IEEE Future Networks Webinar

mmWaves in 5G NR cellular networks: a system level perspective

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DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

mmWaves in 5G NR cellular networks: a system level perspective

Joint work with

- mmWave group at UNIPD – Prof. Michele Zorzi, Marco Giordani, Mattia Rebato, Tommaso Zugno
- NYU Wireless – Prof. Sundeep Rangan, Marco Mezzavilla, Menglei Zhang
- Industrial collaborations: InterDigital, AT&T, Intel
- Acknowledgement to NIST Award 70NANB17H166

Outline

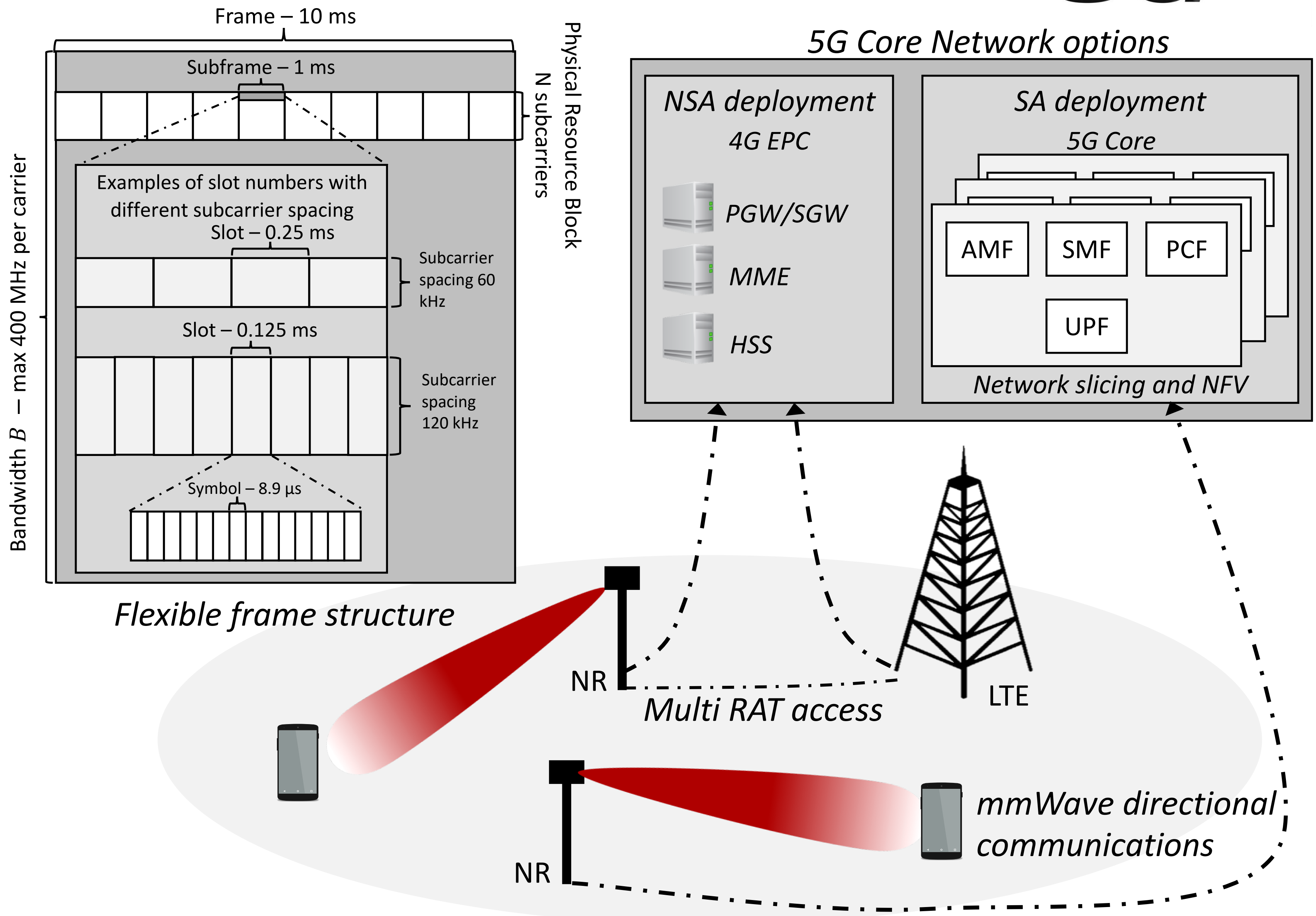
- Introduction
- Mobility at mmWaves
  - Multi connectivity solutions
  - 3GPP NR beam management
- Deployment of mmWave networks
  - Integrated Access and Backhaul
- End-to-end performance and cross-layer interactions
  - TCP and the mmWave RAN
- Conclusions and research directions

3GPP NR: novelties

- New Radio Access Network (RAN)
  - Physical layer with Orthogonal Frequency Division Multiplexing (OFDM)
  - Support for
    - Higher frequencies (mmWaves)
    - Ultra-low latency
  - Stand-alone (SA) or Non Stand-alone (NSA) operations

- New Core Network
  - Network Function Virtualization (NFV)
  - Network slicing

3GPP NR: novelties



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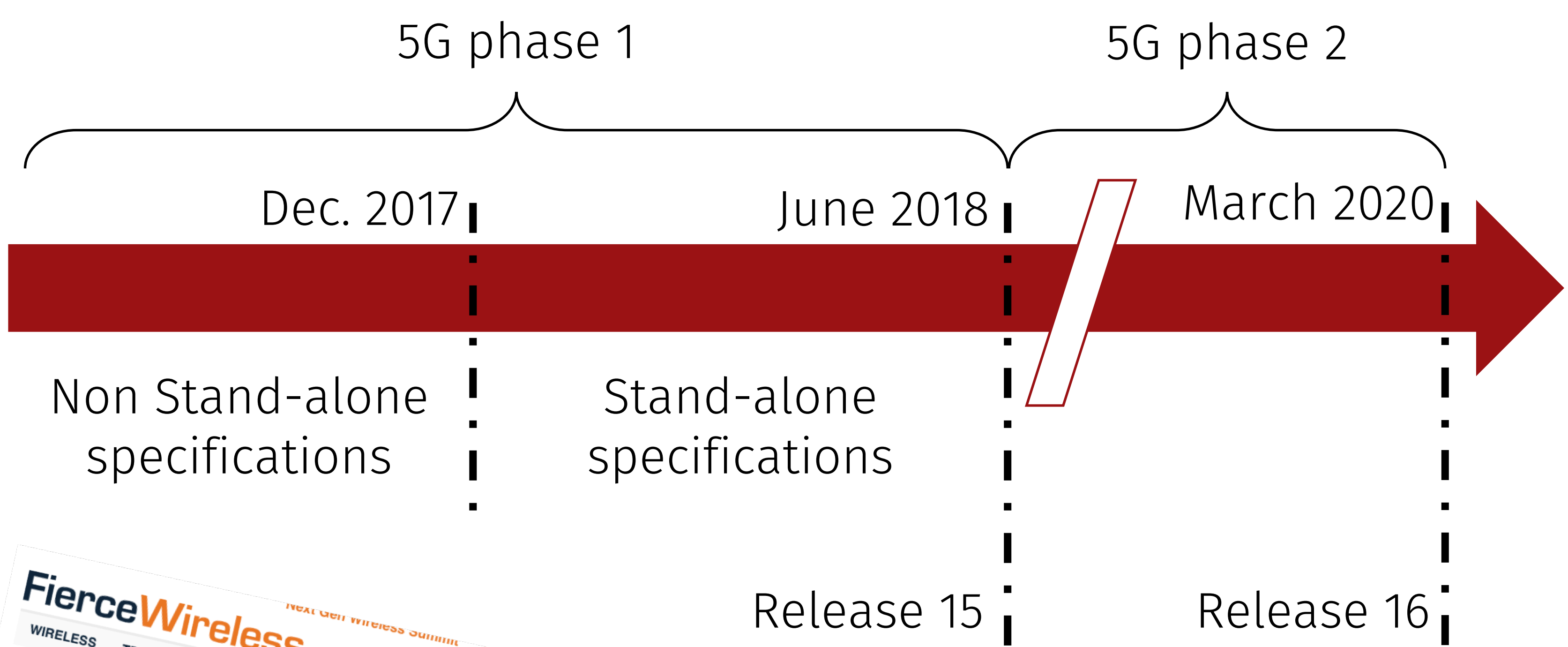
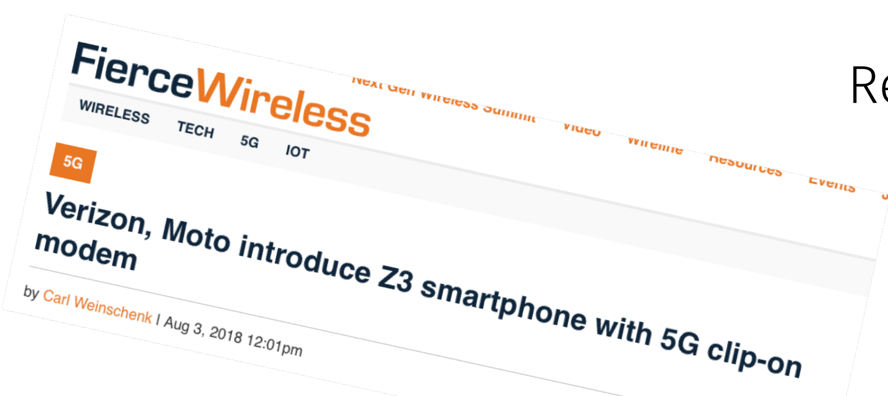
3GPP NR: timeline

Goal: deployment by 2019




FierceWireless

WIRELESS TECH 5G IOT

5G

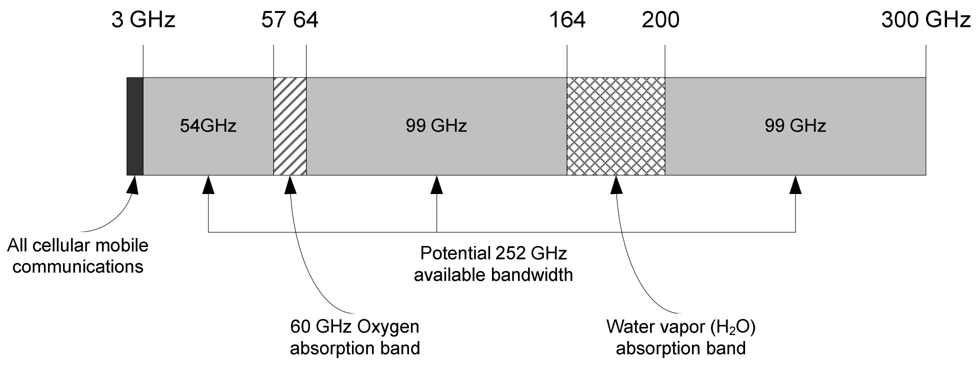
Verizon, Moto introduce Z3 smartphone with 5G clip-on modem

by Carl Weinschenk | Aug 3, 2018 12:01pm

3GPP NR: mmWaves in cellular networks

3GPP NR Release 15 will support frequencies up to 52.6 GHz

- Potentials
  - Bandwidth
  - Large arrays in small space

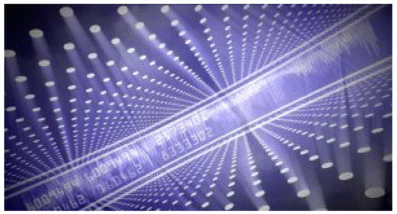


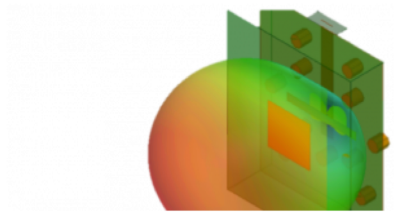
Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," in *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101-107, June 2011.

- Challenges
  - High **propagation** loss
  - Directionality
  - **Blockage**

mmWave research in Padova

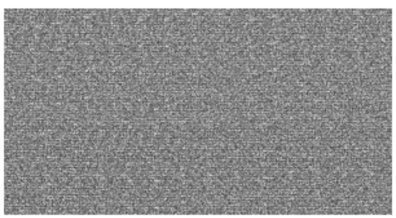
MAC layer and network level perspectives


ADC


Antenna Modeling


Initial Access


Integrated Access and Backhaul


Interference


Mobility

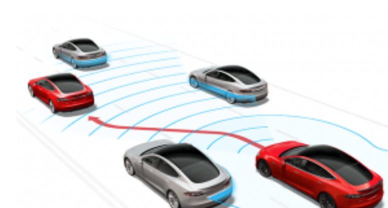

Public Safety Communications


Simulation


Spectrum Sharing


Transport Protocols

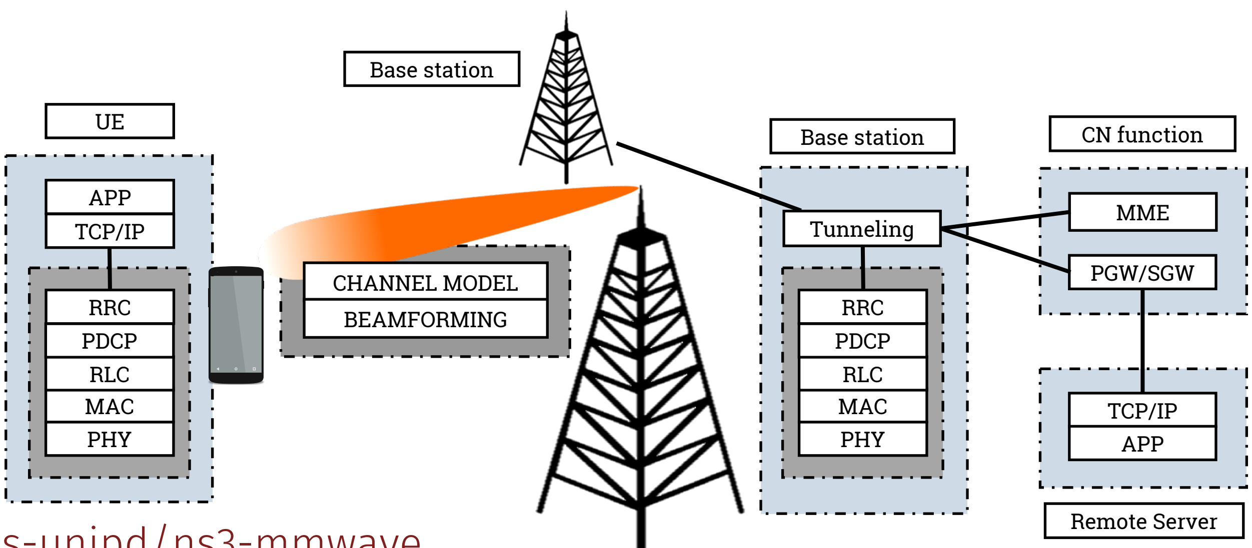

Tracking


Vehicular Communication

From mmwave.dei.unipd.it

ns-3 mmWave module

- Built on top of ns-3 – popular open source network simulator – and the LTE LENA module
- Used in several performance evaluations presented in this talk
- **End-to-end** performance analysis
  - Multiple scenarios (cellular, public safety, vehicular)
  - Realistic channel model implementation (3GPP)
  - Custom PHY/MAC
  - Mobility with dual connectivity
  - Full TCP/IP stack
  - Application layer



www.github.com/nyuwireless-unipd/ns3-mmwave

Mobility at mmWaves

Multi connectivity and beam management

The mobility challenge at mmWaves

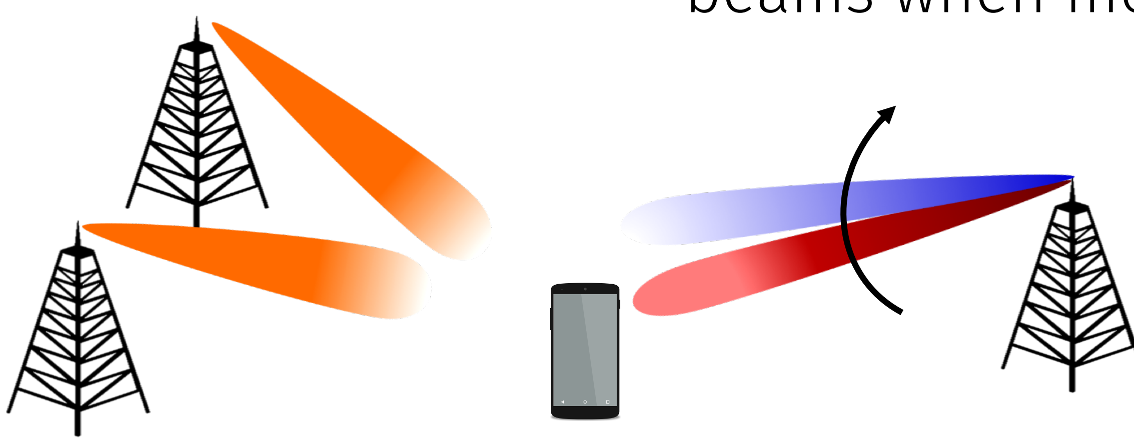
Issues: high propagation loss and blockage

Ultra-dense deployments

High number of handovers

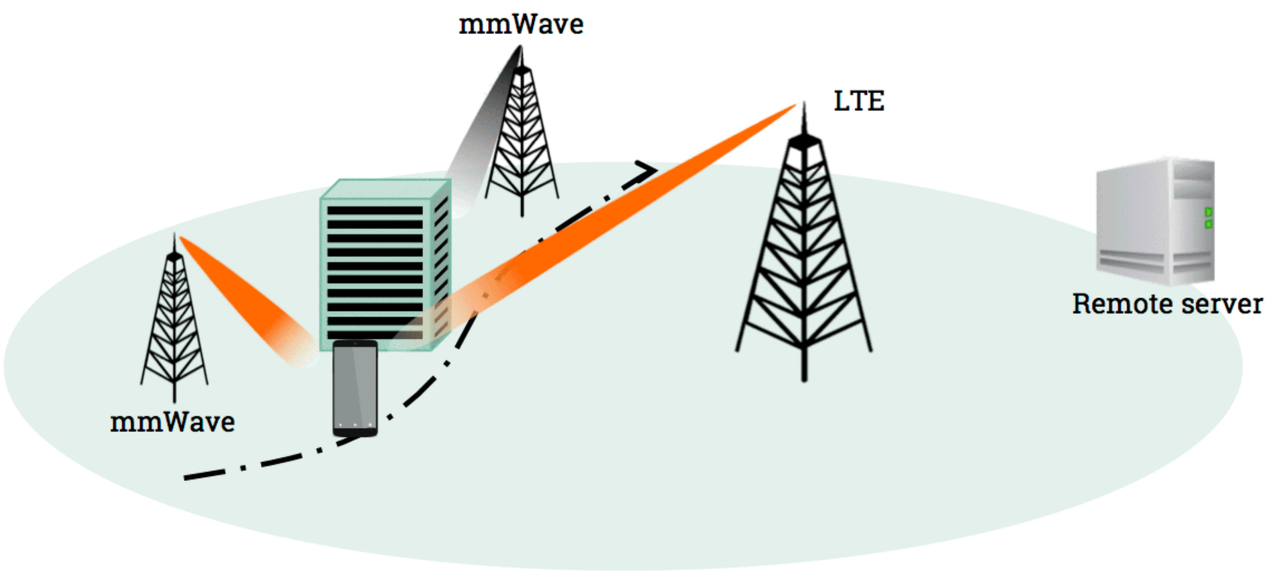
Large antenna arrays increase the link budget, but the power is focused on **narrow beams**

Need to track the narrow beams when moving



Multi connectivity for mmWaves

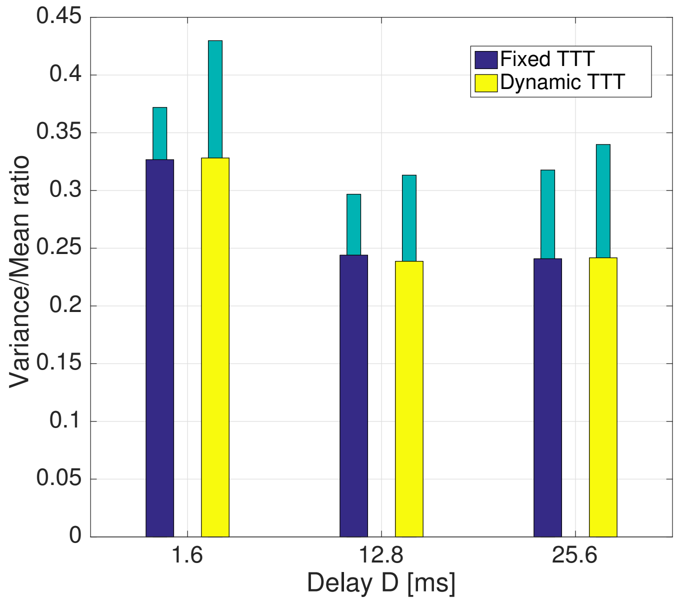
- **Goal:** design a system resilient to fluctuations and outages



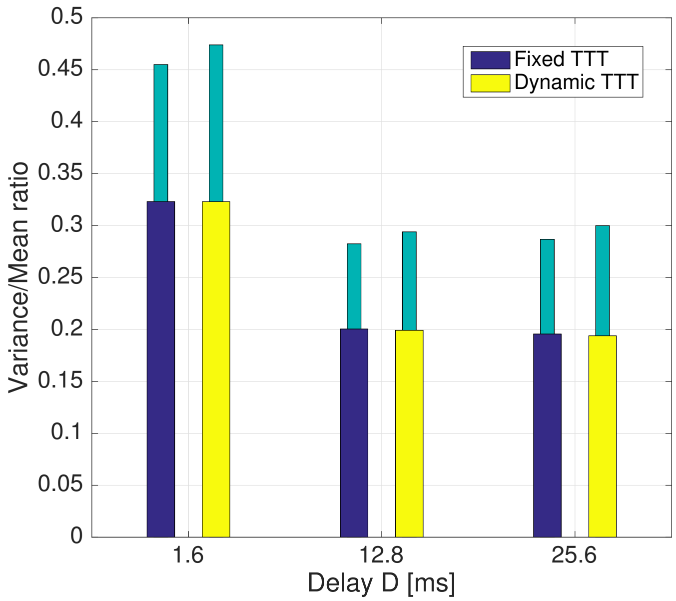
Multi-connectivity combines sub-6 GHz
and mmWave benefits

M. Polese, M. Giordani, M. Mezzavilla, S. Rangan and M. Zorzi, "**Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks**," in *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2069-2084, Sept. 2017.

Results: throughput variance with UDP traffic



(a) Variance/Mean ratio, for $T_{\mathrm{UDP}} = 20\ \mu s$.

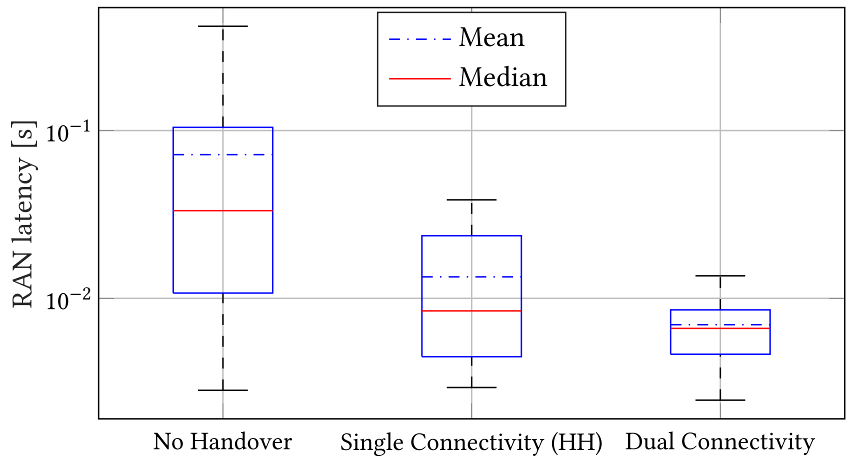


(b) Variance/Mean ratio, for $T_{\mathrm{UDP}} = 80\ \mu s$.

Variance is **lower when multi connectivity** is implemented
(good for real-time applications – prevents buffer overlows)

- UDP traffic (constant bitrate, 400 Mbit/s at application layer)
- Throughput measured in the RAN

Results: latency with TCP traffic



High blockage density

- No handover -> **bufferbloat** with TCP (more on this later)
- **Multi connectivity** (fast handovers – no service interruption) -> lowest RAN latency

M. Polese, M. Mezzavilla, S. Rangan and M. Zorzi, "**Mobility Management for TCP in mmWave Networks**," in *Proceedings of the 1st ACM Workshop on Millimeter-Wave Networks and Sensing Systems 2017 (mmNets)*, pp. 11-16, Snowbird, Utah, USA, Oct. 2017.

Takeaways on multi-connectivity

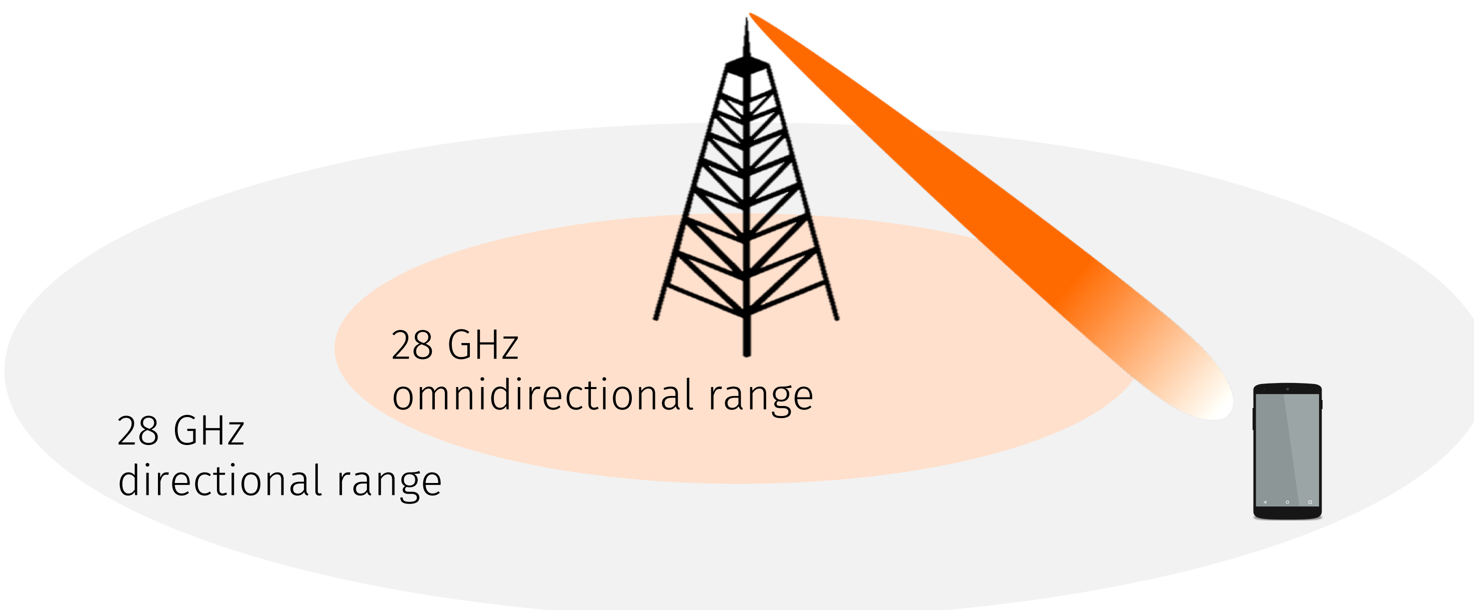
- Generally improved network performance
  - Lower **latency**
  - More **stable** throughput
  - Lower signaling traffic
- **Flexible** solutions for control and user plane coordination
- Cost
  - RAT integration
  - **Backhaul** traffic

Beam management in 3GPP NR - motivation

INITIAL ACCESS

- *Challenge*: at mmWaves **antenna gains** are needed already during the IA phase

Directional initial access schemes



Beam management in 3GPP NR - motivation

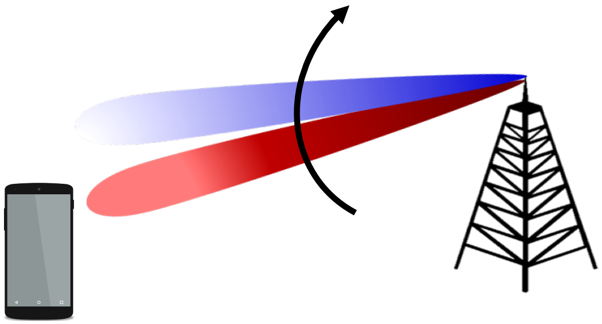
INITIAL ACCESS

- During **Initial Access (IA)** a UE establishes a physical link connection with a gNB

Directional initial access schemes

BEAM TRACKING

- UE and gNB keep tracking which is the **best beam** for communication throughout the whole session
- Possibly trigger **mobility procedures** such as beam switch, handover or radio link failure



Beam management in 3GPP NR

3GPP NR integrates beam management procedures at the PHY and MAC layers

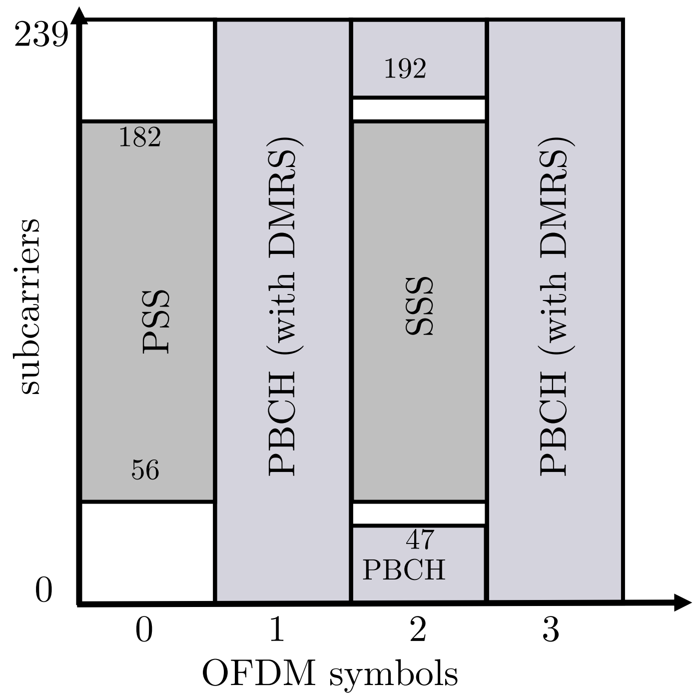
- Novel design of synchronization and reference signals
- Novel procedures for initial access and beam tracking

M. Giordani, M. Polese, A. Roy, D. Castor, M. Zorzi, "**A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies**", *IEEE Communications Surveys and Tutorials*, 2018.
M. Giordani, M. Polese, A. Roy, D. Castor, M. Zorzi, "**Standalone and Non-Standalone Beam Management for 3GPP NR at mmWaves**", *submitted to IEEE Comm Mag*, 2018.

3GPP NR Measurement Signals: *SS block*

SYNCHRONIZATION SIGNAL (SS): the fundamental **DL** measurement signal for users in *idle* mode*

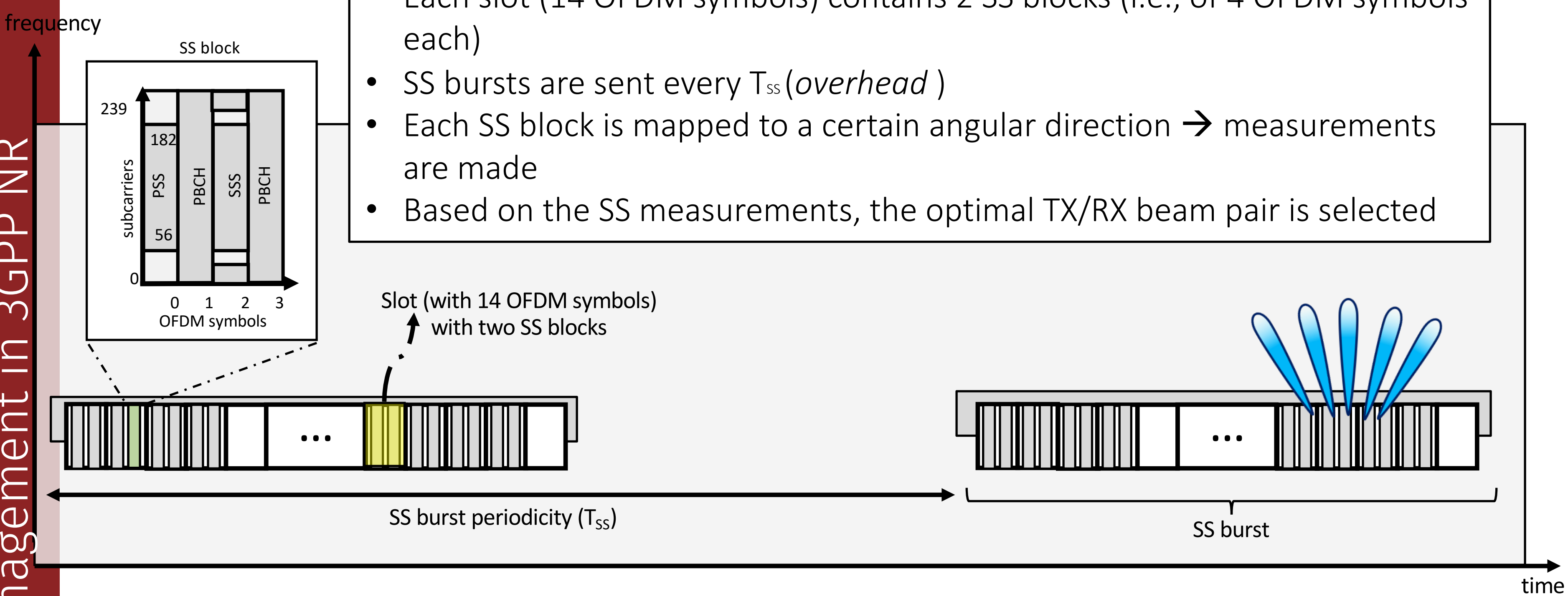
*it can be used also in *connected* mode



- Each gNB transmits directionally the SS blocks, by sequentially sweeping different angular directions to cover a whole cell sector.

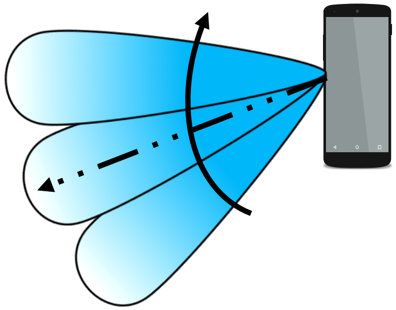
SS block and burst

- Each SS burst is composed of (max) 64 SS blocks
- Each slot (14 OFDM symbols) contains 2 SS blocks (i.e., of 4 OFDM symbols each)
- SS bursts are sent every T_{SS} (*overhead*)
- Each SS block is mapped to a certain angular direction → measurements are made
- Based on the SS measurements, the optimal TX/RX beam pair is selected

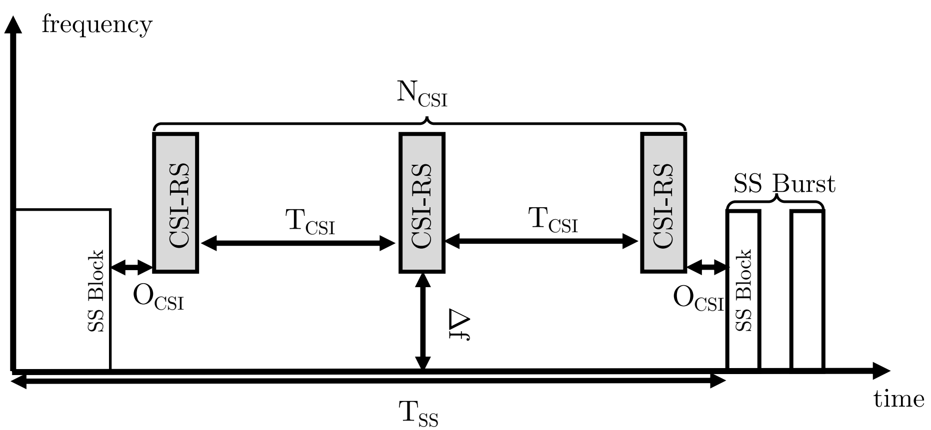


3GPP NR Measurement Signals

SOUNDING REFERENCE SIGNAL (SRS): the fundamental **UL** measurement signal for users in *connected* mode



CHANNEL STATE INFORMATION REFERENCE SIGNAL (CSI-RS): the **DL** measurement signal for users in *connected* mode

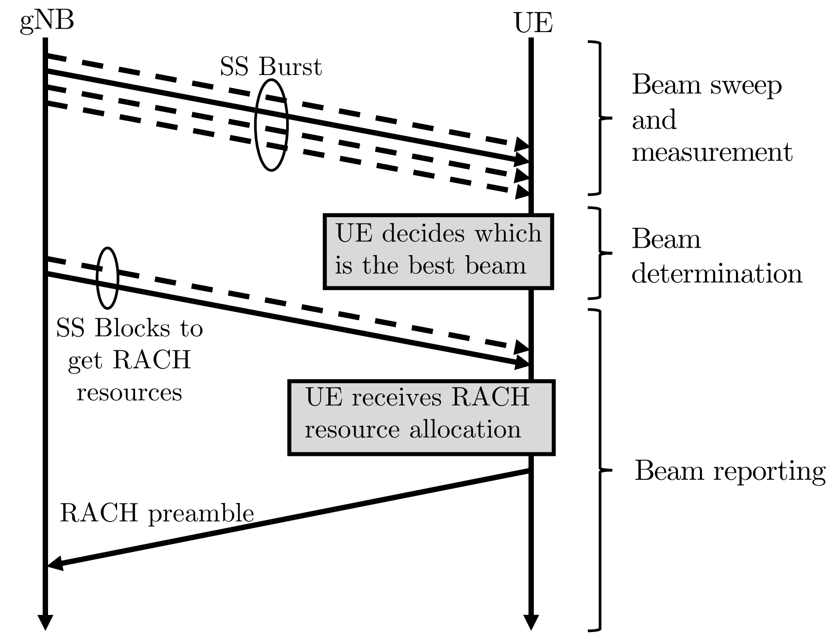


Beam Management in NR

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

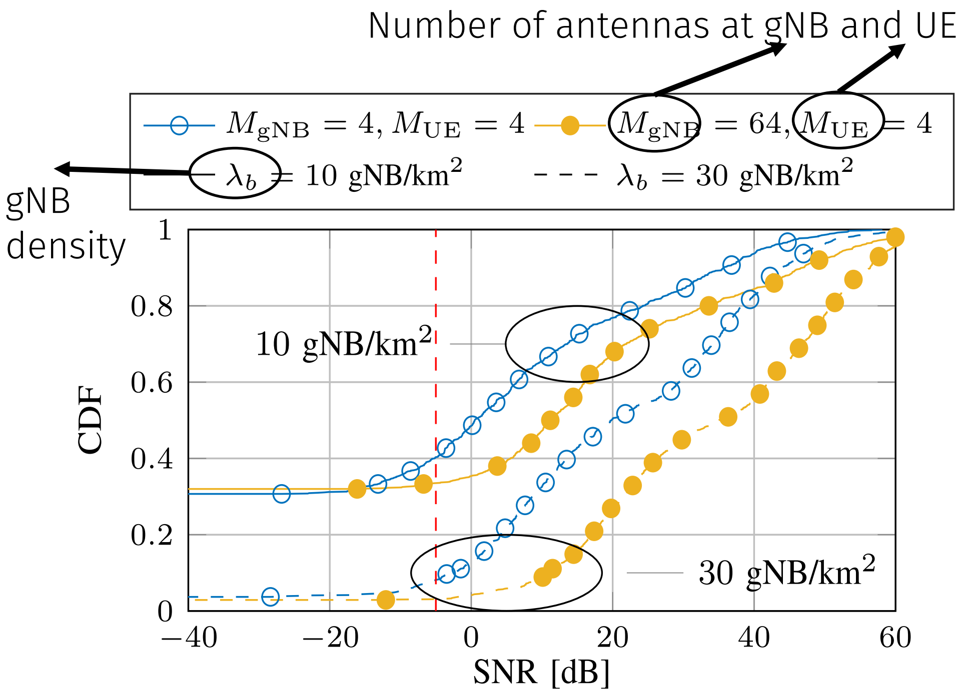
1. *Beam sweeping*
2. *Beam measurement*
3. *Beam determination*
4. *Beam reporting*

Initial Access in a standalone deployment



Results: detection accuracy

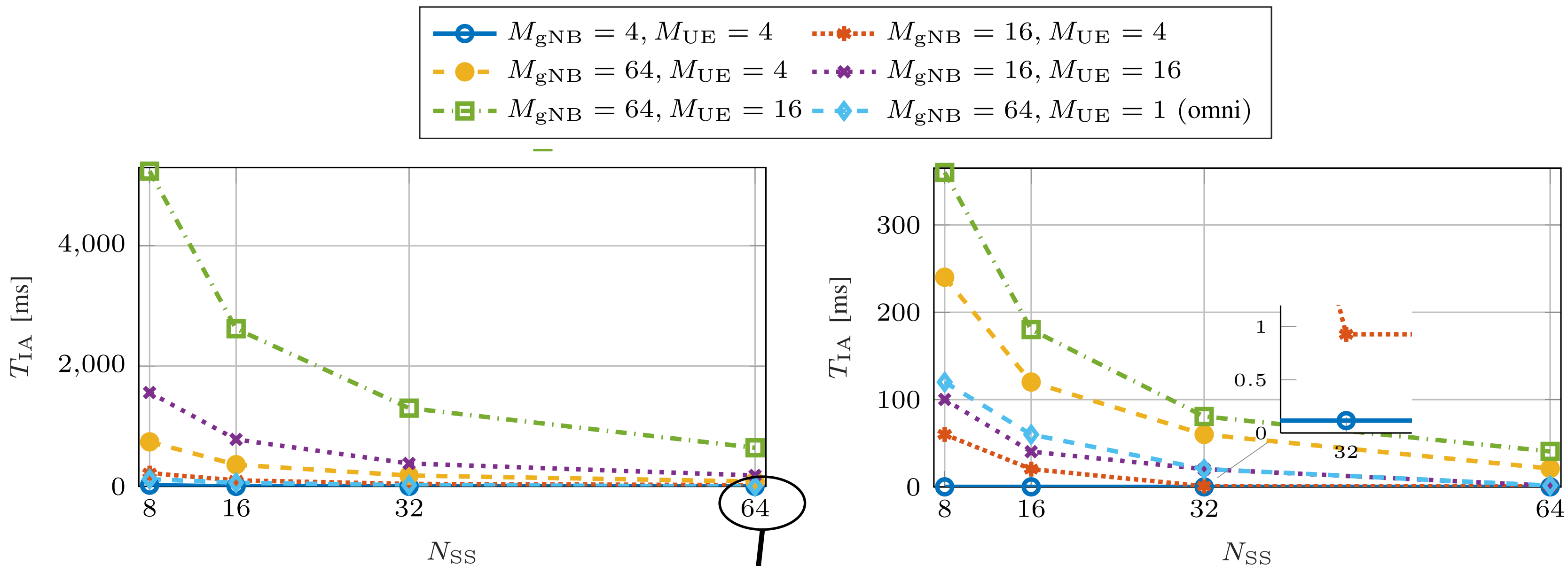
What is the probability of receiving an SS block?



- Better accuracy with **narrow** beams
  (the more antenna elements in the system, the narrower the beams, the more directional the transmission, and the higher the beamforming gain)
- Better accuracy for dense networks

Results: IA reactiveness

How much time does it take to perform IA (or react to a channel update)?



(a) gNB Analog, UE Analog

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

Number of SS blocks per burst

Main takeaways on beam management for NR

- Complete the beam sweep in a <u>single SS burst</u>
(this depends on the number of blocks per burst, the beamforming and the antenna array architectures)

- With low network density, larger antenna arrays enable the communication with farther users, and provide a wider coverage. However, **as the gNB density (λ_b) increases, it is possible to use a configuration with wide beams for SS bursts**

- **Multi-connectivity** frameworks can help for *beam reporting* during *beam tracking*

M. Giordani, M. Polese, A. Roy, D. Castor, M. Zorzi, "**A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies**", *IEEE Communications Surveys and Tutorials*, 2018.

Deployments at mmWaves

Integrated Access and Backhaul

Backhaul for mmWave Deployments

High propagation loss + blockage → High deployment density

? How is it possible to provide high-capacity backhaul in such a dense scenario?

Integrated Access and Backhaul

3GPP Work Item for Release 16

- Goals:
  - Provide **backhaul** in dense deployments without densifying the transport network
  - Support in-band and out-of-band backhauling
  - IAB nodes should be **transparent** to UEs (no difference for the handset)
  - Support **multiple hops**
  - Perform **self**-adaptation of topology
  - **Reuse** Rel.15 NR specifications

3GPP, “Study on Integrated Access and Backhaul”, TR 38.874 – V1.0 Rel. 15

Integrated Access and Backhaul

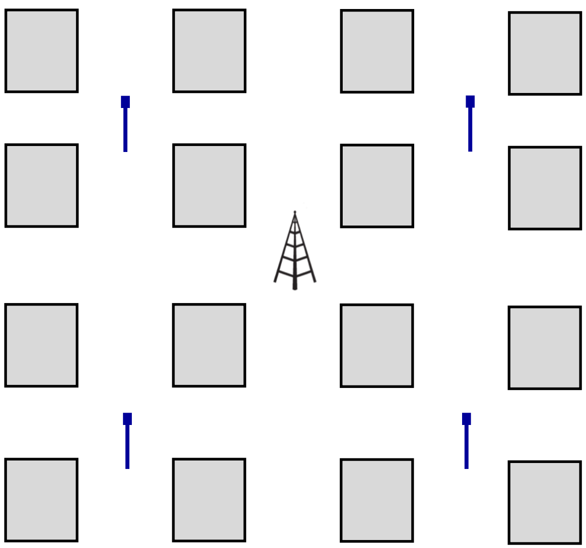
- Opportunities
  - mmWave: high bandwidth for backhaul + spatial reuse
  - In-band backhaul -> no need for multiple frequency licenses
  - Plug-and-play design – self-configuration of IAB nodes
- Challenges
  - Scalability
  - Efficient scheduling
  - Analyze cross-layer interactions

How will IAB perform?

- End-to-end performance in a grid scenario

IAB Performance in grid scenario

- Preliminary evaluation: simple outdoor scenario

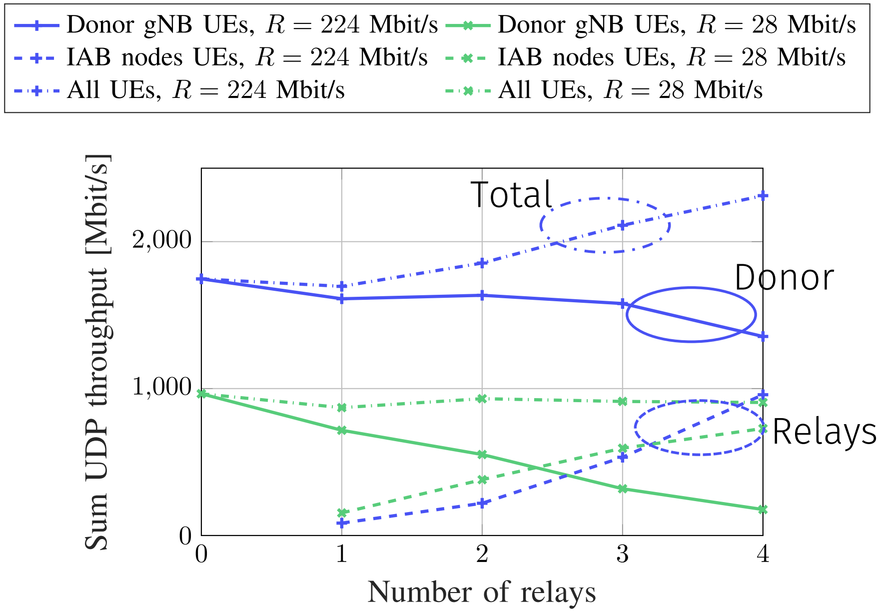


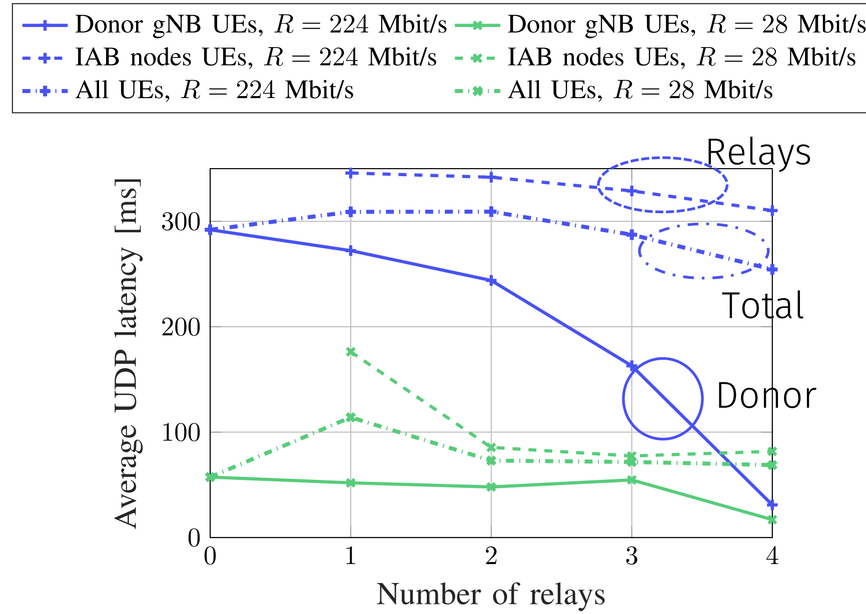
Parameter	Value
mmWave carrier frequency	28 GHz
mmWave bandwidth	1 GHz
3GPP Channel Scenario	Urban Micro
mmWave max PHY rate	3.2 Gbit/s
MAC scheduler	Round Robin
Subframe duration	1 ms
Donor gNB to remote server latency	11 ms
RLC buffer size B_{RLC} for UEs	10 MB
RLC buffer size B_{RLC} for IAB nodes	40 MB
RLC AM reordering timer	2 ms
UDP rate R	$\{28, 224\}$ Mbit/s
UDP packet size	1400 byte
Number of independent simulation runs	50

TABLE I: Simulation parameters

- From 0 to 4 IAB nodes
- 40 users randomly placed outdoor
- 3GPP channel model
- UDP traffic at rate $R \in \{28, 224\}$ Mbit/s per UE

End-to-end Performance for IAB





- Main findings:
  - For high source rate, the relays improve the UDP throughput by improving the link quality for **cell-edge users**
  - Offload the wired base station of cell-edge users -> **lower latency** for its UEs

Main takeaways on IAB

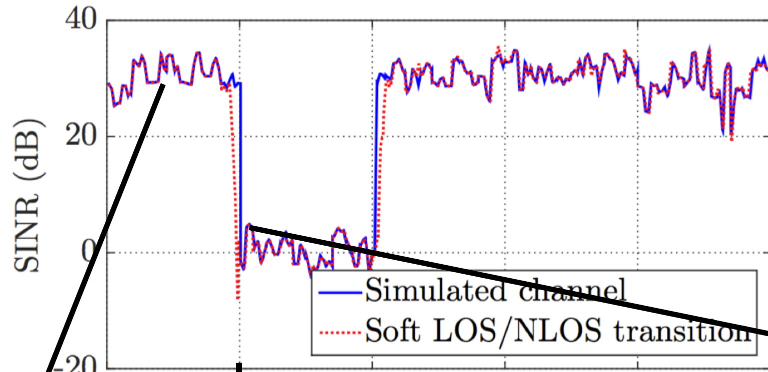
- IAB can provide an alternative to fiber for initial ultra-dense NR deployments
- We provide a tool for **end-to-end performance** evaluation
- Key design parameters for improved end-to-end performance:
  - Scheduler
  - Multi-hop attachment strategies
  - Spatial multiplexing (to be investigated)

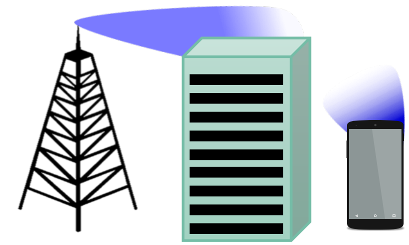
M. Polese, M. Giordani, A. Roy, D. Castor, M. Zorzi, "**Distributed Path Selection Strategies for Integrated Access and Backhaul at mmWaves**", IEEE GLOBECOM, 2018.
M. Polese, M. Giordani, A. Roy, S. Goyal, D. Castor, M. Zorzi, "**End-to-End Simulation of Integrated Access and Backhaul at mmWaves**", IEEE CAMAD, 2018.
https://github.com/signetlabdei/ns3-mmwave-iab

End-to-end performance at mmWaves

TCP issues in mmWave networks

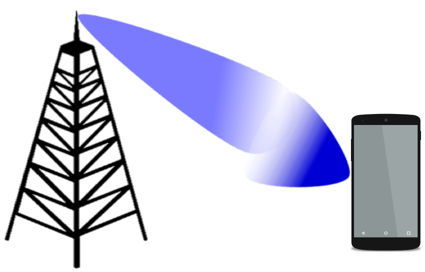
TCP issues on mmWave links

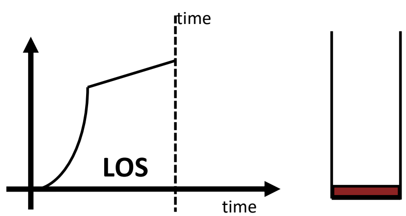




NLOS
After transition from LOS

LOS

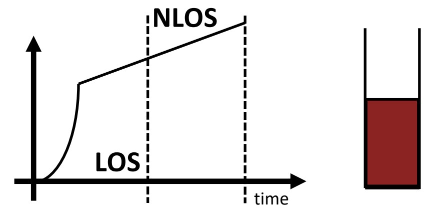




congestion window

RLC buffer occupancy

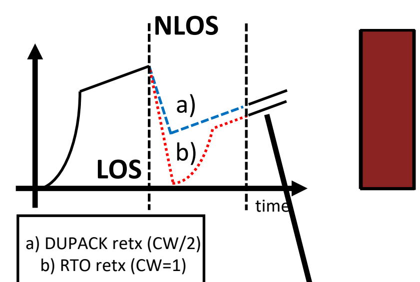
1 **Large buffer**
Bufferbloat
High latency



congestion window

RLC buffer occupancy

2 **Small buffer**
Buffer overflow
Low throughput



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

Possible solutions

To cope with wireless channel fluctuations (LOS-NLOS-LOS), we need:

1. A shorter control loop, to react faster
2. Faster window ramp-up mechanisms, to exploit the available data rate
3. Mobility management or multiple paths (avoid LOS-NLOS)
4. A **cross-layer approach** to better discipline the TCP sending rate

M. Zhang, M. Polese, M. Mezzavilla, J. Zhu, S. Rangan, S. Panwar, M. Zorzi, "**Will TCP work in 5G mmWave Cellular Networks?**", to appear on *IEEE Communication Magazine*, 2018

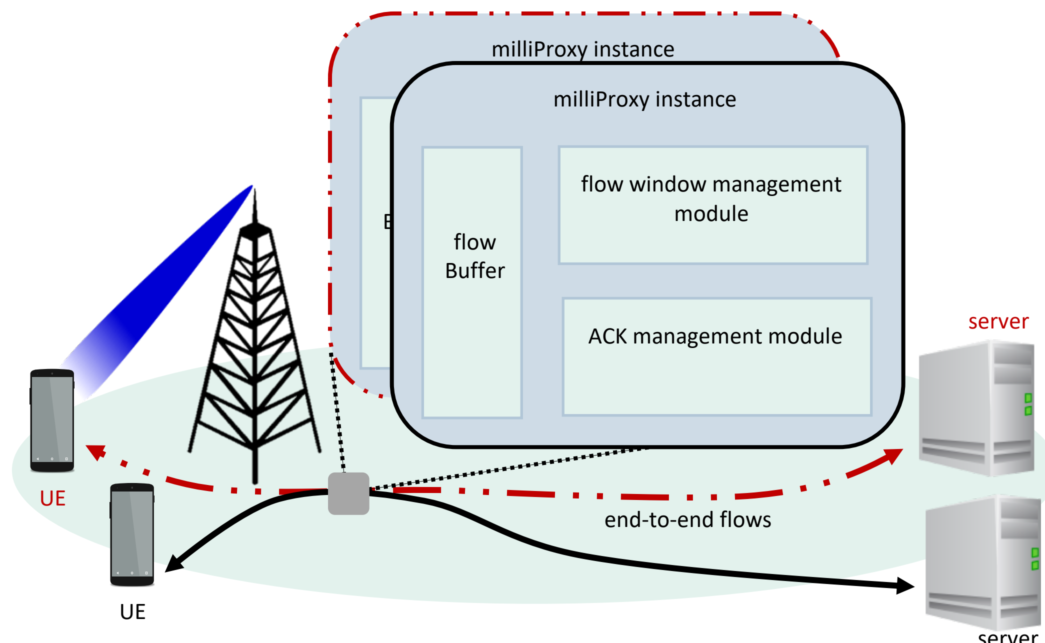
M. Polese, M. Zhang, M. Mezzavilla, J. Zhu, S. Rangan, S. Panwar, M. Zorzi, "**milliProxy: a TCP Proxy Architecture for 5G mmWave Cellular Systems**", *51st Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, 2017, pp. 951-957

M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, "**Mobility Management for TCP on mmWave Networks**", in *Proceedings of the 1st ACM Workshop on Millimeter-Wave Networks and Sensing Systems 2017 (mmNets)*, pp. 11-16, Snowbird, Utah, USA, Oct. 2017

M. Polese, R. Jana and M. Zorzi, "**TCP and MP-TCP in 5G mmWave Networks**," in *IEEE Internet Computing*, vol. 21, no. 5, pp. 12-19, 2017

milliProxy – a TCP proxy for mmWaves

- Goal: 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])



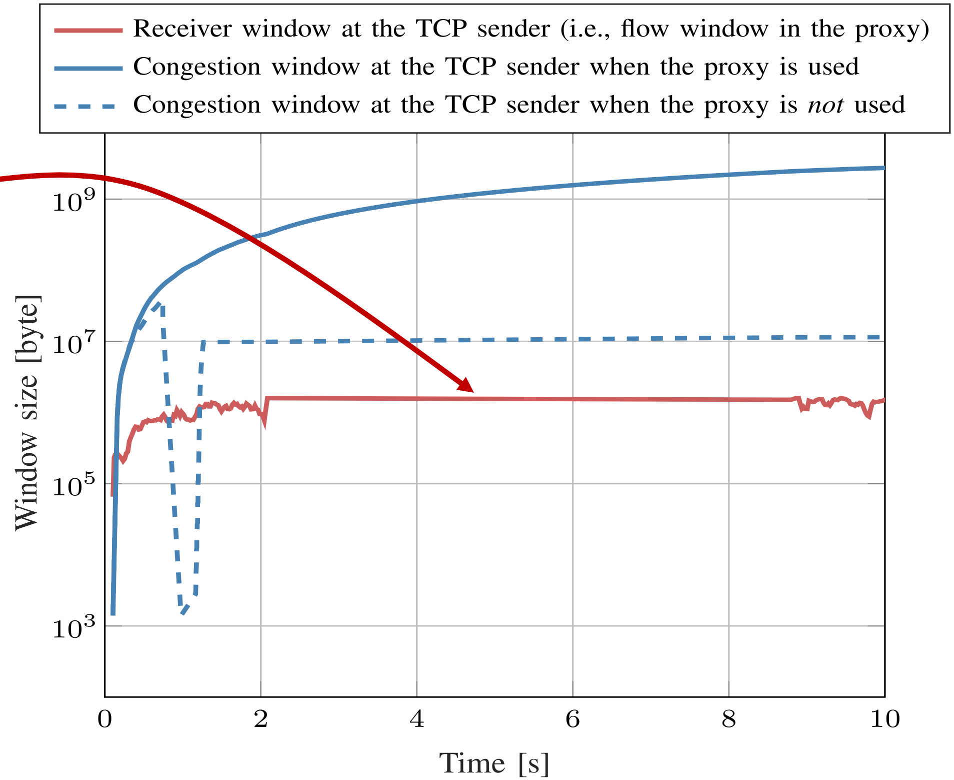
[1] M. Casoni et al., “Implementation and validation of TCP options and congestion control algorithms for ns- 3,” in *Proc. WNS3, 2015*

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)*

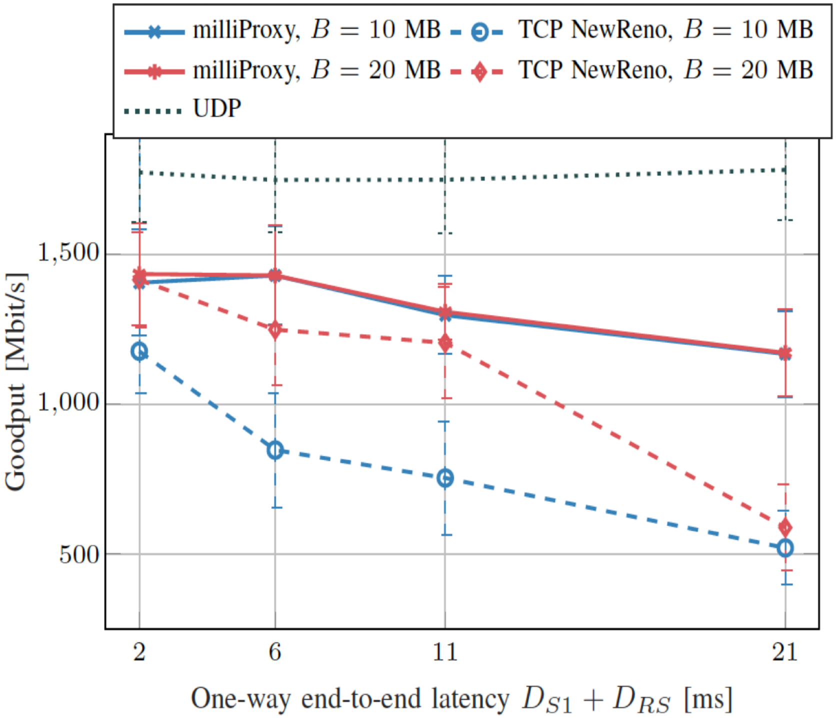
Advertised window (receiver's feedback sent on ACK packets)

Congestion window (computed by the sender)



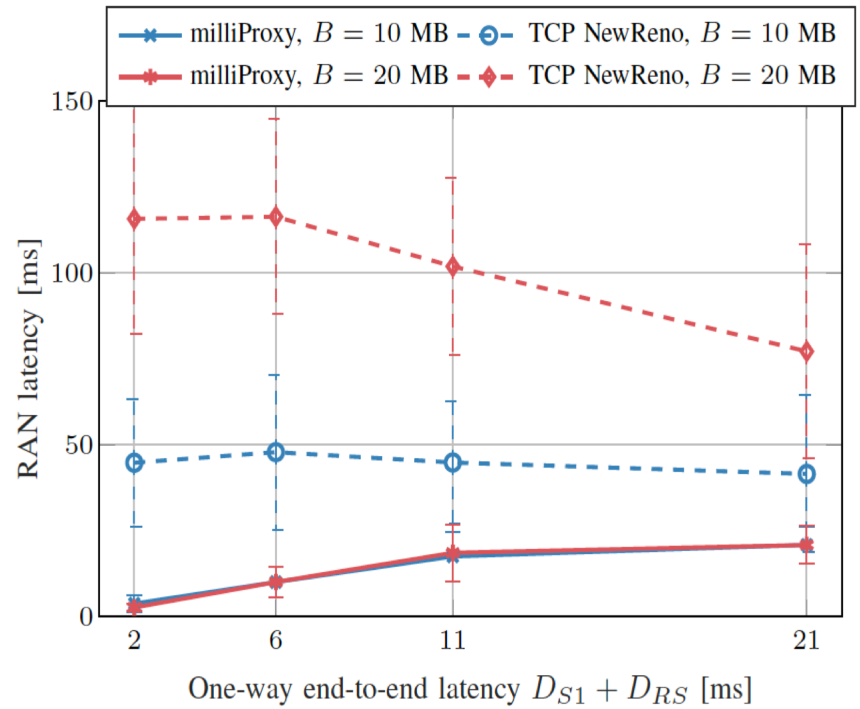
Results: scenario with many LOS/NLOS transitions

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
$B_{RLC} = 10$ MB	1.1941	1.6875	1.7202	2.2430
$B_{RLC} = 20$ MB	1.0135	1.1448	1.0765	1.9901

Throughput gain w milliProxy

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

Latency reduction w milliProxy

Main takeaways end-to-end TCP

- Performance issues with intermittent mmWave links
- Solutions have been proposed and should be integrated in new NR mmWave deployments

M. Zhang, M. Polese, M. Mezzavilla, J. Zhu, S. Rangan, S. Panwar, M. Zorzi, “**Will TCP work in 5G mmWave Cellular Networks?**”, to appear on *IEEE Communication Magazine*, 2018

M. Polese, M. Zhang, M. Mezzavilla, J. Zhu, S. Rangan, S. Panwar, M. Zorzi, “**milliProxy: a TCP Proxy Architecture for 5G mmWave Cellular Systems**”, *51st Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, 2017, pp. 951-957

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Conclusions

- mmWave is the new frontier of wireless
- Research and standardization groups are addressing the main issues
- But the research is still active:
  - New applications of mmWave (vehicular)
  - End-to-end performance
  - Circuit design
  - Testbeds and deployments
  - Fundamental trade-offs

Resources

- ns-3 mmWave module can be downloaded from Github
  - www.github.com/nyuwireless-unipd/ns3-mmwave
  - IAB extension https://github.com/signetlabdei/ns3-mmwave-iab
  - Tutorial paper on the module https://ieeexplore.ieee.org/document/8344116/
- UNIPD mmWave website
  - http://mmwave.dei.unipd.it
  - All the relevant publications with links to arXiv/IEEExplore/ACM DL

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IEEE Future Networks Webinar

mmWaves in 5G NR cellular networks: a system level perspective

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