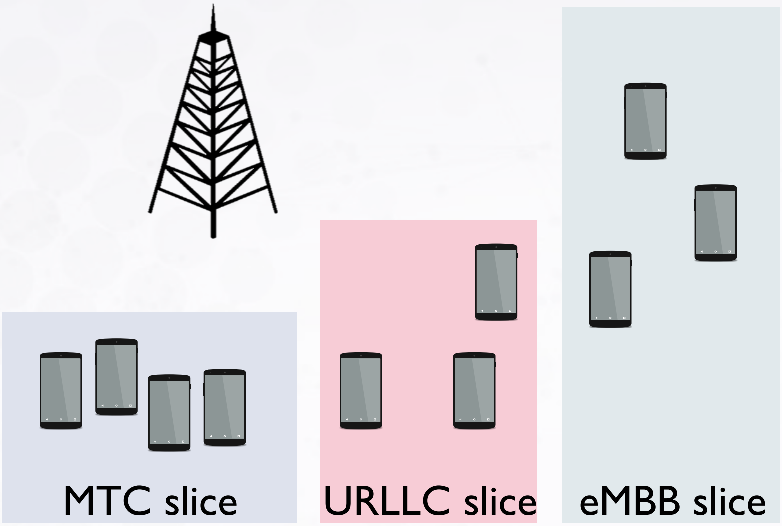




Average results on all clusters

Institute for the Wireless Internet of Things at Northeastern

Intelligent scheduling for RAN slicing



Challenging environment:

- Dynamic channel
- Dynamic resource allocations for each slice

Exploit **data-driven** closed-loop control with the **near real-time RIC** to **automatically** tune the RAN parameters for **each slice**

We focus on scheduling policy selection through Deep Reinforcement Learning (DRL)

More info: L. Bonati, S. D'Oro, M. Polese, S. Basagni, and T. Melodia, "Intelligence and Learning in O-RAN for Data-driven NextG Cellular Networks", arXiv:2012.01263 [cs.NI], December 2020

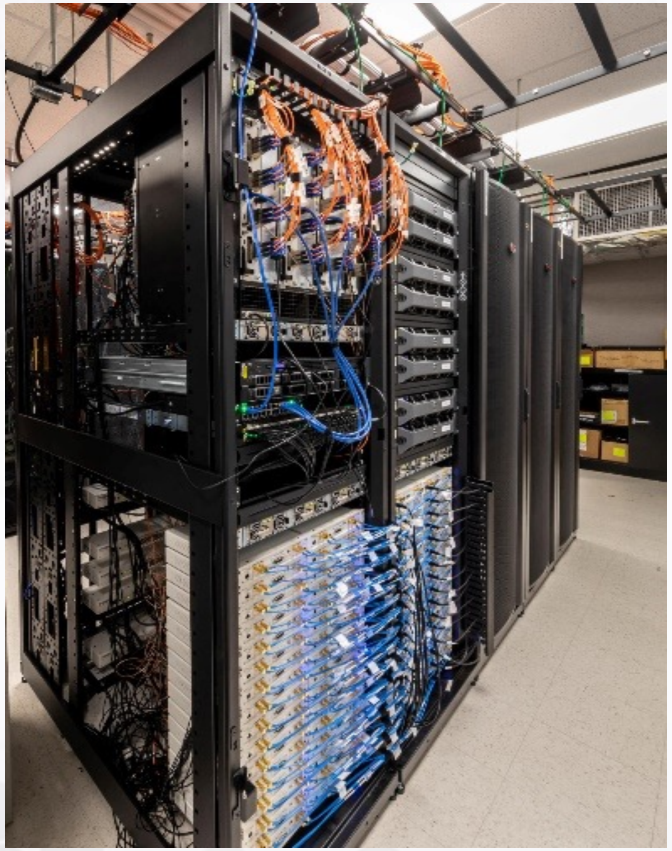
Institute for the Wireless Internet of Things at Northeastern

Data-driven clustering and load prediction

Scheduling selection with deep reinforcement learning

O-RAN integration in Colosseum

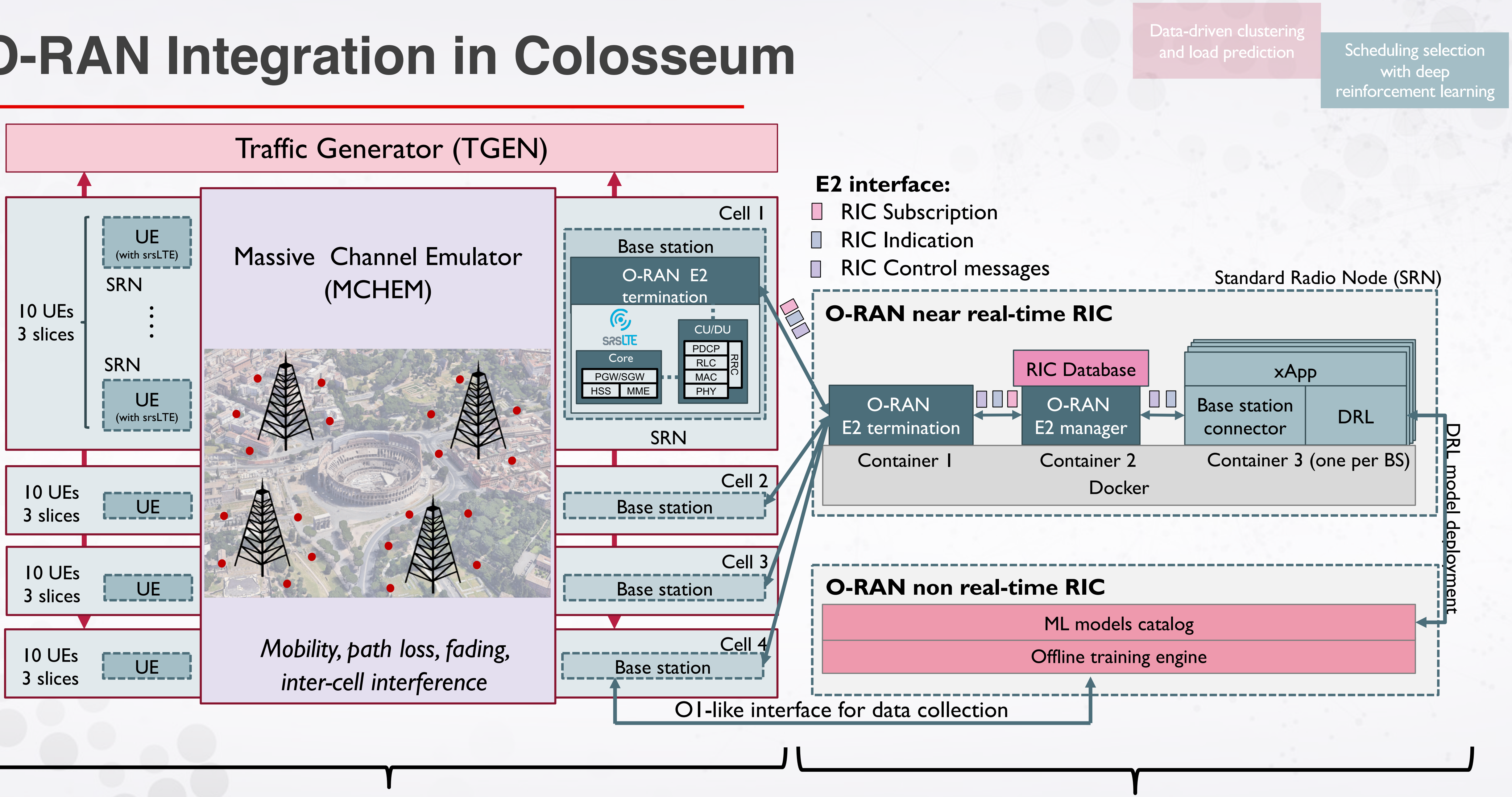
Colosseum is the world most powerful hardware-in-the-loop network emulator



- 256 software-defined radios
- 25.6 GHz of emulated bandwidth, 52 TB/s RF data
- 21 racks of radios, 171 high-performance servers w/ CPUs, GPUs
- Massive computing capabilities (CPU, GPU, FPGA):
    - > 900 TB of storage
    - 320 FPGAs
    - 18 10G switches
    - 19 clock distribution systems
    - 52 TB/s of digital RF data

We can create and test complex 5G scenarios

O-RAN Integration in Colosseum



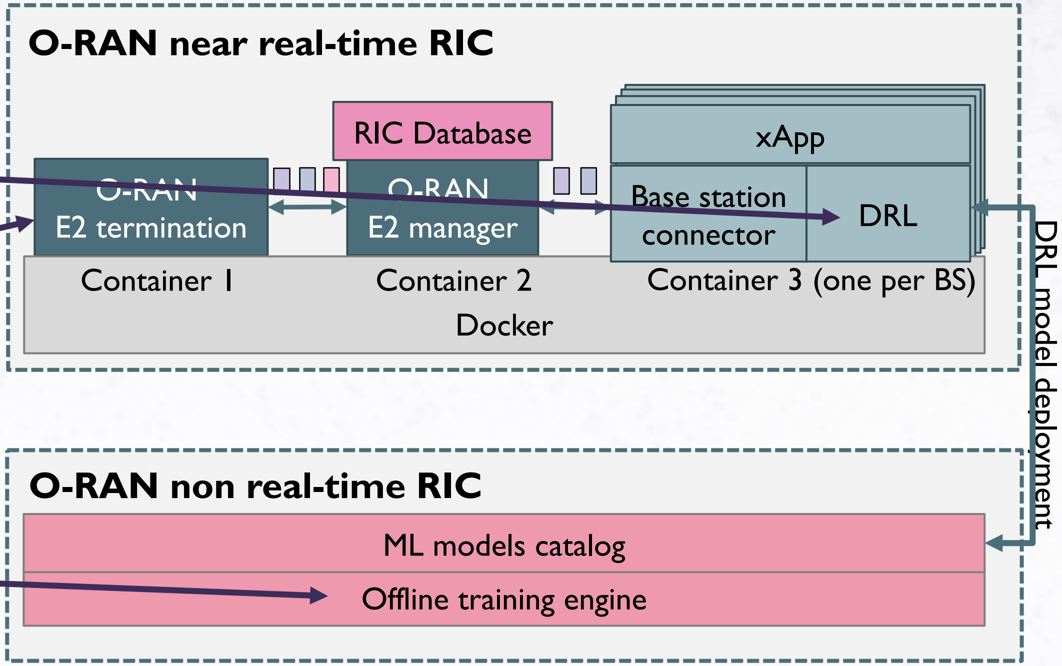
Fully virtualized RAN on white-box hardware

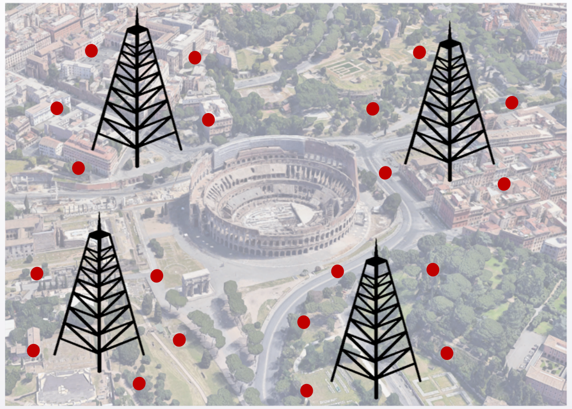
O-RAN open-source infrastructure

O-RAN Integration in Colosseum

12 DRL agents running in parallel

- Fully-connected neural network (5 layers & 30 neurons each)
- *Online* inference w/ real-time RAN performance data
- Trained *offline* on 6 GB of data & 63 hours of experiments
- Decisions on scheduling policies of each BS slice
    - Round-robin (RR)
    - Waterfilling (WF)
    - Proportional fair (PF)





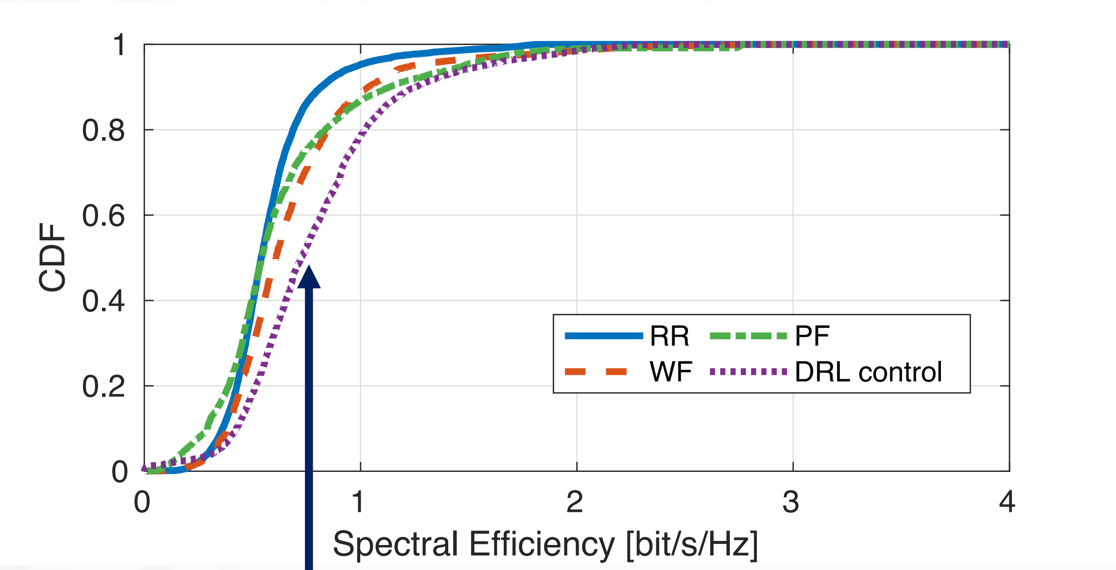
Dense urban scenario, 4 BSs, 40 UEs w/ pedestrian mobility

Experimental results

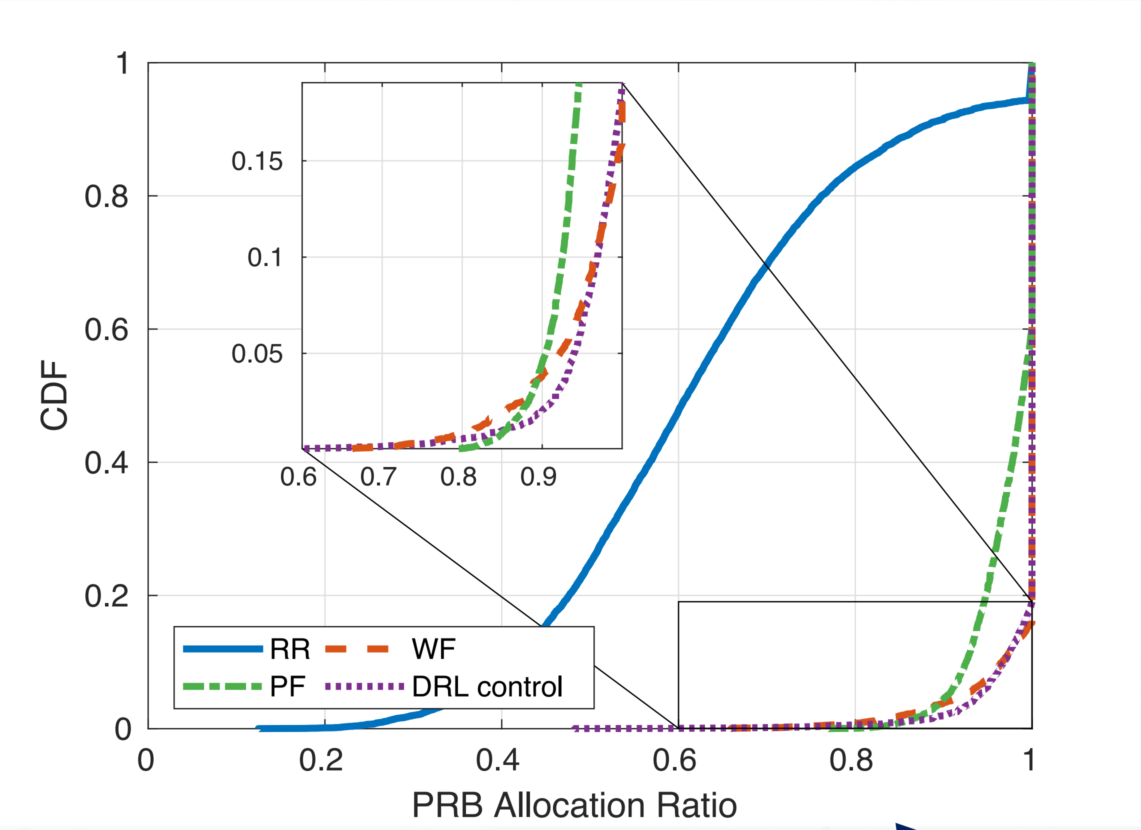
Data-driven clustering and load prediction

Scheduling selection with deep reinforcement learning

eMBB slice



URLLC slice

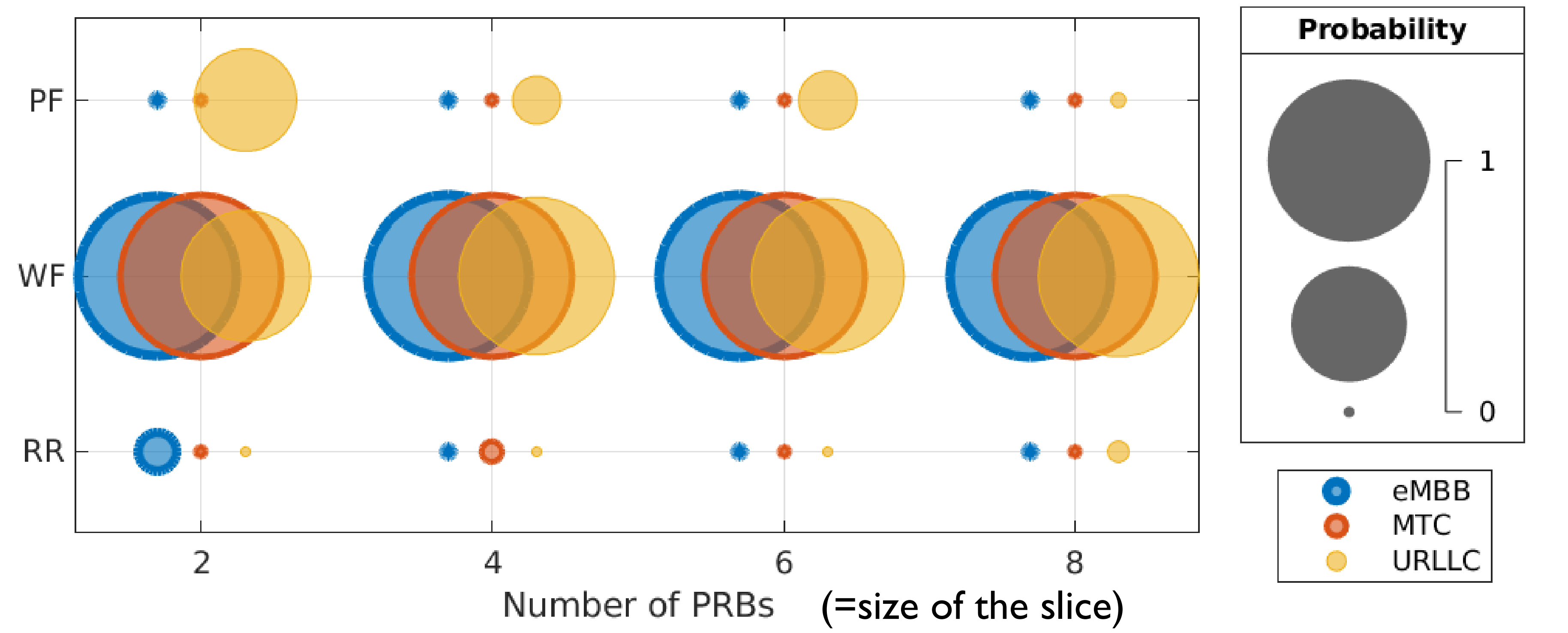


- Improve spectral efficiency for eMBB users
- Satisfy URLLC users requests
- Reduce RLC buffer occupancy by 20%

Institute for the Wireless Internet of Things at Northeastern

Experimental results – policy selection

Probability that the DRL agent selects a certain policy



- Different behaviors for the 3 slices
- Different behaviors for different slice sizes

Need data-driven, adaptable approach

Conclusions

Future cellular networks will be

Open	Programmable	Virtualized

truly enabling the vision of data- and AI-driven networks

Road ahead:

- Testbeds and platforms for intelligent RAN development
- Dataset availability
- More involvement toward open-source protocol stacks

Resources

- Open source 5G software website: https://open5g.info
- Colosseum website: https://colosseum.net
- PAWR platforms: https://advancedwireless.org

- Institute for the Wireless Internet of Things: https://www.northeastern.edu/wiot/

Institute for the Wireless Internet of Things at Northeastern

open5g.info colosseum.net

Institute for the Wireless Internet of Things at Northeastern University

Toward Open, Programmable, and Virtualized 5G Networks

Michele Polese
Institute for the Wireless Internet of Things
Northeastern University
m.polese@northeastern.edu