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

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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

Examples of slot numbers with different subcarrier spacing:
- Slot – 0.25 ms
- Subcarrier spacing 60 kHz
- Slot – 0.125 ms
- Subcarrier spacing 120 kHz
- Symbol – 8.9 μs

Flexible frame structure

Bandwidth $B$ – max 400 MHz per carrier

Frame – 10 ms
Subframe – 1 ms
Physical Resource Block (N subcarriers)

Physical frame structure

5G Core Network options

NSA deployment
- 4G EPC
- PGW/SGW
- MME
- HSS

SA deployment
- 5G Core
- AMF
- SMF
- PCF
- UPF

Network slicing and NFV

Multi RAT access

mmWave directional communications

IEEE Future Networks Webinar

SA deployment

NR

LTE

PGW/SGW
MME
HSS
AMF
SMF
PCF
UPF

Network slicing and NFV

Flexible frame structure

Multi RAT access

mmWave directional communications
3GPP NR: timeline

Goal: deployment by 2019

5G phase 1
- Dec. 2017: Non Stand-alone specifications
- June 2018: Stand-alone specifications
- Release 15

5G phase 2
- March 2020: Release 16

IEEE Future Networks Webinar

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

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

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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**
- **Large antenna arrays** increase the link budget, but the power is focused on **narrow beams**
- High number of handovers
- 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

Results: throughput variance with UDP traffic

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

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

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

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

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

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

*it can be used also in *connected* mode
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 $\rightarrow$ 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?

<table>
<thead>
<tr>
<th>gNB density</th>
<th>CDF</th>
<th>SNR [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 gNB/km²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 gNB/km²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Number of antennas at gNB and UE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{gNB}} = 4, M_{\text{UE}} = 4$</td>
</tr>
<tr>
<td>$\lambda_b = 10 \text{ gNB/km}^2$</td>
</tr>
<tr>
<td>$M_{\text{gNB}} = 64, M_{\text{UE}} = 4$</td>
</tr>
<tr>
<td>$\lambda_b = 30 \text{ gNB/km}^2$</td>
</tr>
</tbody>
</table>
Results: IA reactivity

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

Number of SS blocks per burst
Main takeaways on beam management for NR

- Complete the beam sweep in a **single SS burst**
  (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 \( \lambda_b \) 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*

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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

- 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

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

TABLE I: Simulation parameters
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)

https://github.com/signetlabdei/ns3-mmwave-iab
End-to-end performance at mmWaves

TCP issues in mmWave networks
TCP issues on mmWave links

1. Large buffer
   - Bufferbloat
   - High latency

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


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])

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 $ARW = BW \times RTT$
    - More conservative $ARW = \min([RTT \times PHY_{rate}] - B, 0)$
Results: scenario with many LOS/NLOS transitions

TCP performance on mmWave links

Throughput

![Throughput Graph](image)

Latency

![Latency Graph](image)

<table>
<thead>
<tr>
<th>$D_S + D_R$ [ms]</th>
<th>2</th>
<th>6</th>
<th>11</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{RLC} = 10$ MB</td>
<td>1.1941</td>
<td>1.6875</td>
<td>1.7202</td>
<td>2.2430</td>
</tr>
<tr>
<td>$B_{RLC} = 20$ MB</td>
<td>1.0135</td>
<td>1.1448</td>
<td>1.0765</td>
<td>1.9901</td>
</tr>
</tbody>
</table>

Throughput gain w milliProxy

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


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](https://github.com/nyuwireless-unipd/ns3-mmwave)
  - IAB extension [https://github.com/signetlabdei/ns3-mmwave-iab](https://github.com/signetlabdei/ns3-mmwave-iab)
- UNIPD mmWave website
  - [http://mmwave.dei.unipd.it](http://mmwave.dei.unipd.it)
  - All the relevant publications with links to arXiv/IEEEExplore/ACM DL
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