mmWave for PSC

# mmWave for Future Public Safety Communications


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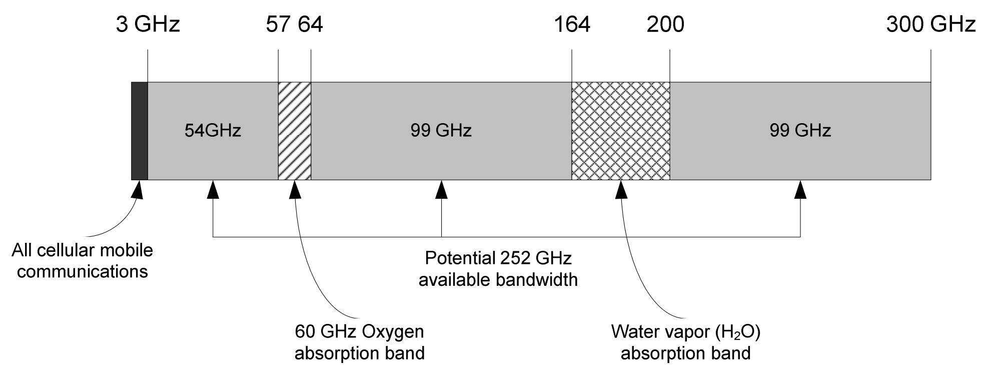
# Outline

- Introduction on mmWaves
- PSC requirements and challenges above 6 GHz
- End-to-end mmWave simulations
- Algorithms and architectures for low-latency and reliable mmWave operations
- Conclusions

# 3GPP NR: mmWaves in cellular networks

3GPP NR Rel. 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**

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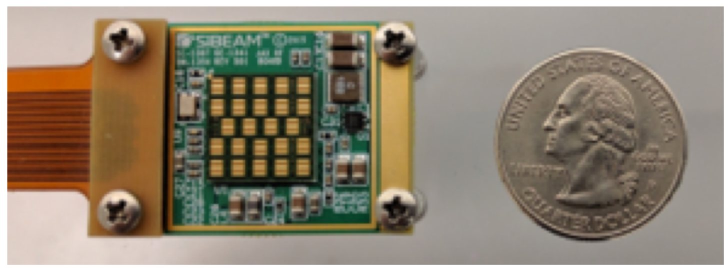
# mmWave limitations – propagation loss

Need to use directional transmission




Impact on PHY and MAC layer procedures

*Challenges*:

- Maintain alignment in dynamic scenarios [4]
- Autonomous network discovery & reconfiguration [5]

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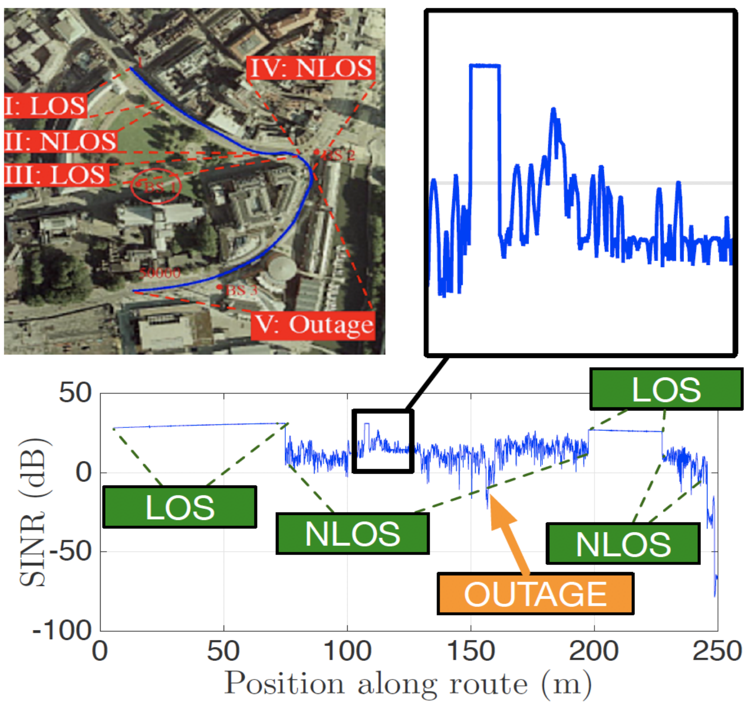
# mmWave limitations – blockage

Fast variations of the channel quality



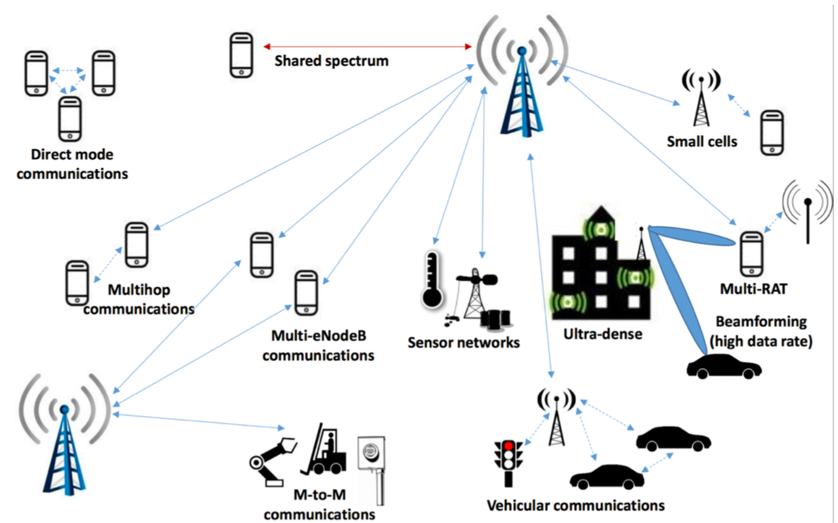

*Challenges*:

- How to get around obstacles
- Avoid losing connectivity
- Transport layer performance [6,7]

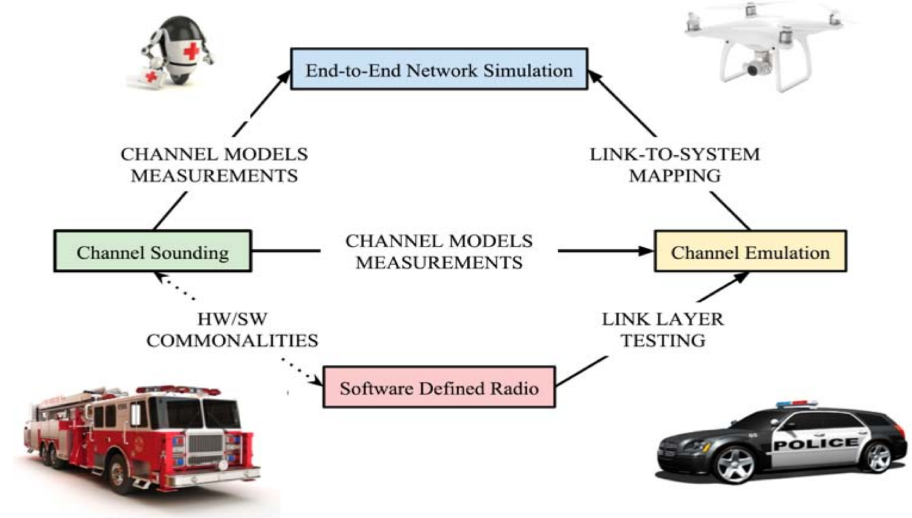
# PSC and mmWave

Increase the connectivity of first responders

- Real-time *high quality* video from incident to command station
- AR/VR content to first responders
- Different kind of sensors (e.g., LIDAR) in different vehicles
- Low latency communications




Tracy McElvaney, "*5G: From a Public Safety Perspective*," 2015




# End-to-end research platform for PSC over mmWave [1,2]

- Measure **dynamic directional channels** in Public Safety (PS) scenarios.
- Prototyping new **ultra-low latency MAC and synchronization** algorithms likely to be used in the PS links.
- Provide the first scalable **real-time emulation** of complex mmWave channels in PS settings.
- Development and integration of PS specific scenarios in **end-to-end mmWave network simulator**.

# PSC requirements

- Support to command and control hierarchy
- Interactive/non interactive
- Data and voice transmissions
- **Resilient and robust networks**
- Low latency

➡ How can mmWaves meet these demands?

SAFECOM, US communications program of the Department of Homeland Security, “Public Safety Statements of Requirements for Communications and Interoperability Vols. I and II.”

# mmWave challenges in PSC use cases

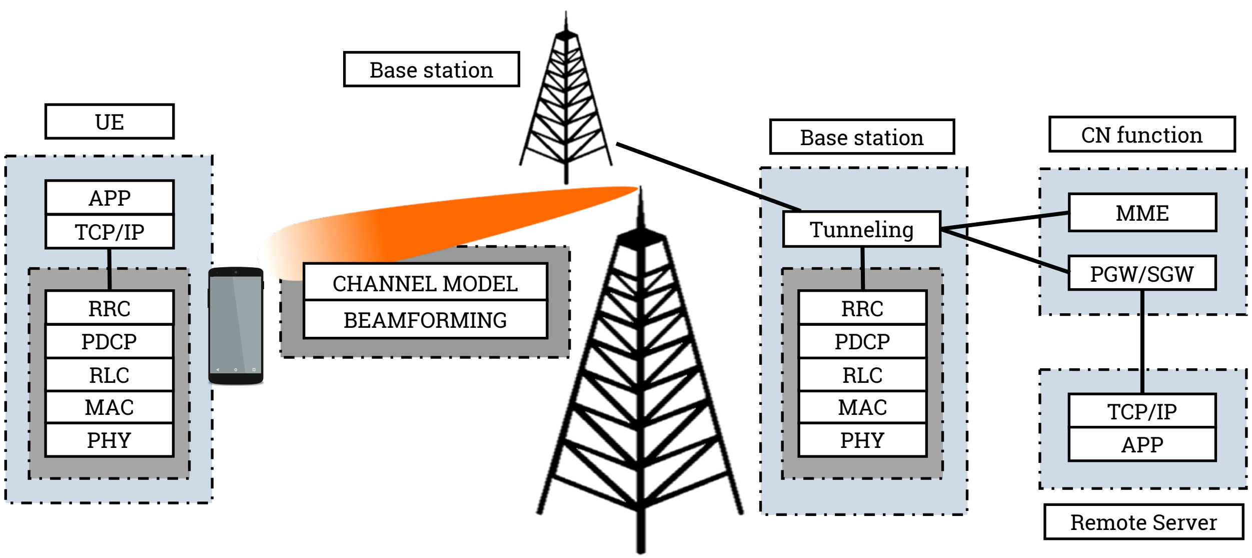
- Aerial/UAV and vehicular communication
  - Lack of measurements at mmWave frequencies
  - Need sophisticated tracking
- Ad-hoc and resilient deployments
  - Frequent link adaptation/handovers
  - High capacity backhaul for ad-hoc deployments
  - Suboptimal end-to-end performance
- Machine-type communications
  - Still unexplored

# Contributions

- Development of end-to-end ns-3 mmWave simulator
- Analysis of requirements and performance in wildfire scenario
- Architectures and algorithms for enhanced performance in PSC scenarios
  - Low latency end-to-end communications
  - Mobility management schemes in challenging scenarios
  - Integrated access and backhaul architectures

# ns-3 mmWave module

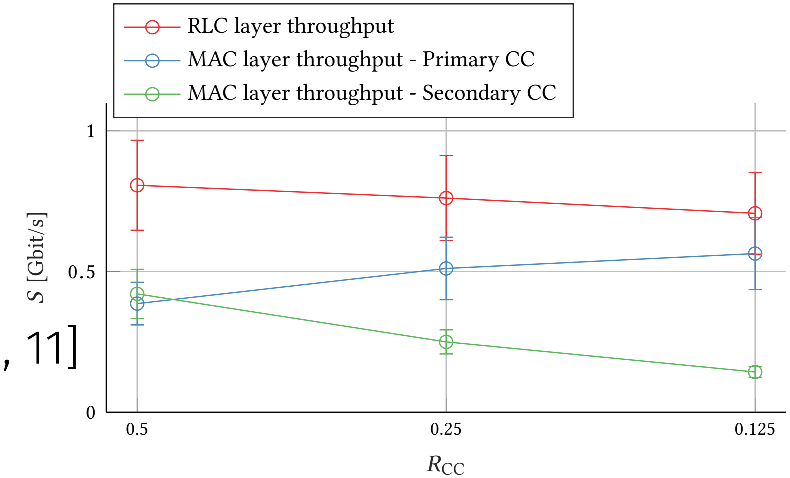
- Built on top of ns-3 – popular open source network simulator – and the LTE LENA module
- Available in the new ns-3 App Store
- **End-to-end** performance analysis [3]
  - Multiple scenarios (cellular, public safety, vehicular)
  - Realistic channel model implementation (3GPP)
  - Custom PHY/MAC
  -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

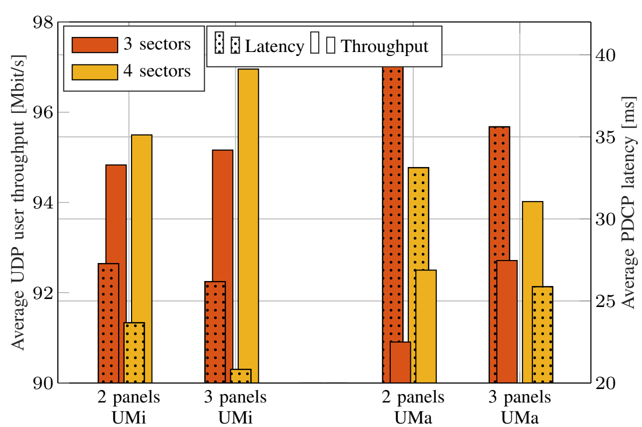


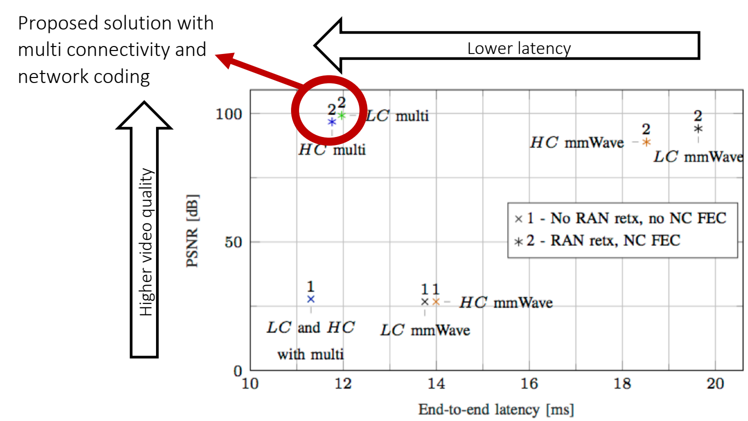

www.github.com/nyuwireless-unipd/ns3-mmwave

# Recent ns-3 mmWave extensions

- Mobility and RAN features [8,9]
  - Implementation of **Carrier Aggregation**
  - Integration with **Dual Connectivity**
- Integrated Access and Backhaul [10, 11]
- Channel modeling [12, 13]
  - Sectorized and multi panel 3GPP model
- Application layer [14]
  - End-to-end performance evaluation with real video traces
  - Realistic app-layer evaluation of QoE metrics

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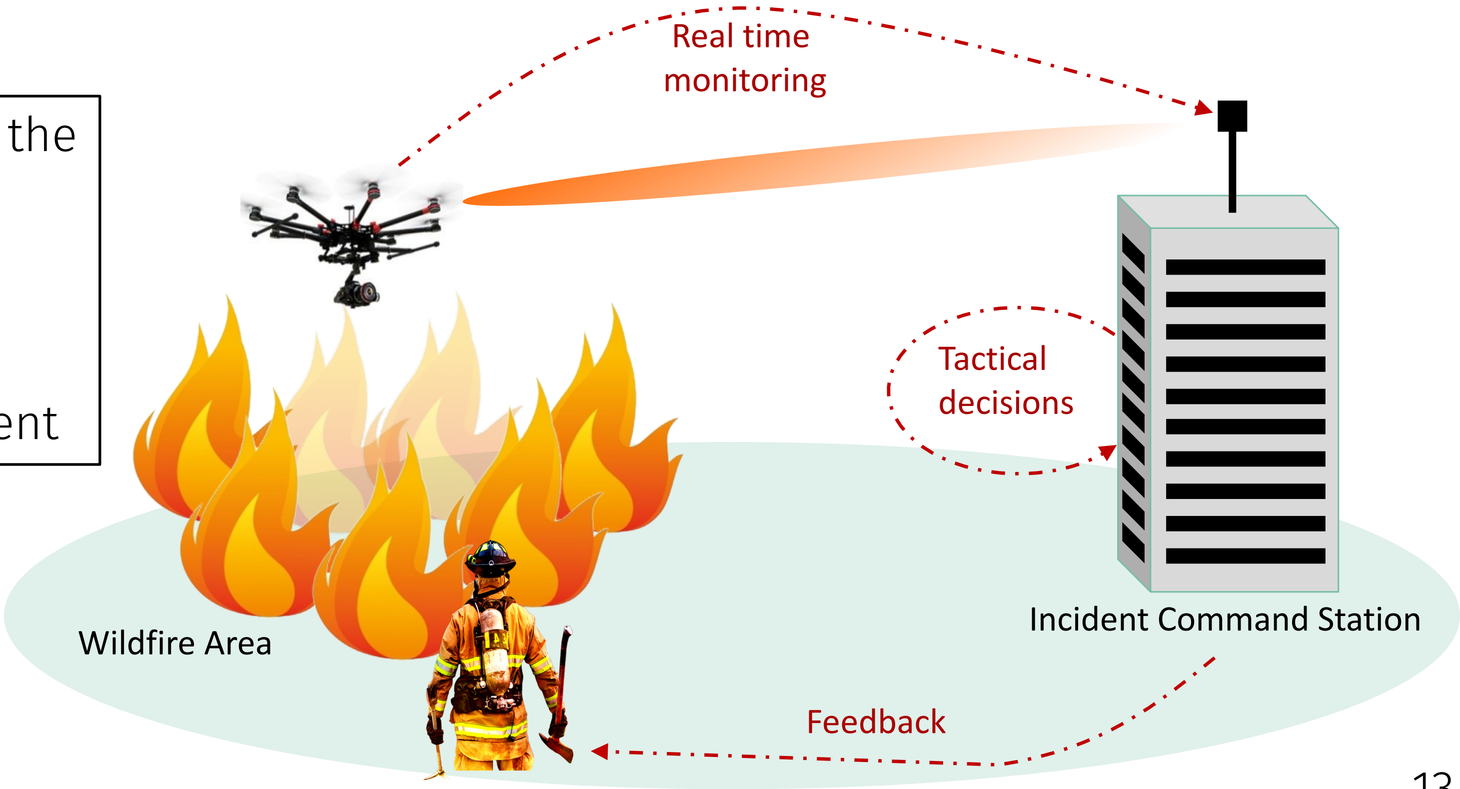
# Example: wildfire scenario [1,2]

- Current operations
  - Physically transfer video on SD card – use low rate links (3G/4G)
- Ideally
  - Use multiple high-resolution lenses for photos and videos / 360 video

Suggested by the Robotic Emergency Deployment team - Austin Fire Department

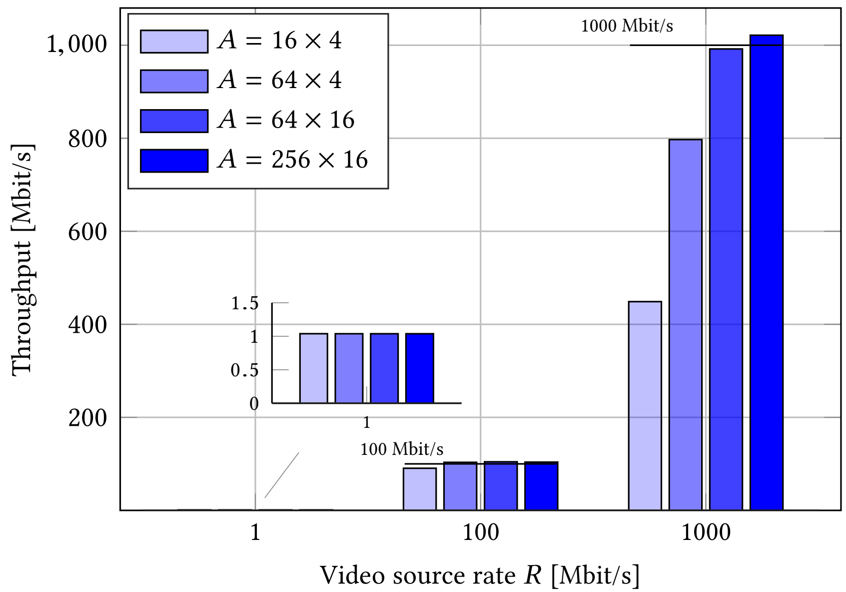


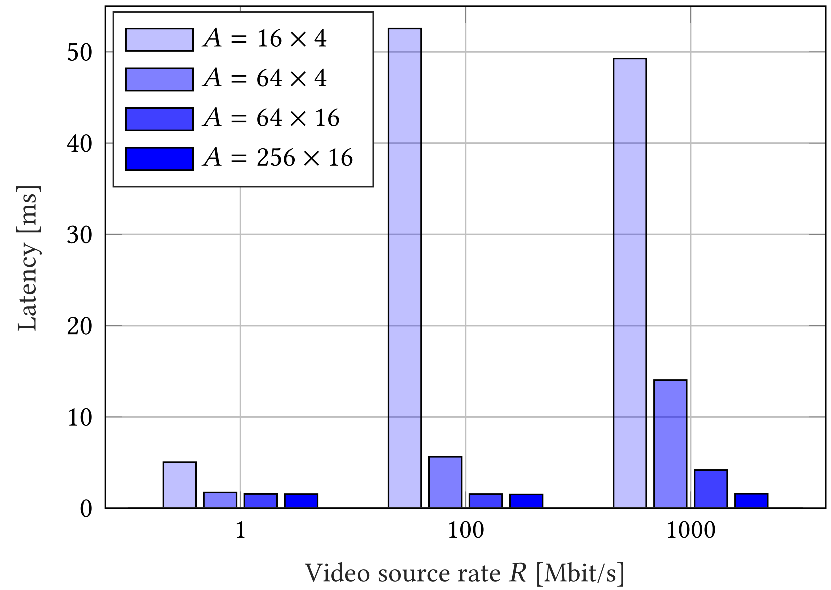
# Performance evaluation

- Gauss-Markov UAV mobility
  - 1.6 to 2.4 km IC – UAV distance
- Channel model with
  - Free space pathloss
  - Single LOS ray
  - Doppler + shadowing
  - BF update every 5 ms

| Parameter | Value |
|---|---|
| mmWave carrier frequency $f_c$ | 28 GHz |
| mmWave bandwidth | 1 GHz |
| mmWave max PHY rate | 3.2 Gbit/s |
| Beamforming vector update period | 5 ms |
| Antenna combinations $A = N_{\text{eNB}} \times N_{\text{UE}}$ | $\{16 \times 4, 64 \times 4,$ $64 \times 16, 256 \times 16\}$ |
| Video source rate $R$ | $\{1, 100, 1000\}$ Mbit/s |
| Transport protocol | UDP |
| Max UAV speed $v$ | 30 m/s |
| Wildfire - IC distance | $\{1.6, 2.4\}$ km |
| UAV height | 30 m |

# UAV throughput and latency

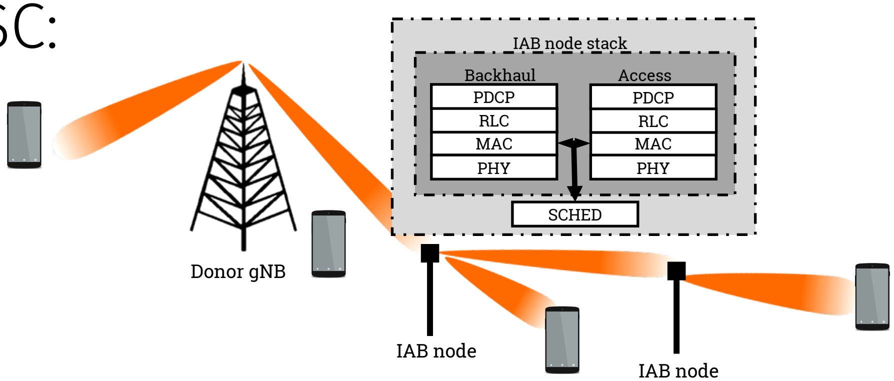



- Test different source rates (using UDP to avoid cross-layer effects)
- Large antenna arrays are fundamental for this scenario:
  - Improve throughput
  - Reduce latency (fewer retransmissions)

# Integrated wireless access and backhaul at mmWaves

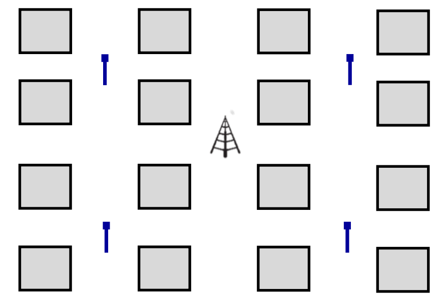
- Goal: provide flexible deployment options for mmWave networks [10, 11]
- 3GPP is considering IAB solutions for relay nodes
- Possible extensions to PSC:
  - Nomadic nodes
  - UAVs
  - Emergency deployments

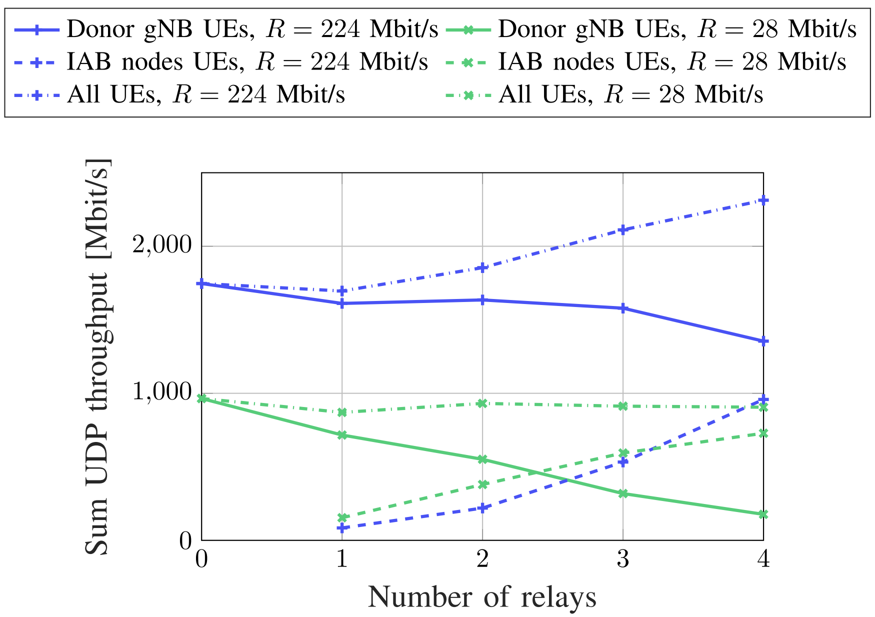


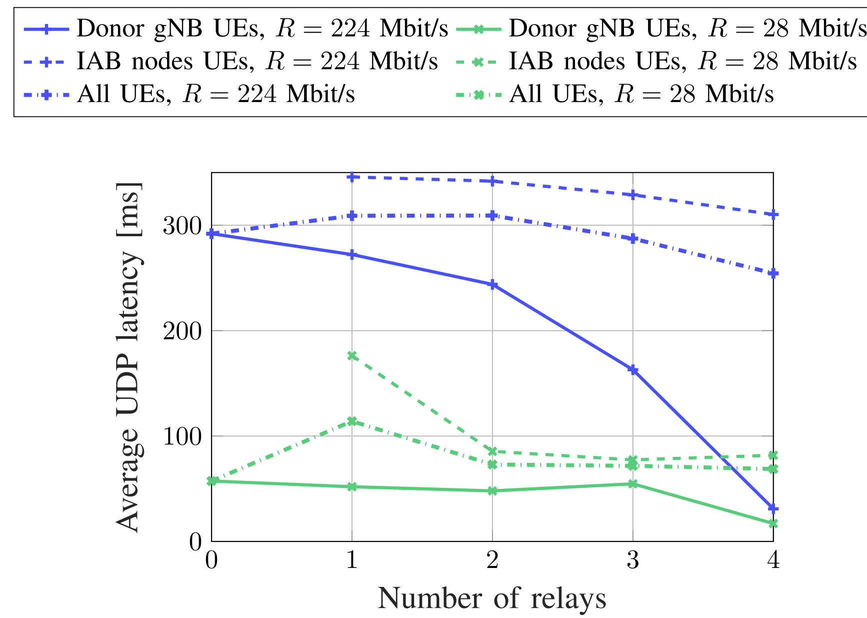

- Interesting research opportunities
  - Optimal path selection in challenging environments
  - Scalability and feasible relaying architectures
  - Scheduling for in-band multiplexing

# End-to-end Performance for IAB

Performance evaluation [10]
- With IAB stack implemented in ns-3 mmWave
- Outdoor scenario with relays



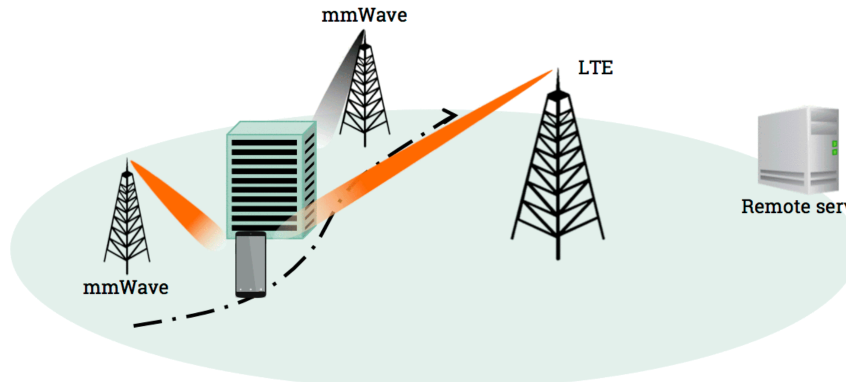


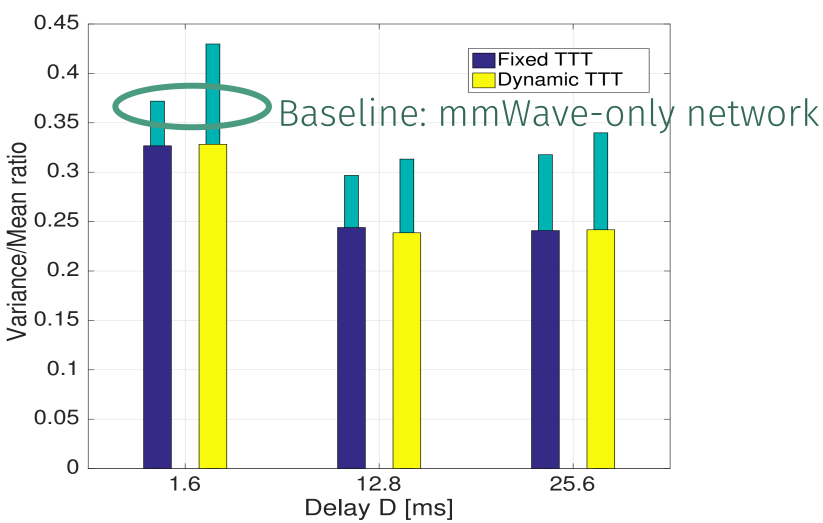

- Main findings:
  - For high source rate, the relays improve the UDP throughput by improving the link quality for **cell-edge users**
  - Offload the wired base station of cell-edge users -> **lower latency** for its UEs

# Multi-connectivity for mmWaves

- Exploit links at different frequencies [15]
  - Reliable sub-6 GHz link for robust control and coverage
  - mmWaves for high capacity hotspots

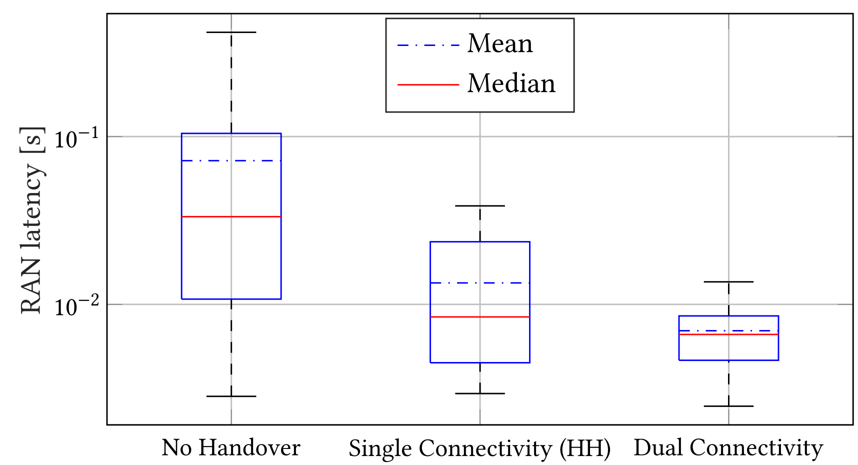



Lower throughput variance




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

Lower latency



# Reliable and low-latency mmWave for PSC

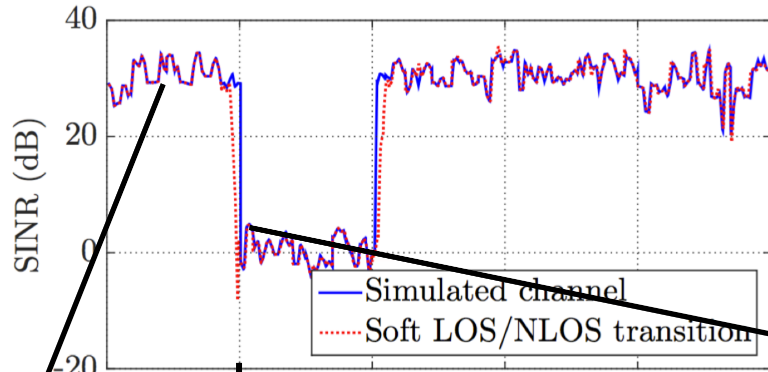
End-to-end perspective: from first responder to IC station

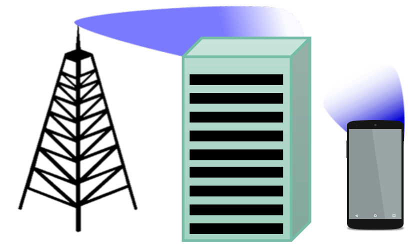
- Besides deployment and networking issues, the end-to-end latency and reliability is also given by the **transport** and **application performance** [6, 7, 14]
- UDP: unreliable – need to rely on application for retx
- **TCP**: generally used to provide congestion control and reliability

➡ Assess TCP issues at mmWaves

➡ Propose solutions for low-latency TCP

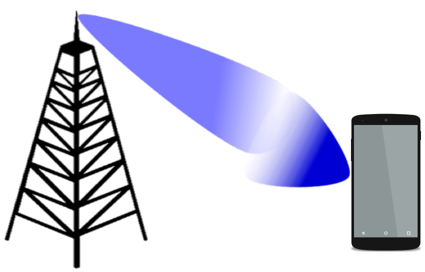
# TCP issues on mmWave links

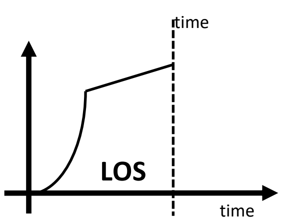


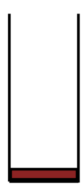



NLOS
After transition from LOS

LOS



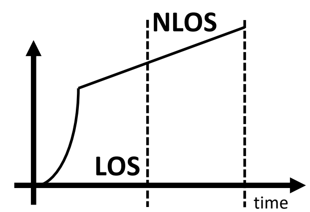


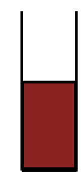



congestion window

RLC buffer occupancy

1 **Large buffer**
Bufferbloat
High latency

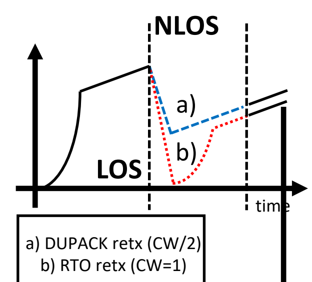


congestion window

RLC buffer occupancy

2 **Small buffer**
Buffer overflow
Low throughput

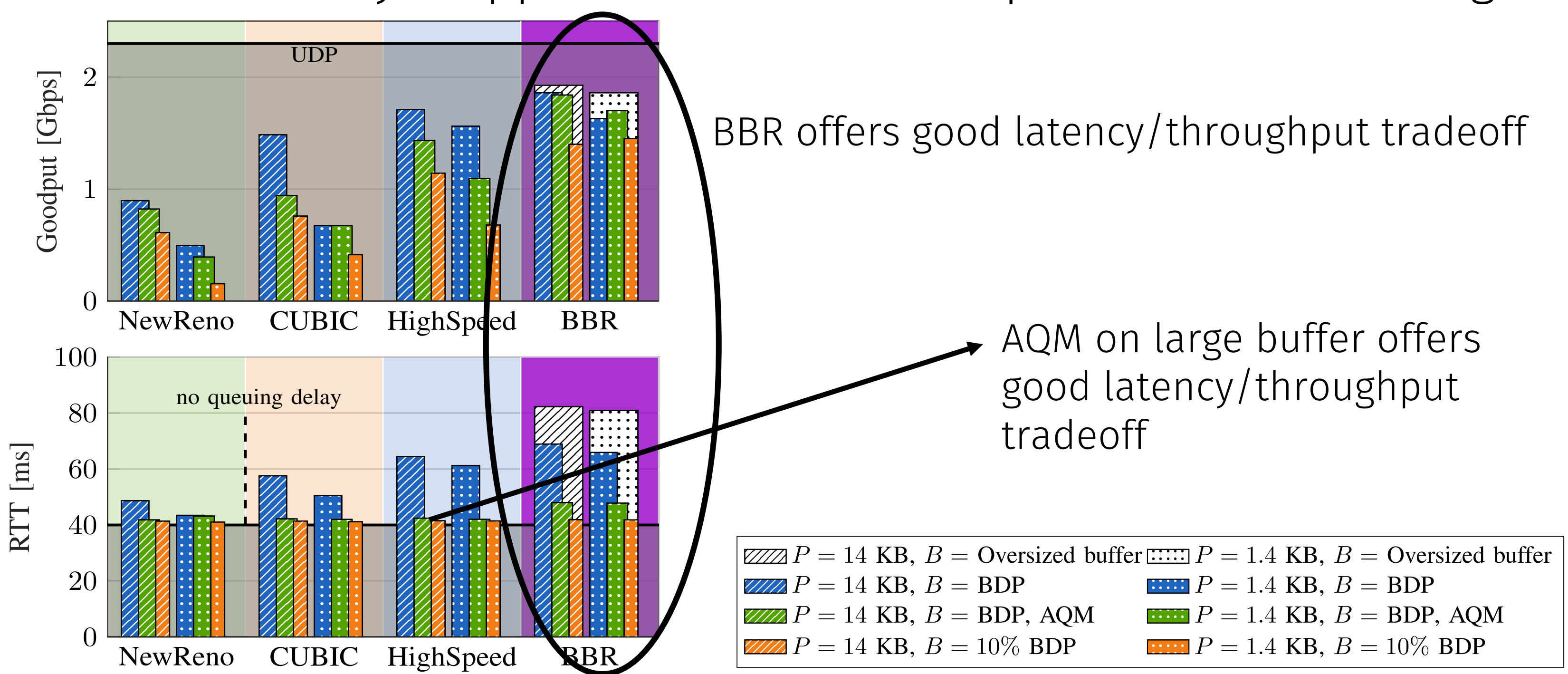



3 **Slow ramp-up** when back in LOS

# Possible solutions

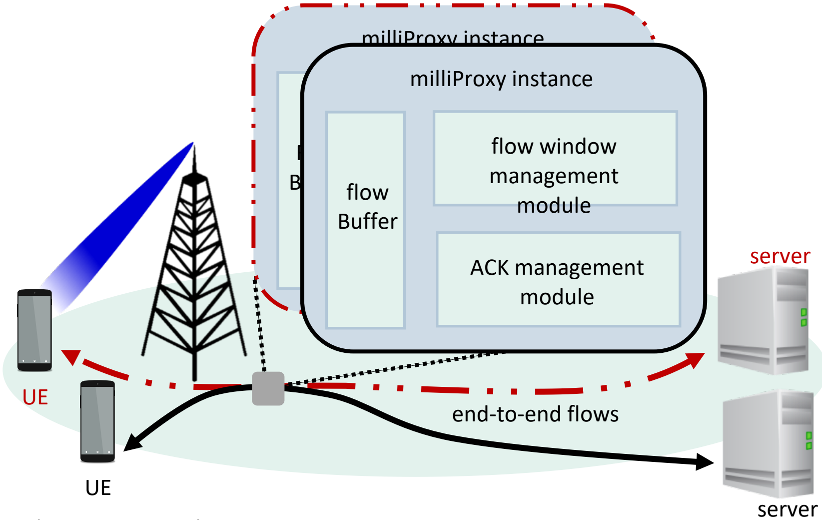
To cope with wireless channel fluctuations (LOS-NLOS-LOS), we need:

1. A shorter control loop, to react faster [16]
2. Faster window ramp-up mechanisms, to exploit the available data rate [16]
3. Mobility management or multiple paths (avoid LOS-NLOS) [17]
4. A cross-layer approach to better discipline the TCP sending rate [18]

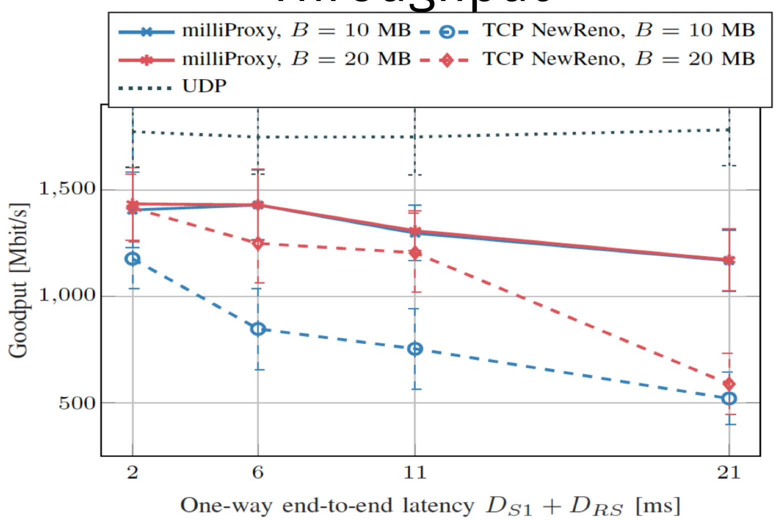


# milliProxy – a TCP proxy for mmWaves

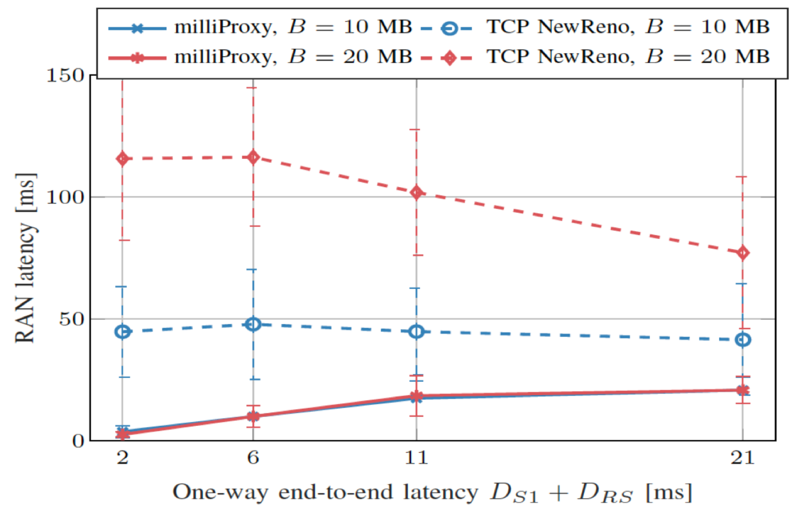
- Goal: reduce buffering latency and increase goodput [18]
- Cross-layer approach
  - Per-UE data rate, RLC buffer occupancy, RTT estimation
- Use the bandwidth-delay product estimation to change the advertised window in ACKs and influence the decisions of the TCP sender




## Throughput




## Latency



# Conclusions

- Next-generation PSCs could benefit from high-capacity and low-latency mmWave links
- We offer a research platform to understand limits and opportunities
- Several challenges are still open, e.g.,
  - Characterization of the mmWave channel in challenging scenarios (e.g., smoke, aerial, etc)
  - Long-range performance
  - Robust ad-hoc mmWave deployments
  - Low complexity and efficient hardware

# Useful resources

- ns-3 mmWave module
  - https://github.com/nyuwireless-unipd/ns3-mmwave
- mmWave networking research @ UNIPD
  - http://mmwave.dei.unipd.it
- NYU Wireless
  - http://wireless.engineering.nyu.edu

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