End-to-End Design and Evaluation of mmWave Cellular Networks

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DIPARTIMENTO
DI INGEGNERIA
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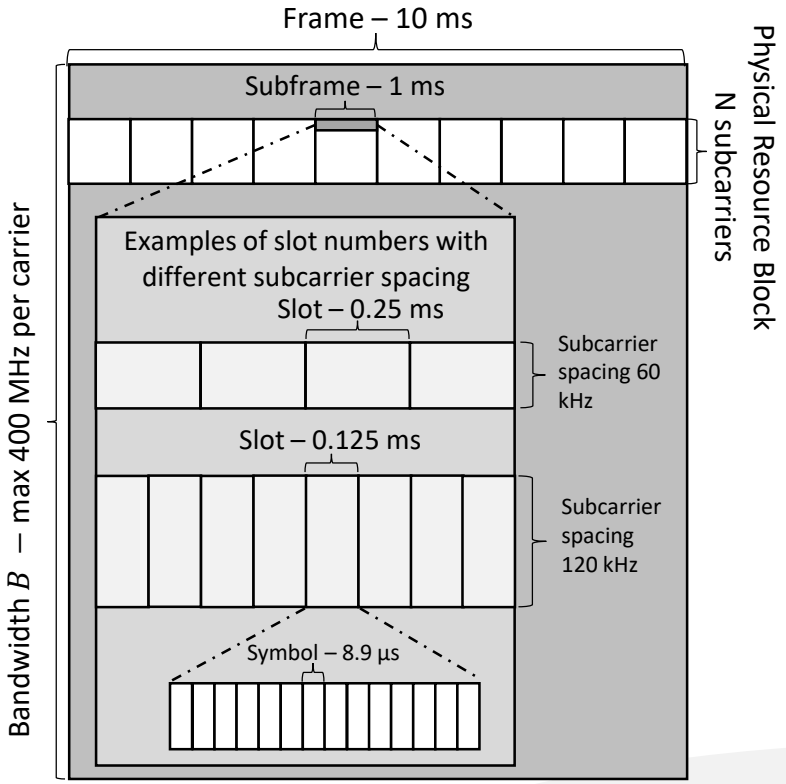
SIGNET

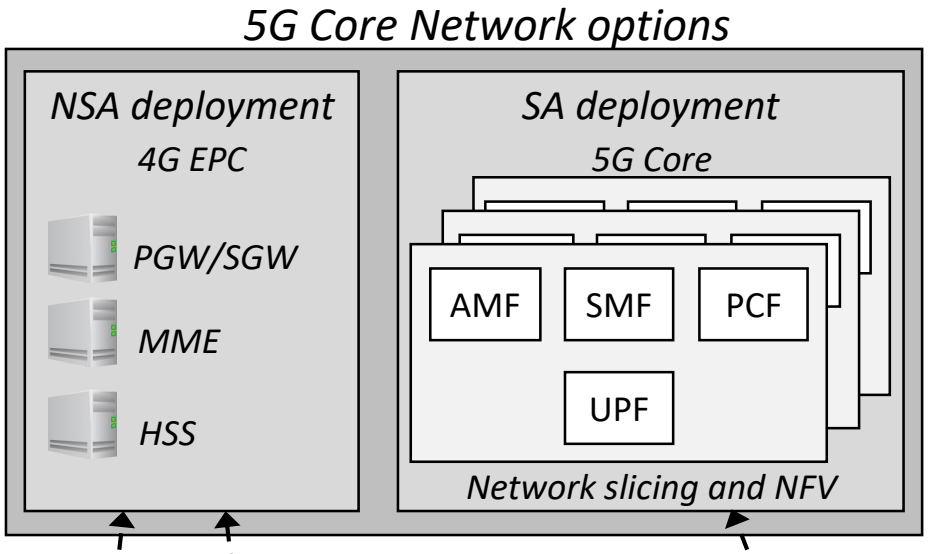
Outline

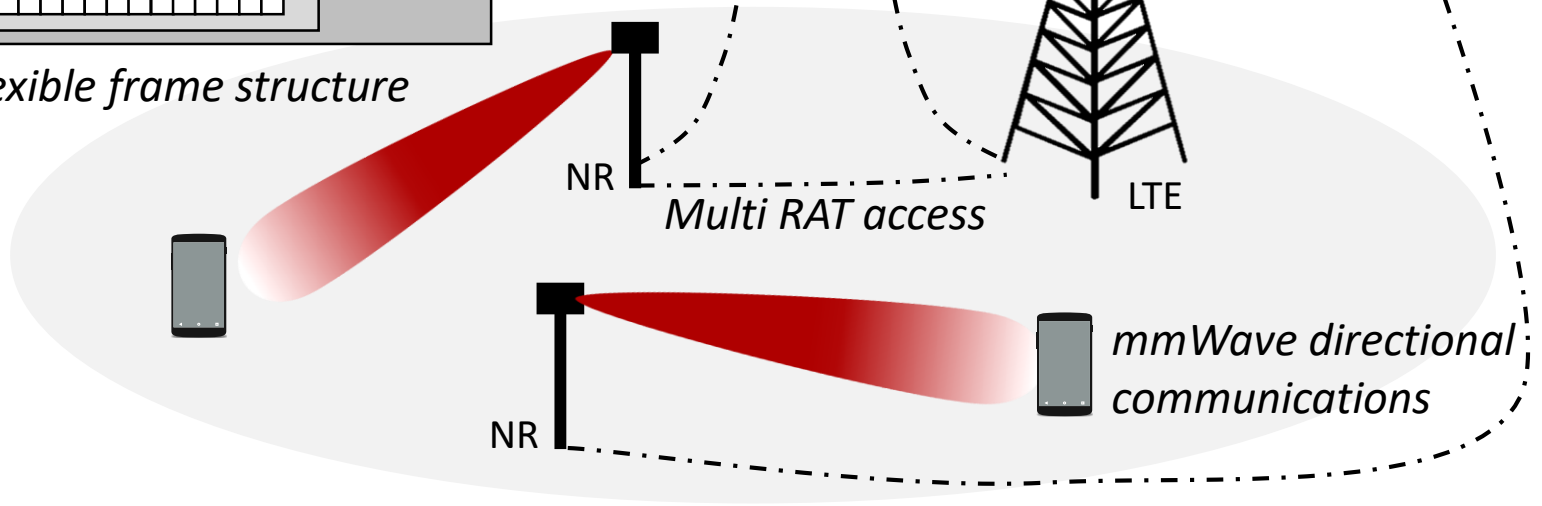
- Introduction
  - A case for end-to-end, full-stack evaluations
- Architectures for 5G mmWaves
- End-to-end protocols for mmWaves
- Data-driven 5G network optimization
- Conclusions and research directions

3GPP NR: novelties



Flexible frame structure





End-to-end mmWaves

3GPP NR: timeline

Goal: deployment by 2020

5G phase 1

5G phase 2

Dec. 2017

June 2018

March 2020

Non Stand-alone specifications

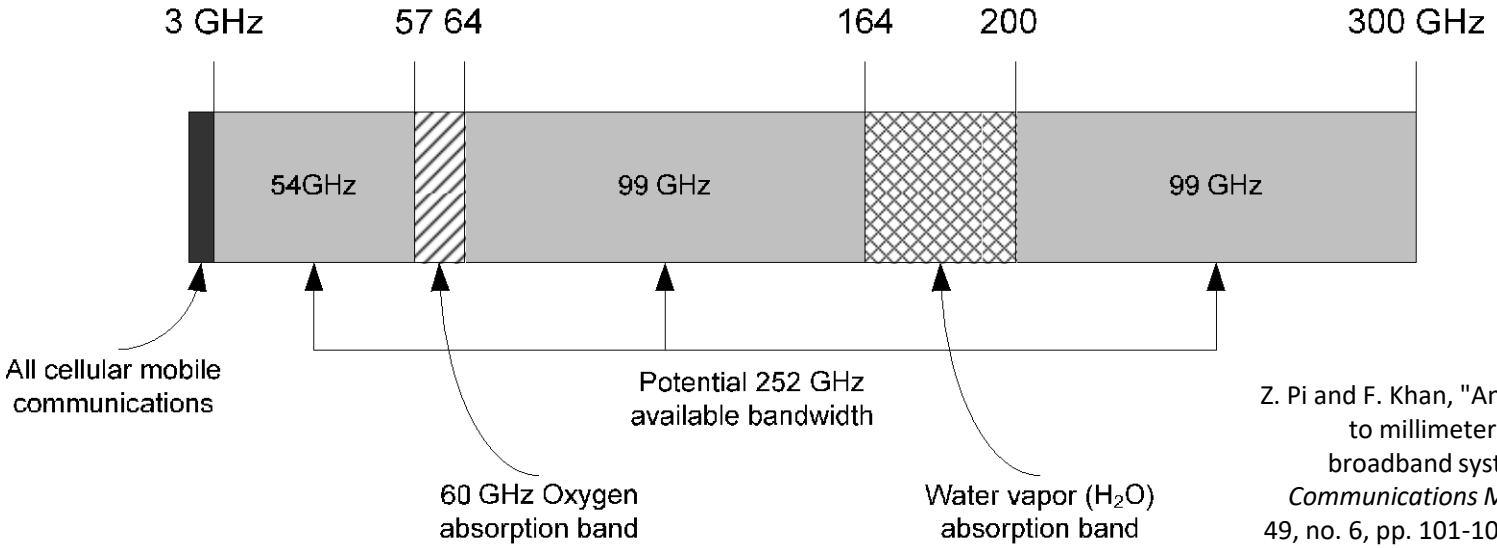
Stand-alone specifications

Release 15

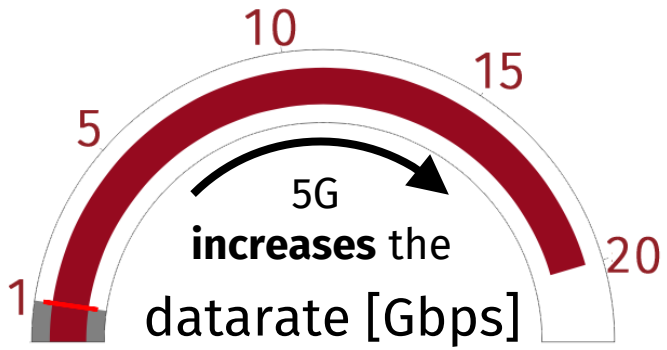
Release 16

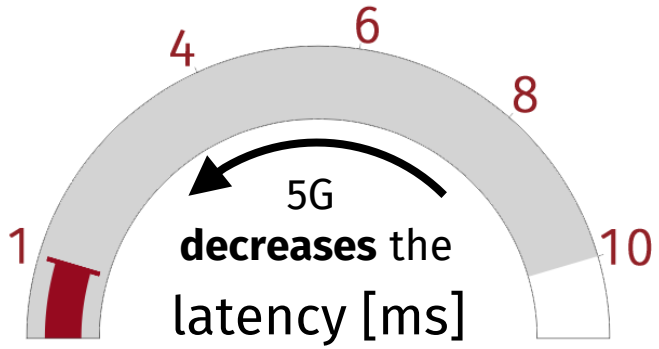
3GPP NR: mmWaves in cellular networks

3GPP NR Release 16 will support **frequencies up to 52.6 GHz**



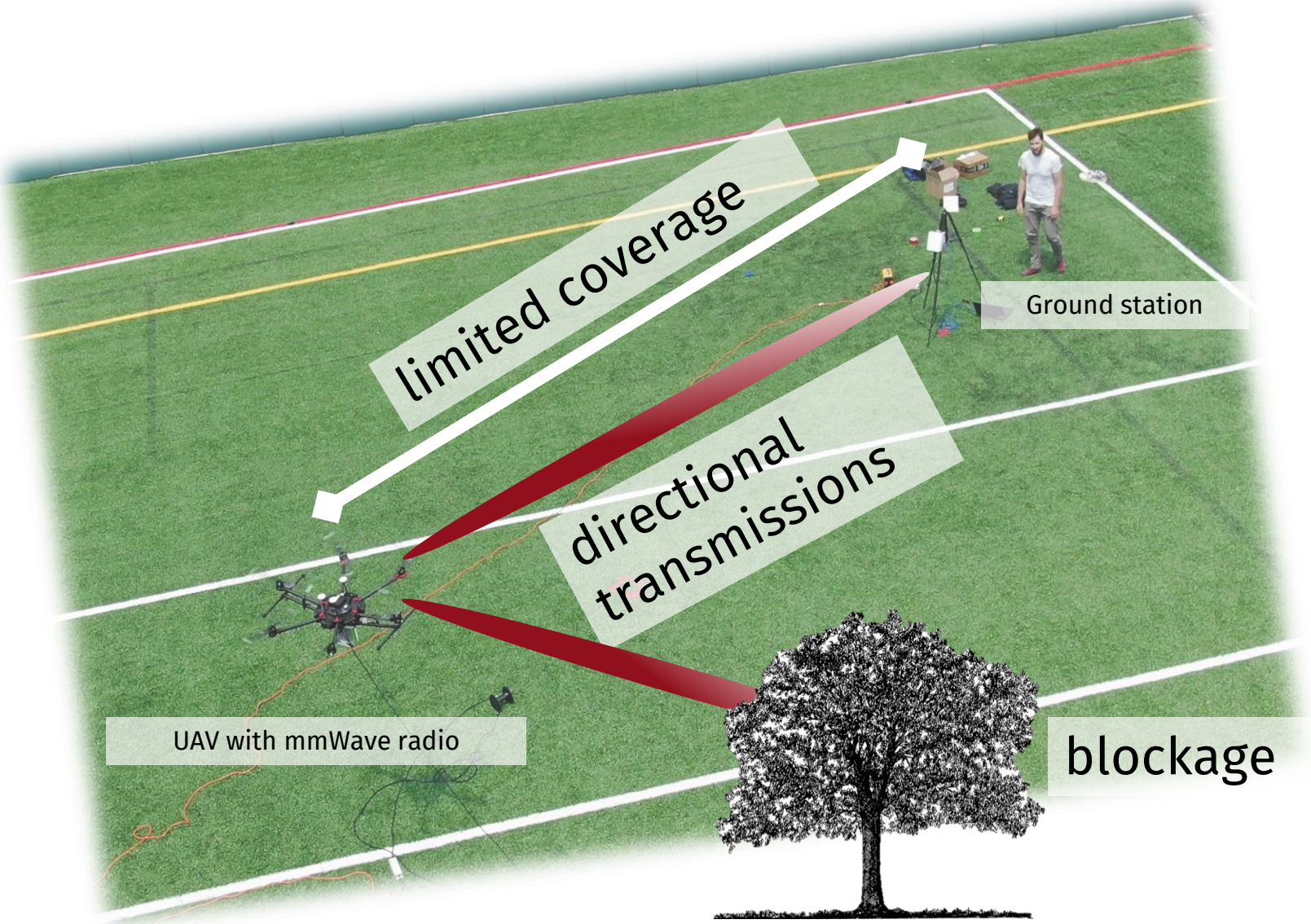
Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," in *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101-107, June 2011.





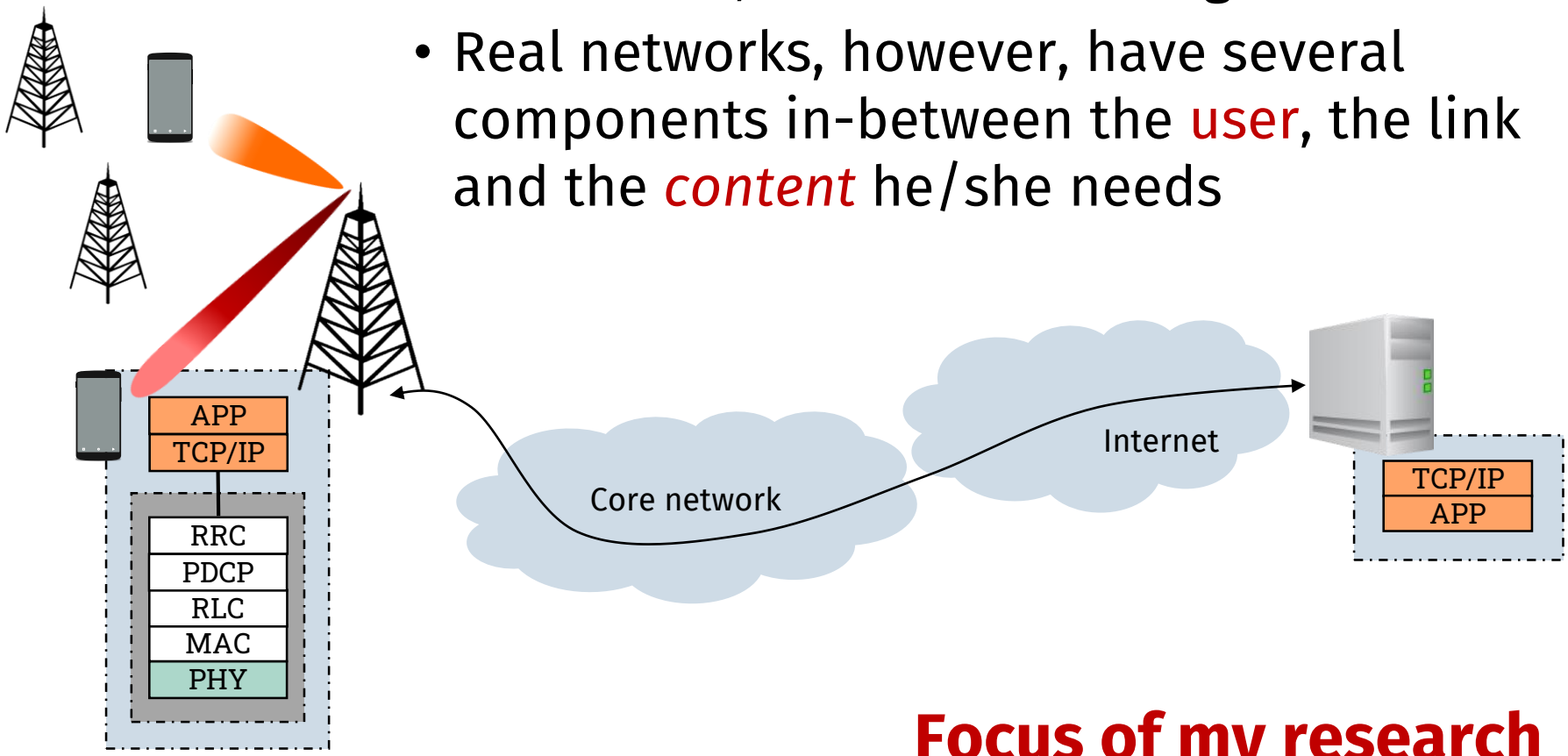
End-to-end mmWaves

3GPP NR: challenges for mmWaves



End-to-end design and performance: why?

- Sometimes, link-level is enough
- Real networks, however, have several components in-between the user, the link and the *content* he/she needs



Focus of my research

end-to-end, system-level design & evaluation of 5G mmWave networks

The Architecture

System Level Design of 5G mmWave Networks

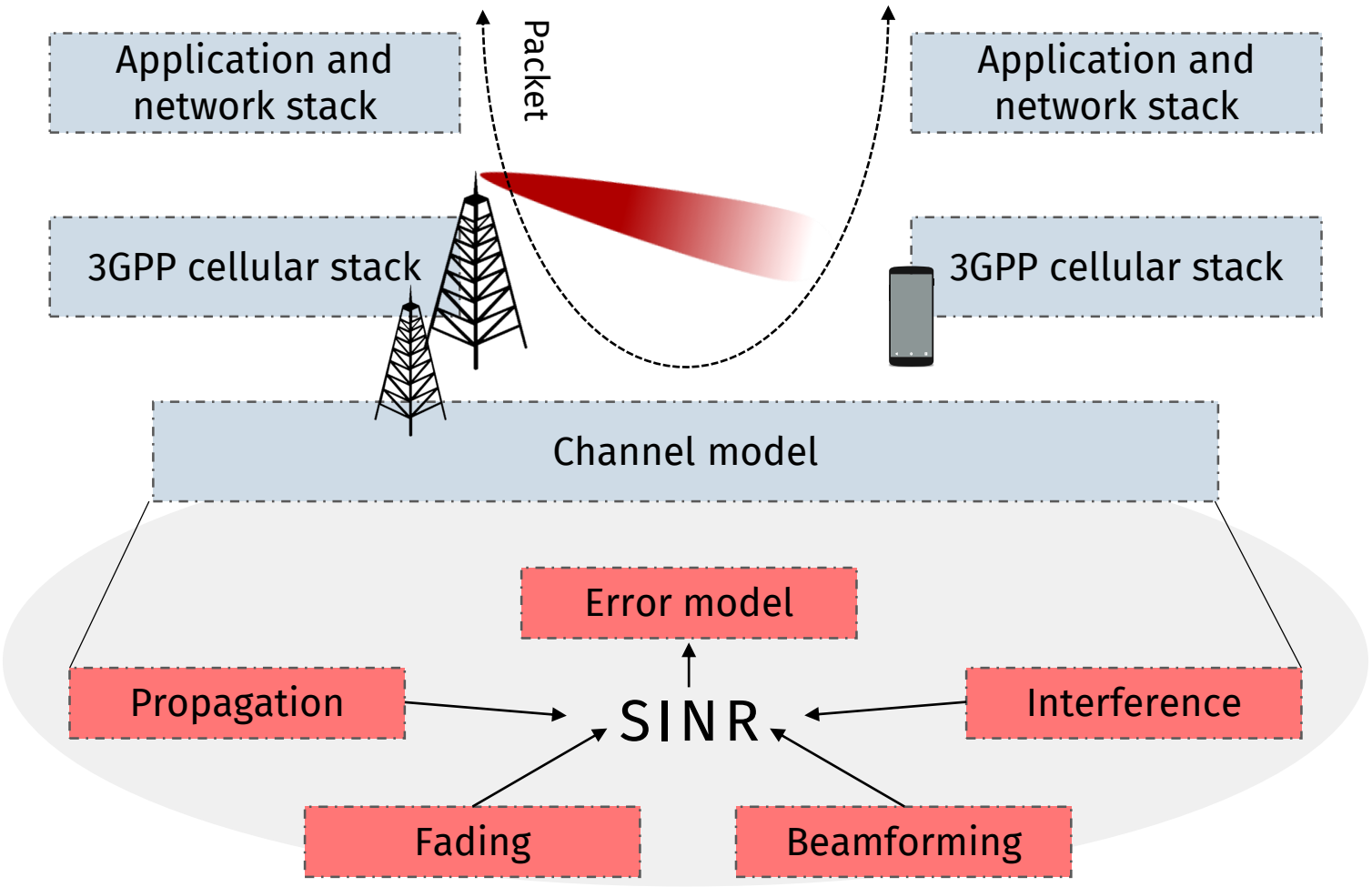
The Protocols

End-to-End and Cross-Layer Analysis of 5G mmWave Networks

The Intelligence

Data-Driven 5G Networks Optimization

The tool: ns-3 mmWave module



https://github.com/nyuwireless-unipd/ns3-mmwave
https://github.com/signetlabdei/ns3-mmwave-iab

https://github.com/signetlabdei/quic
https://github.com/signetlabdei/mmwave-psc-scenarios

The Architecture
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System Level Design of 5G mmWave Networks

Multi connectivity, beam management and Integrated Access and Backhaul

The Architecture

System-level challenges at mmWaves

Issues: high propagation loss and blockage

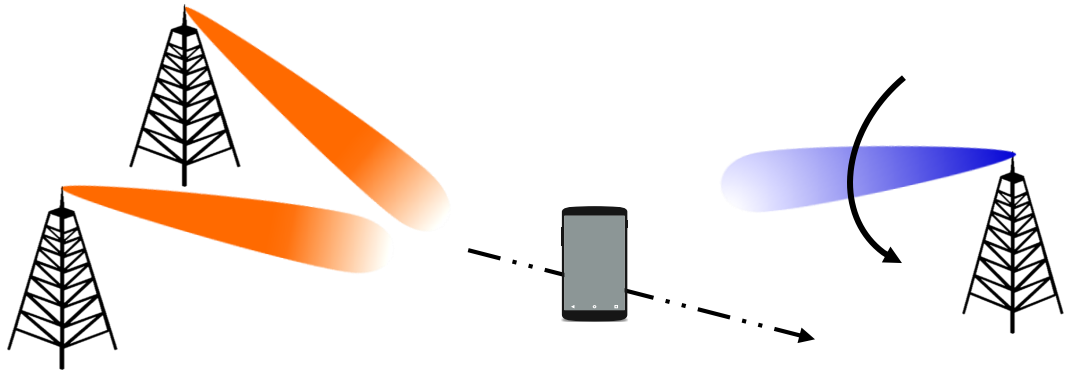
Ultra-dense deployments

1 High number of handovers

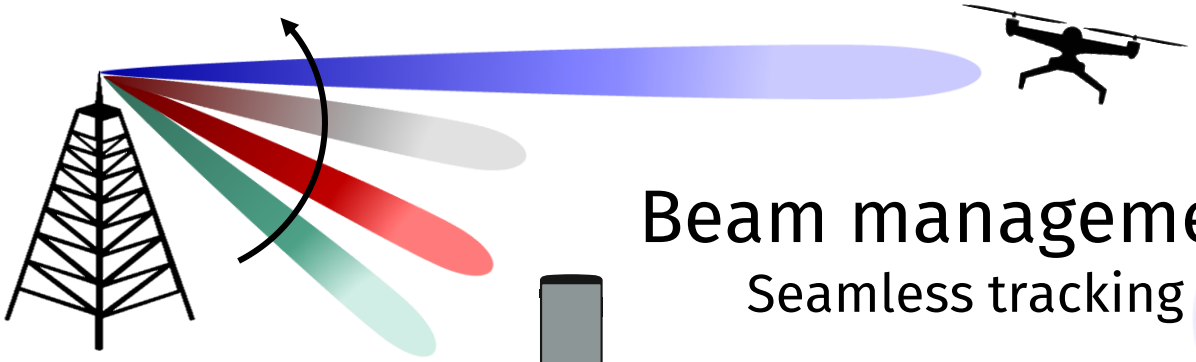
Provide backhaul to all the base stations 2

Large antenna arrays increase the link budget, but the power is focused on **narrow beams**

Need to track the narrow beams when 3 moving

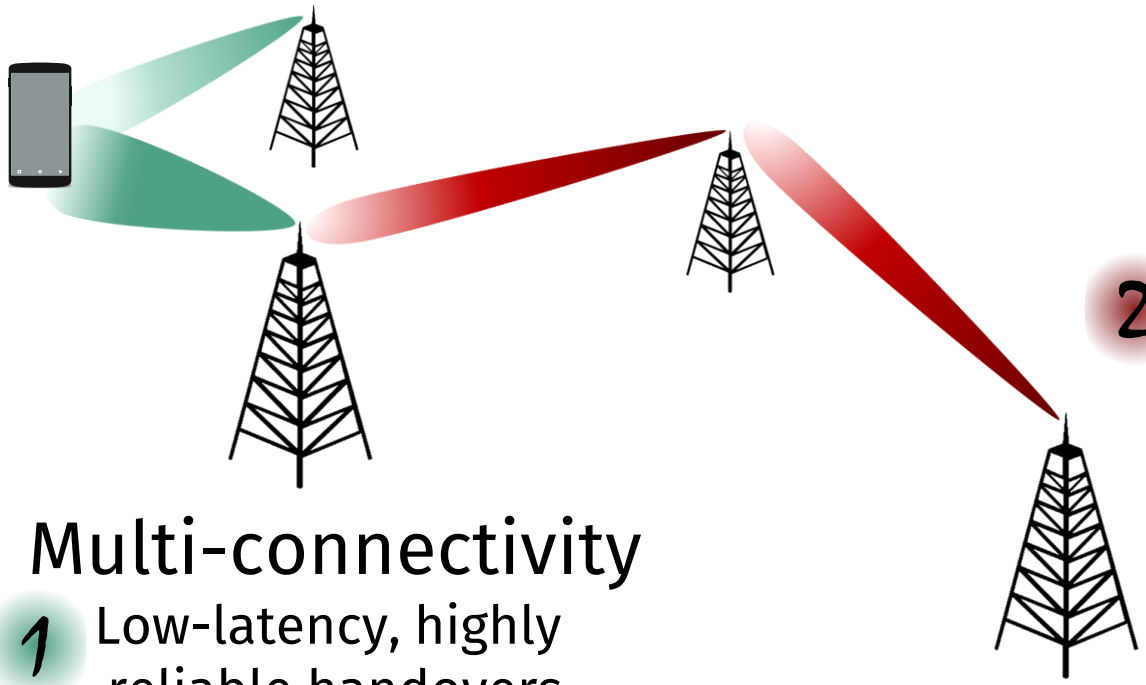


System level solutions at mmWaves



Beam management

Seamless tracking 3



Integrated Access and 2 Backhaul

Low cost, high density mmWave deployments

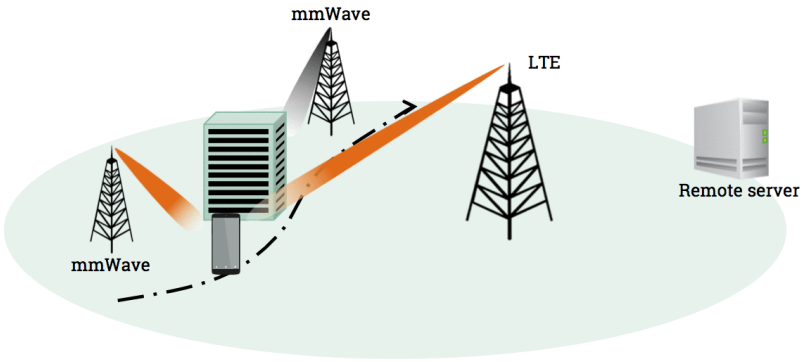
Multi-connectivity

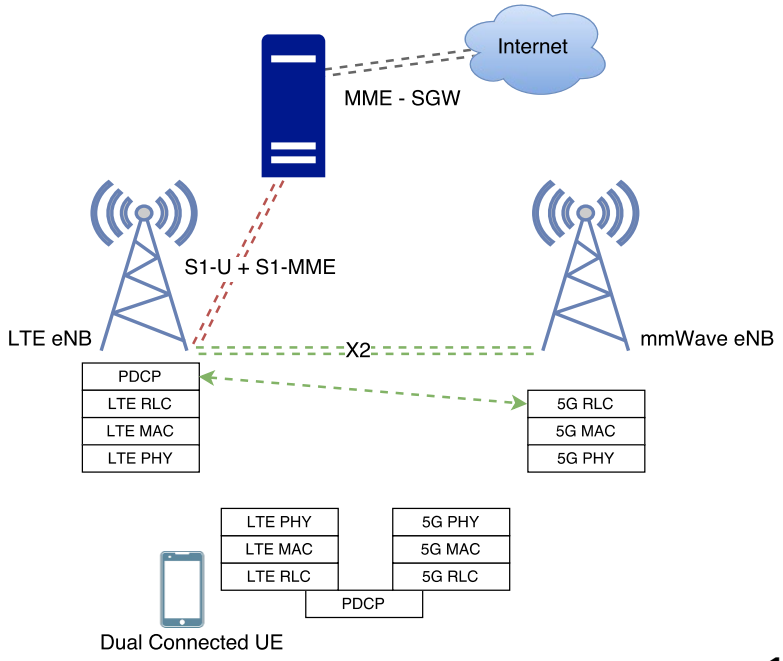
1 Low-latency, highly reliable handovers

Mobility management

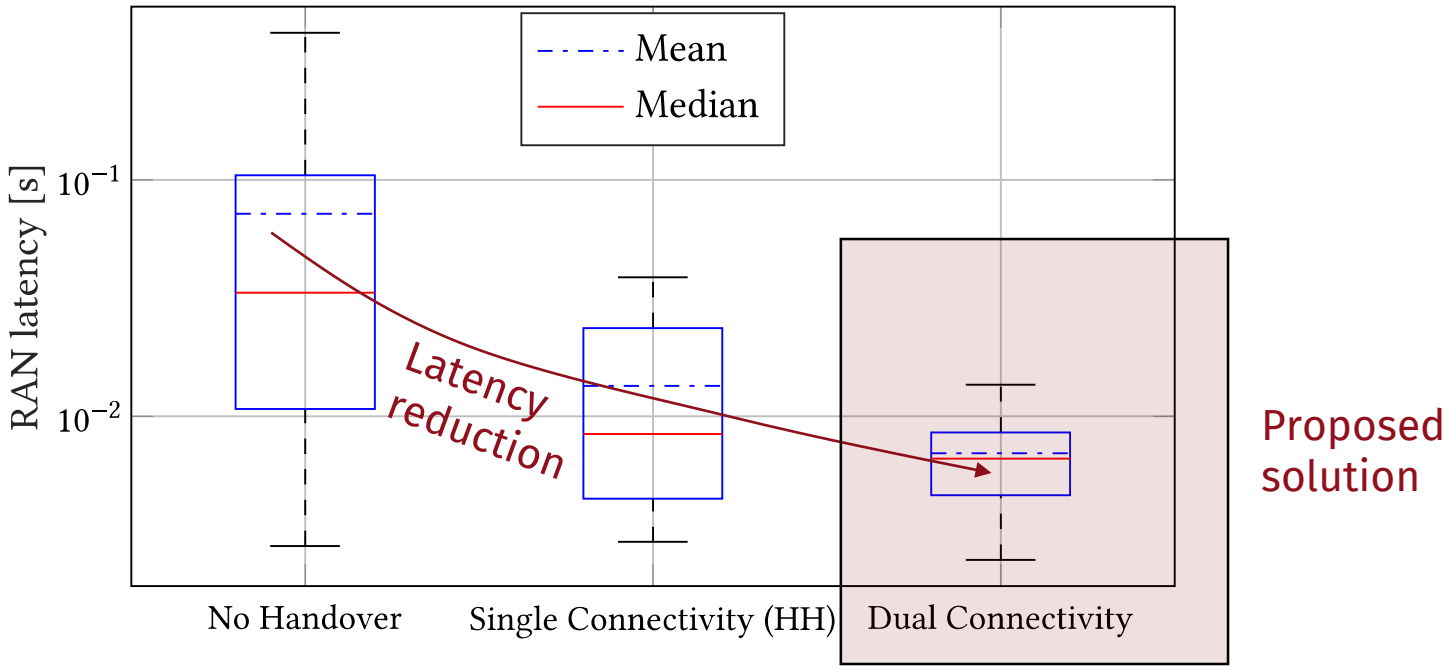
- **Goal:** design a system resilient to fluctuations and outages
- **Contribution:**

Multi-connectivity architecture
to combine sub-6 GHz and mmWave benefits





Results: latency with TCP traffic



- *No handover* (always keep the same BS)
- *Single connectivity* (traditional HO architecture)
- ***Multi connectivity*** (fast handovers – no service interruption)

Integrated Access and Backhaul

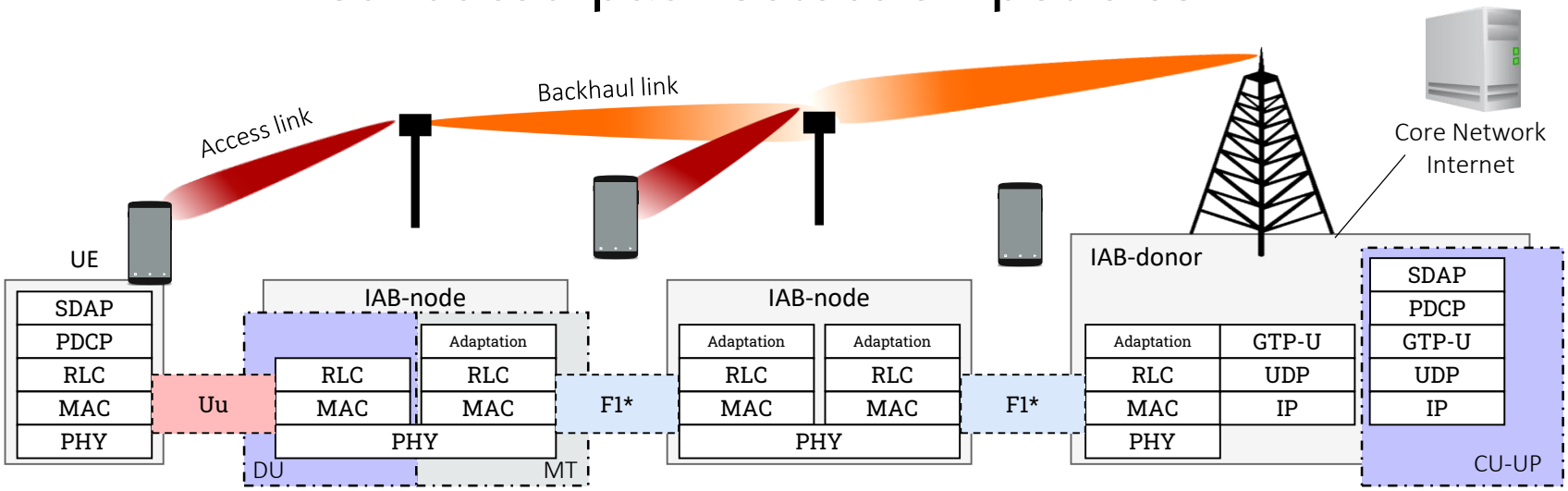
3GPP Work Item for Release 16

- **Goal:** provide wireless backhaul to ultra-dense mmWave networks
- **Contributions:**

IAB module for ns-3 mmWave

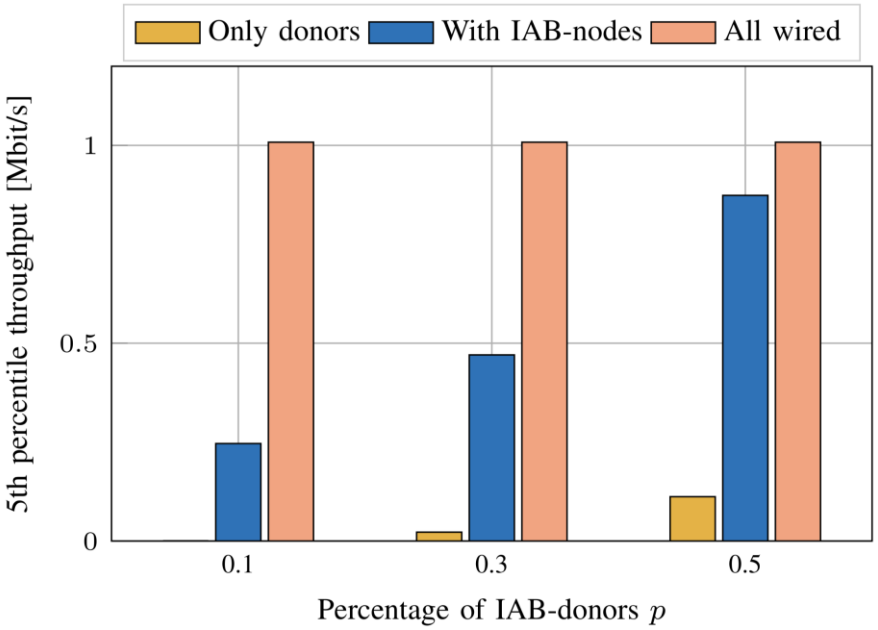
Analysis of IAB end-to-end performance

Distributed path selection policies

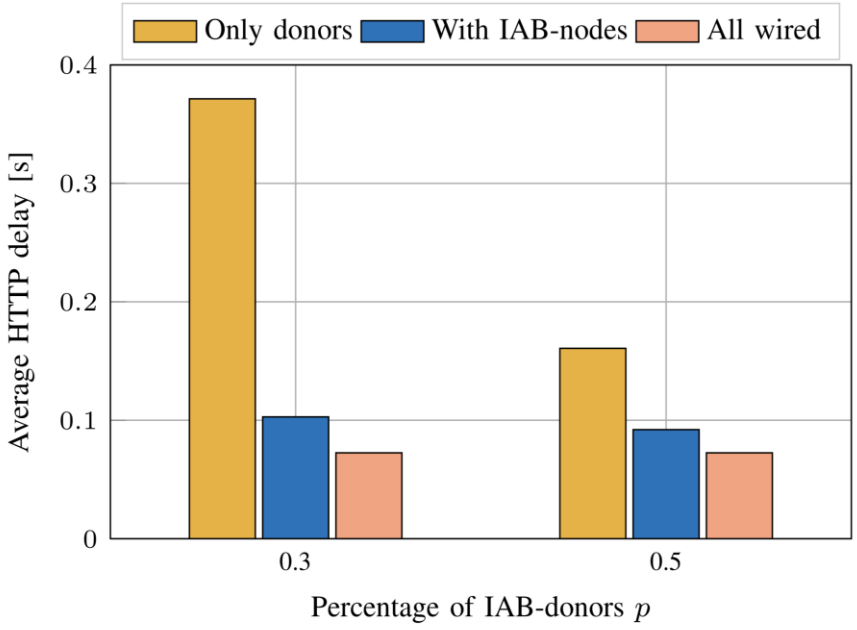


End-to-end Performance for IAB

Impact of synchronous vs. bursty traffic



Throughput with full buffer source



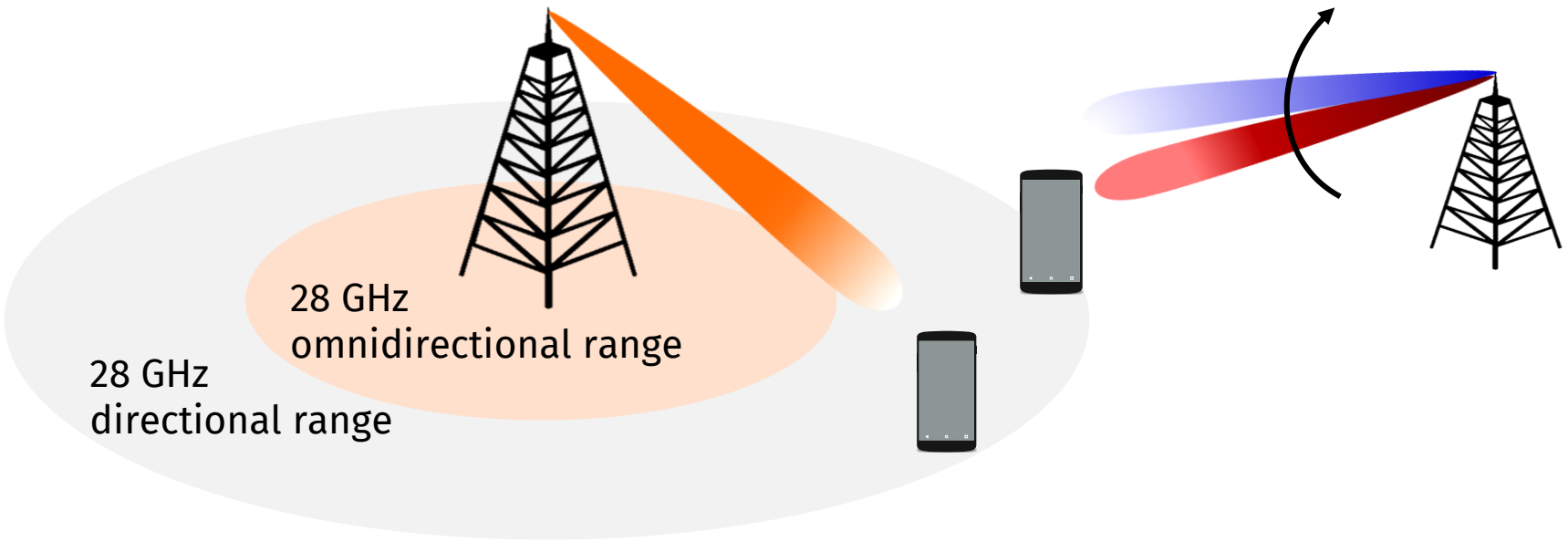
Webpage loading time with browsing model

Beam management in 3GPP NR

- **Goal:** perform directional initial access and tracking
- **Contributions:**

  Study of 3GPP NR beam management schemes

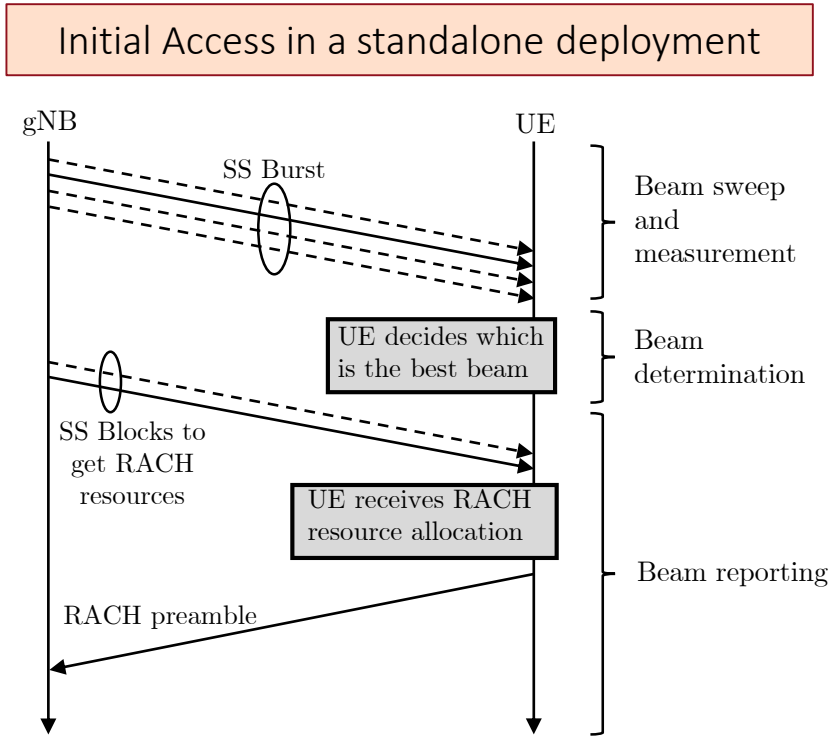
  Analysis of their performance with design insights



Beam Management in NR

The 3GPP has specified **a set of procedures** for the control of multiple beams at mmWave frequencies which are categorized under the term BEAM MANAGEMENT

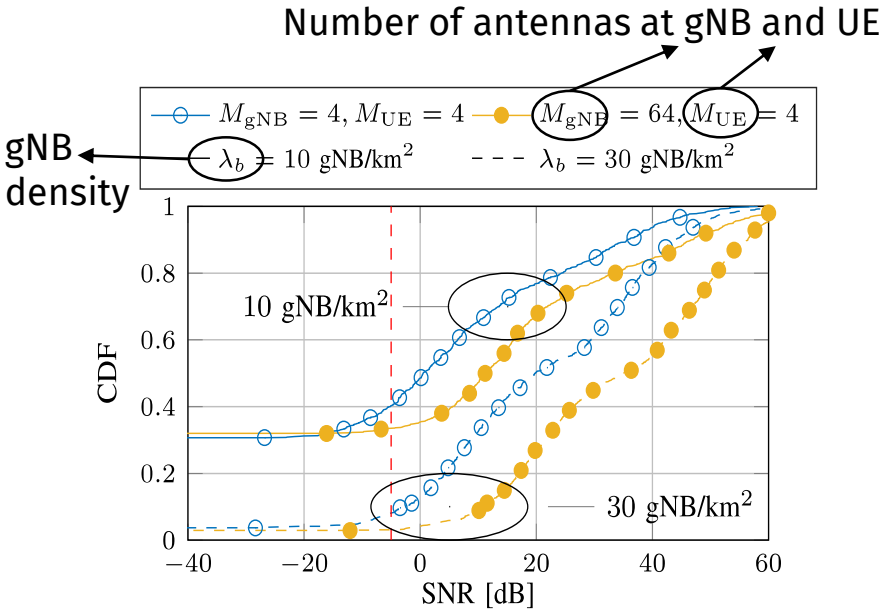
1. *Beam sweeping*
2. *Beam measurement*
3. *Beam determination*
4. *Beam reporting*

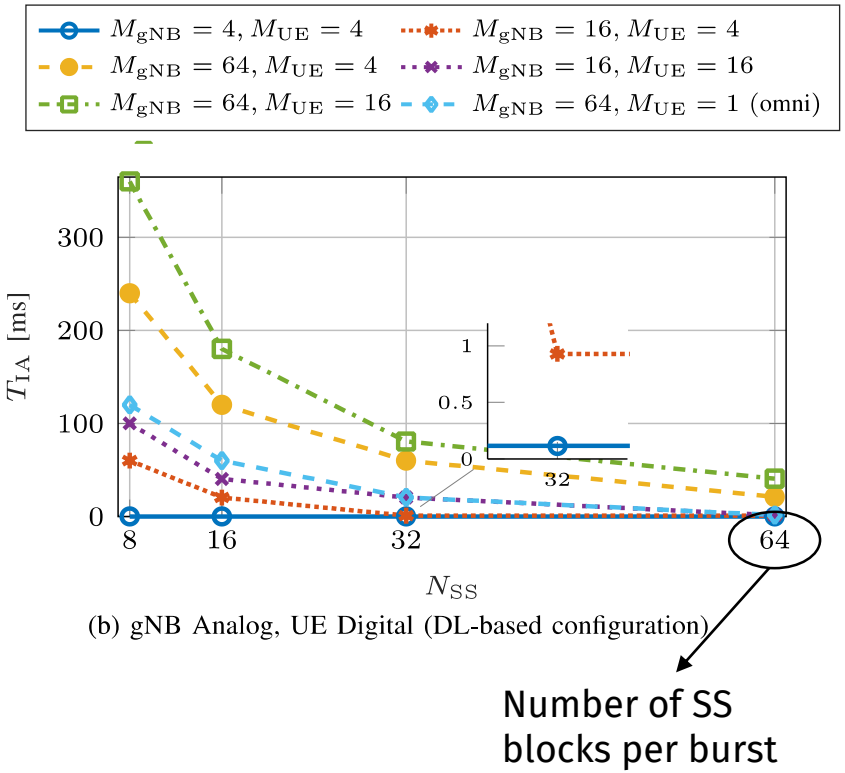


Accuracy-reactiveness tradeoff in NR

Accuracy: what is the probability of receiving an SS block?

Reactiveness: how much time does it take to perform IA?





(b) gNB Analog, UE Digital (DL-based configuration)

Number of SS blocks per burst

Beam management for UAVs

Proposed location-based beam management for UAVs
Experimental evaluation

The Architecture

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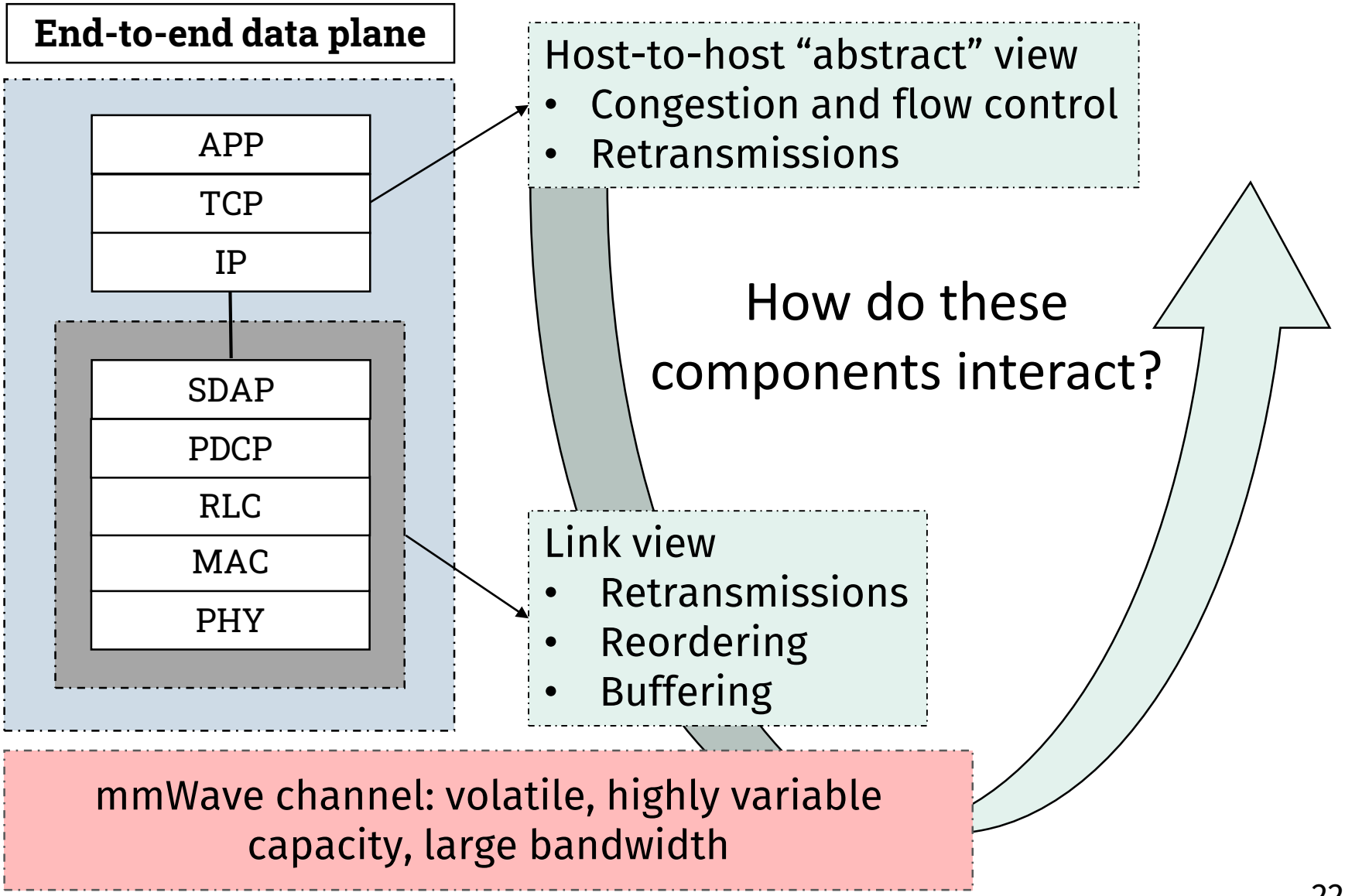
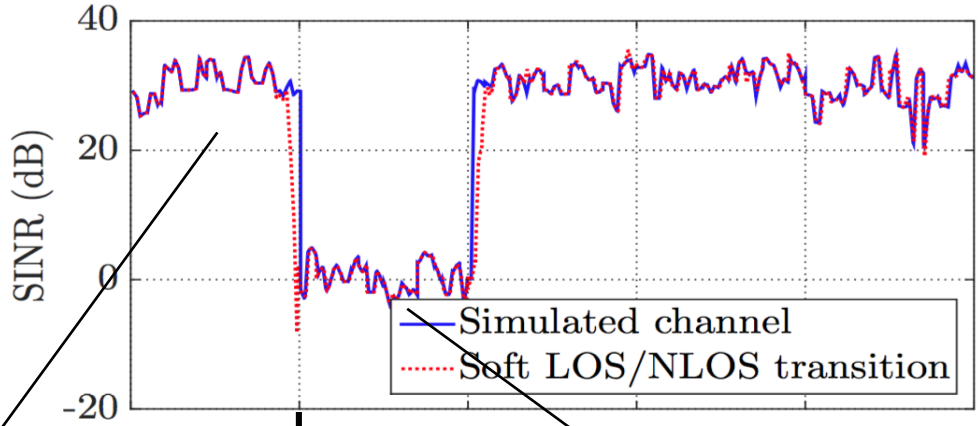
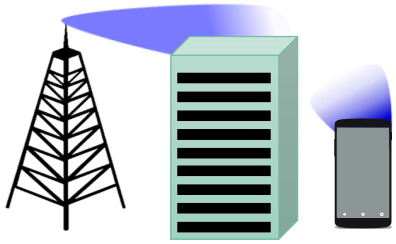
TCP issues in mmWave networks

The Protocols

TCP issues in mmWave networks

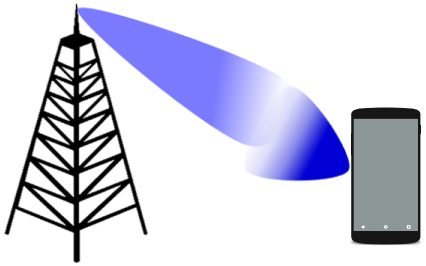




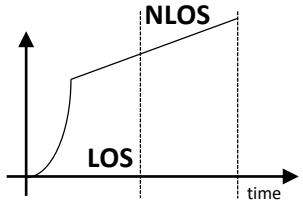


LOS

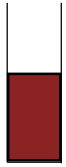
NLOS
After transition from LOS



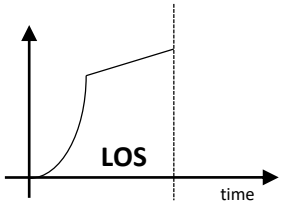
1 **Large buffer**
Bufferbloat
High latency



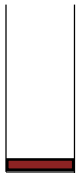
congestion window



RLC buffer occupancy

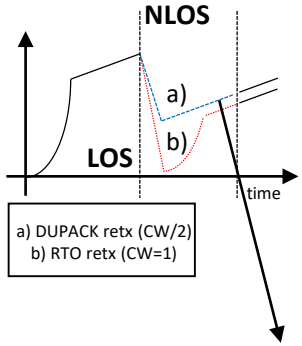


congestion window



RLC buffer occupancy

2 **Small buffer**
Buffer overflow
Low throughput



3 **Slow ramp-up** when back in LOS

Possible solutions

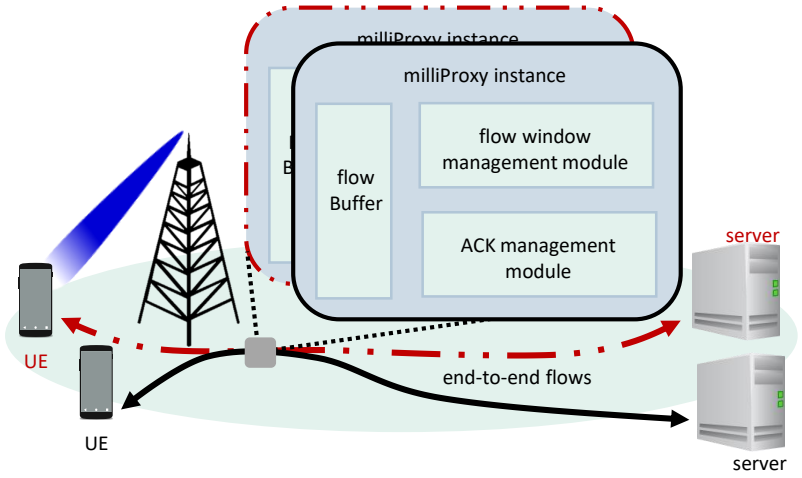
- **Goal:** improve TCP end-to-end performance on mmWaves
- **Contributions:**

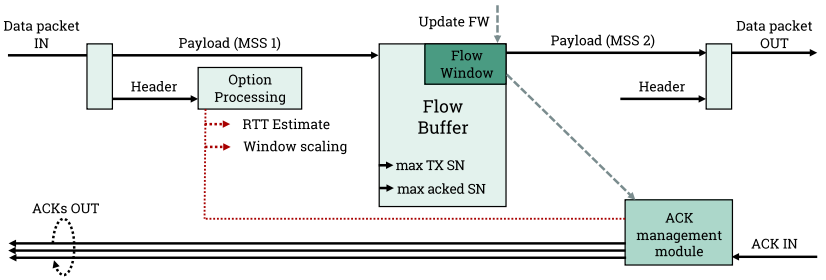
Edge deployments: a shorter control loop, to react faster

CC algorithms: faster window ramp-up mechanisms

Exploit multiple paths: mobility management or MP-TCP

milliProxy: cross-layer approach to better control the TCP sending rate

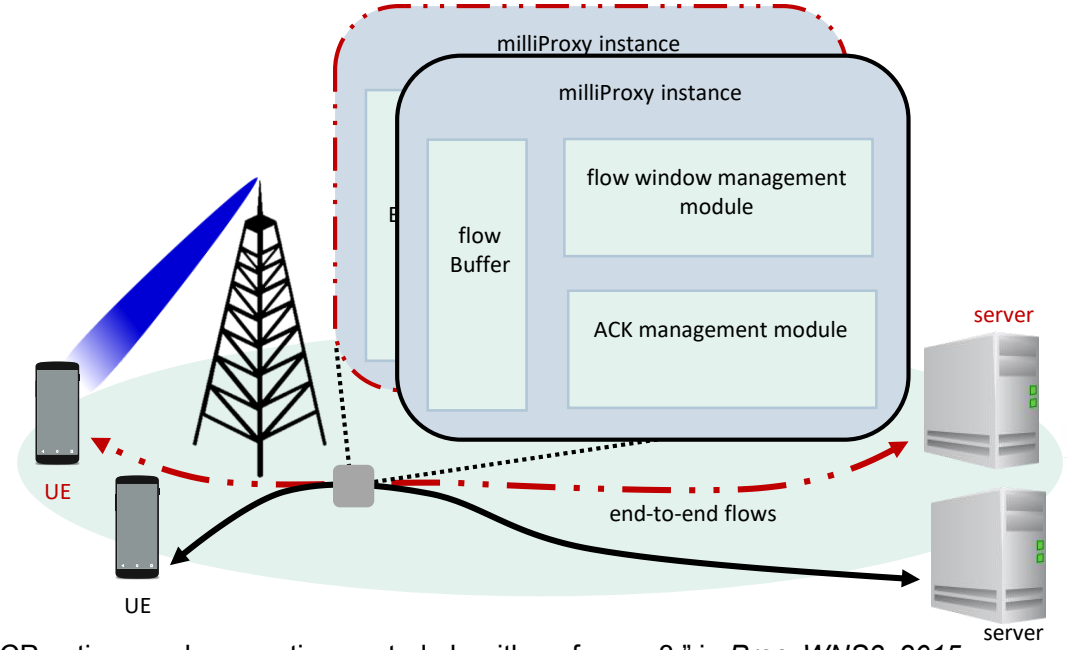




milliProxy – a TCP proxy for mmWaves

Reduce buffering latency + increase goodput

- Transparent to the end-to-end flow
- Installed in the gNB – or at the edge
- Cross-layer approach
  - Per-UE data rate
  - RLC buffer occupancy
  - RTT estimation
- Modular
  - Plug-in different flow control algorithms (inspired to [1])



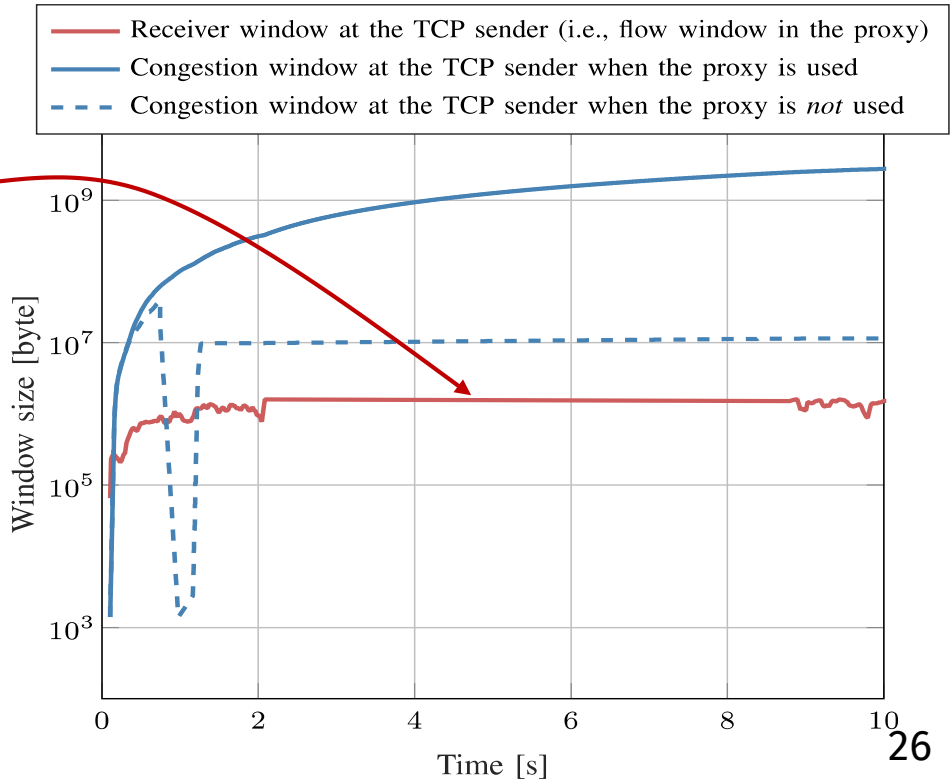
[1] M. Casoni et al., "Implementation and validation of TCP options and congestion control algorithms for ns- 3," in *Proc. WNS3, 2015*

milliProxy – flow control

- Interaction with the TCP sender
  - TCP sending rate is *min(CW,ARW)*
  - milliProxy modifies the ARW in the ACKs, according to the flow control policy used
    - Bandwidth-Delay Product (BDP) based *ARW = BW*RTT*
    - More conservative *ARW = min([RTT*PHY$_{rate}$]-B, 0)*

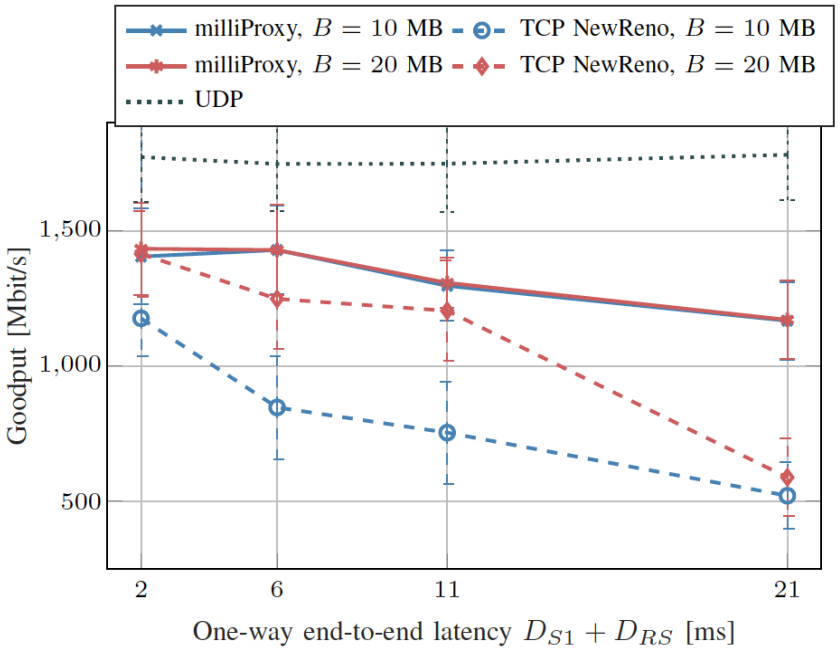
Advertised window (receiver's feedback sent on ACK packets)

Congestion window (computed by the sender)



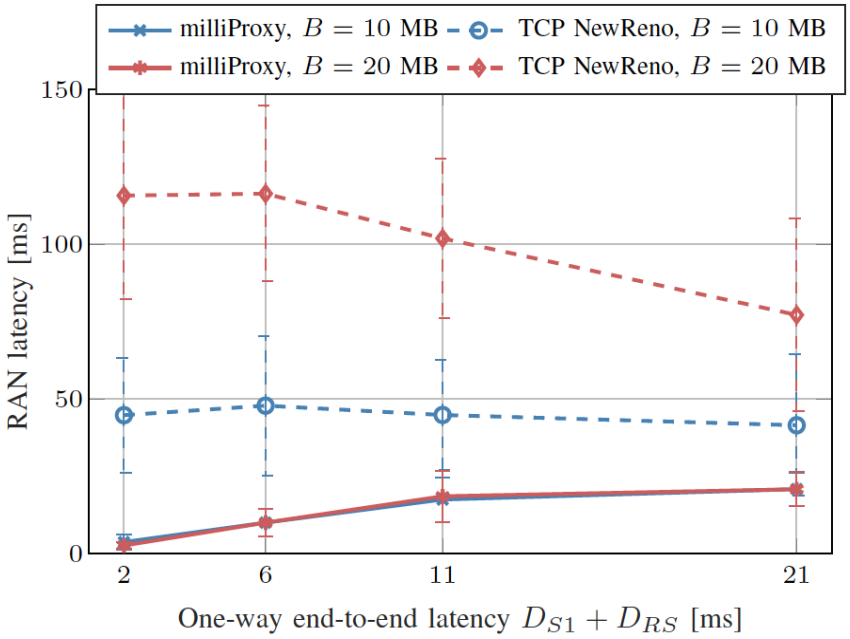
Results: scenario with many LOS/NLOS transitions

Throughput



(a) TCP goodput

Latency



(b) Latency in the RAN (from the PDCP at the eNB that at the UE)

$D_{S1} + D_{RS}$ [ms]	2	6	11	21
$B_{\text{RLC}} = 10$ MB	1.1941	1.6875	1.7202	2.2430
$B_{\text{RLC}} = 20$ MB	1.0135	1.1448	1.0765	1.9901

Throughput gain w milliProxy

$D_{S1} + D_{RS}$ [ms]	2	6	11	21
$B_{\text{RLC}} = 10$ MB	11.8008	4.7547	2.5574	1.9888
$B_{\text{RLC}} = 20$ MB	43.3299	11.5578	5.8104	3.6988

Latency reduction w milliProxy

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Data-Driven 5G Networks Optimization

Machine Learning at the Edge

The Intelligence

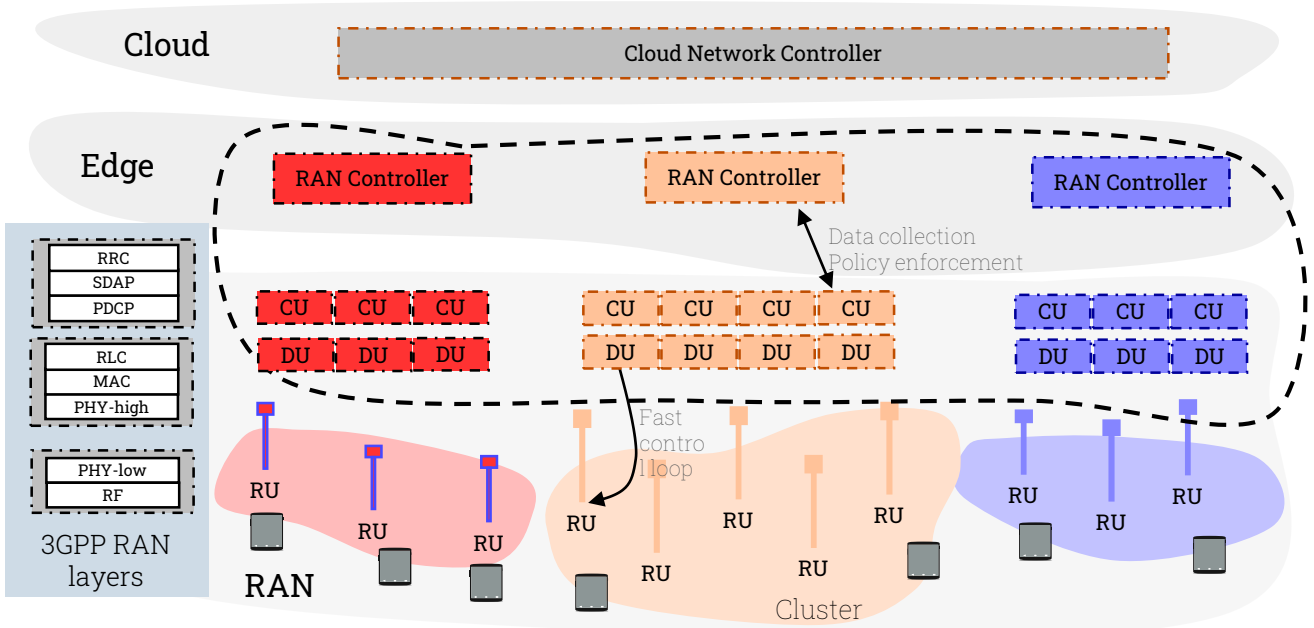
Machine learning at the edge

- **Goal:** deploy intelligent and data-driven techniques in 5G networks
- **Contributions:**

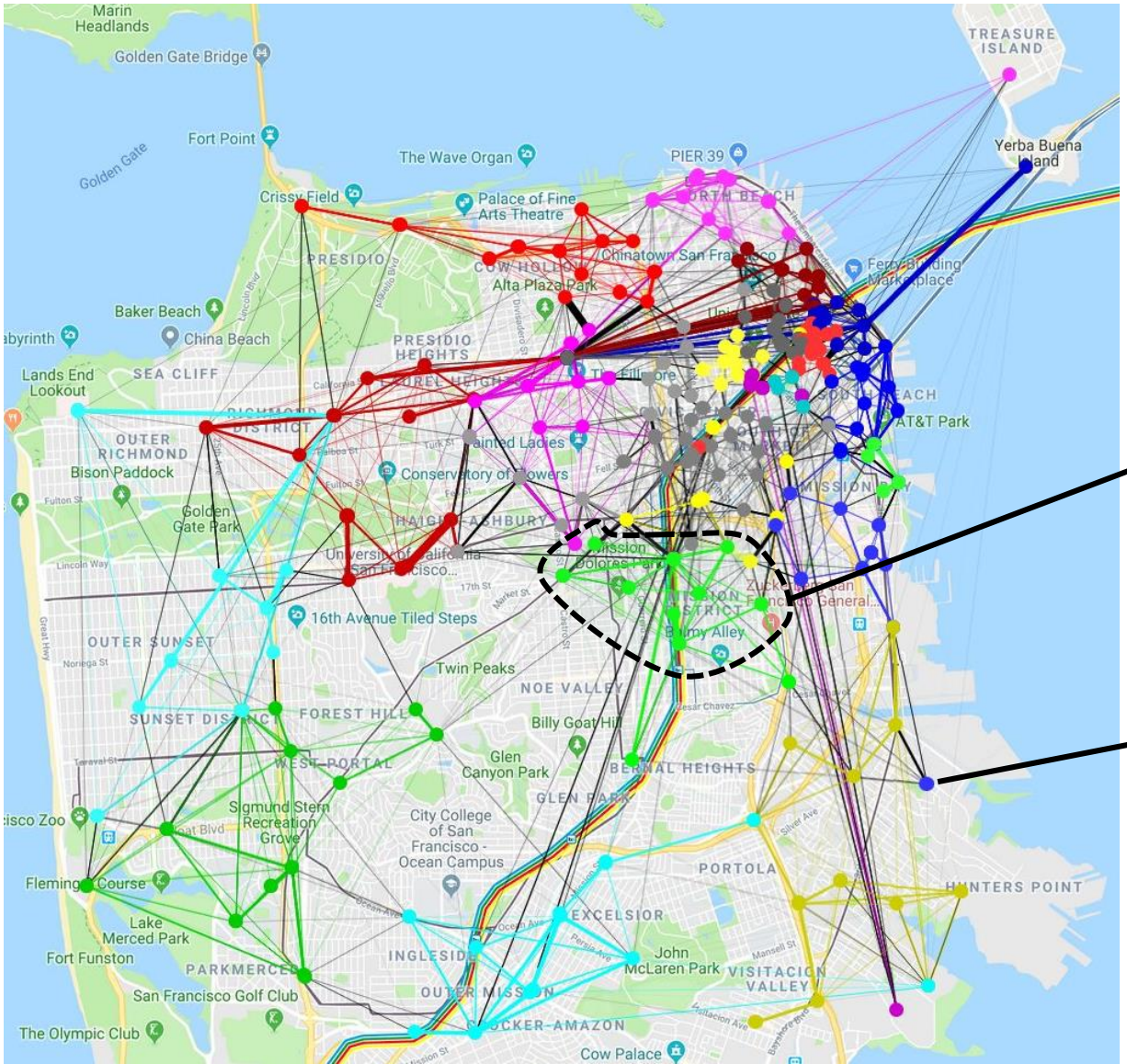
Mobile-edge controller-based **architecture**

Data-driven **dynamic clustering** of base stations

Prediction accuracy of the number of **UEs** per base station



Data-driven clustering example



Each color is a cluster

Base station locations

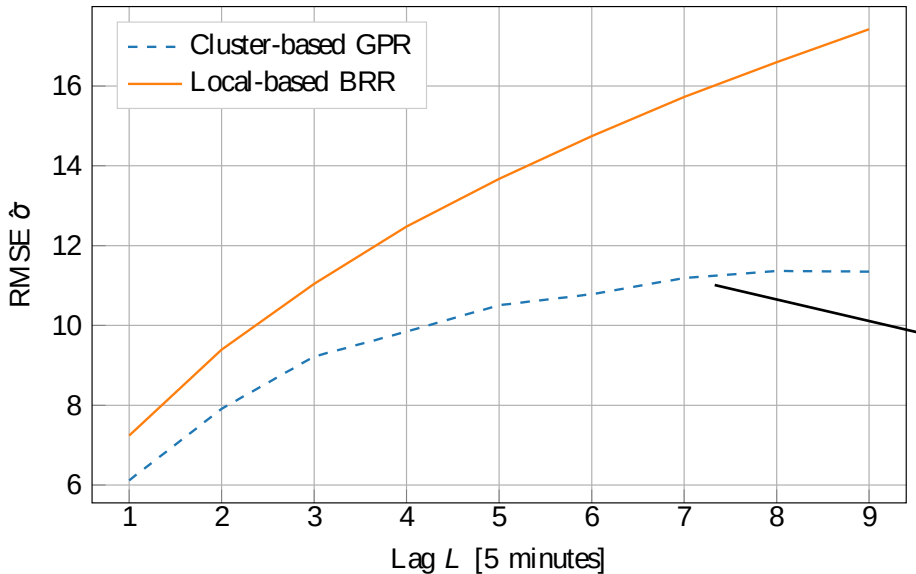
Prediction of the number of UEs

- Spatial correlation (**cluster-** vs local-based) is more impactful than temporal correlation

53% RMSE reduction

5% RMSE reduction when increasing W

- Exploit geographic constraints on mobility flows
- When considering all the 472 eNBs (in 22 clusters):



Approach based on the proposed architecture

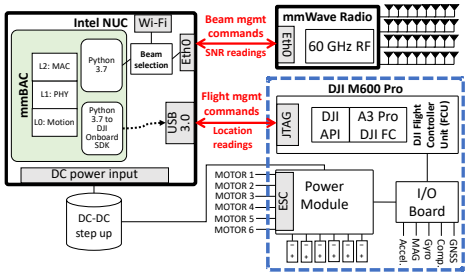
Conclusions

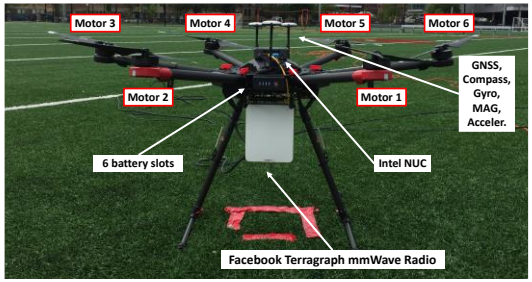
Conclusions

- System–level, end-to-end approach throughout all the topics
- Considered different components of a **complex system** and introduce novel contributions for
  - **Architectures**
  - **Protocols**
  - **Intelligence**
- Thorough and **realistic performance evaluation**
- End-to-end, full-stack analysis may uncover unexpected behaviors

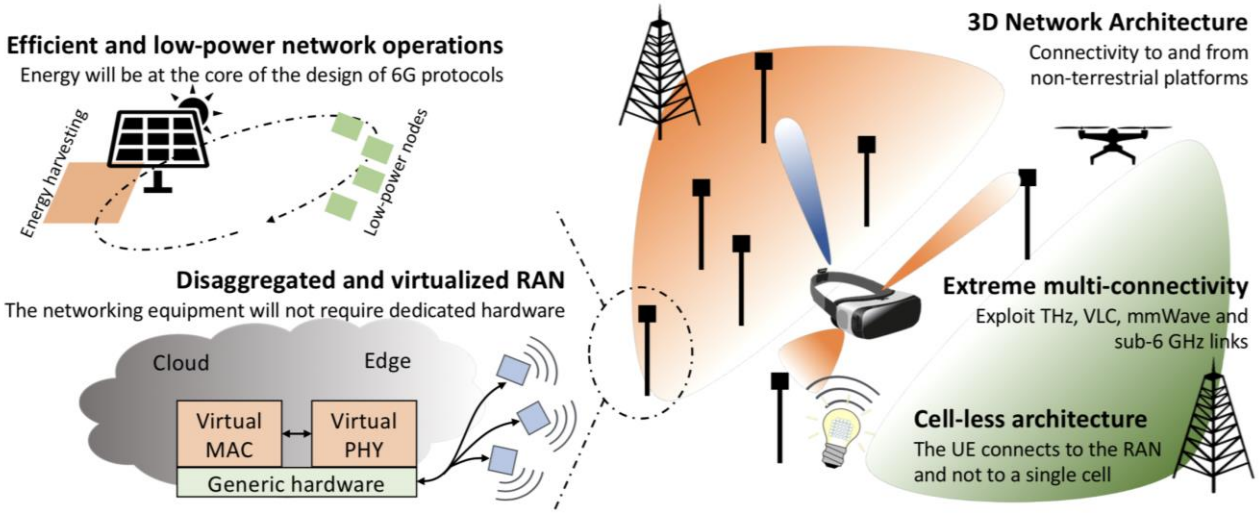
Future work

- Future research will still be focused on a system-level approach, combined with testbeds and experimental results





- **What happens when you consider increasingly complex systems?**



Journals

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