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Outline

• Introduction and some history
• What is 5G NR?
• Ongoing projects
• Already released, to be released and future developments
• Collaboration with Interdigital and objectives
• NR-U system design
• Coexistence network simulator
• NR-U/WiGig coexistence evaluations
• Team and publications
Introduction

• We started working on an extension of ns-3, targeting **NR modeling in 2017**, in the context of a collaboration with **Interdigital**.

• Objective to build a **5G simulator**:
  • Wideband: FR1 and FR2
  • Coexistence frameworks below and above 7 GHz
    • Unlicensed 2.4GHz, 5GHz, 60 GHz
    • Shared 3.5 and 37 Ghz
• We opted to fork from the status in 2017 of **mmWave** (effort of NYU and Uni Padova) module, instead of LTE
  • It was more advanced in terms of beamforming, TDD, 3GPP channel models
  • Already prepared to work at higher bands
• At the moment the simulator **relies on LTE for layers above MAC** (RLC, PDCP, NAS, and EPC)
• We are building an **NR RRC**. In the public version we still rely on LTE RRC
• Has completely **new PHY and MAC**
What is 5G NR?

- NR is the new Radio Access Technology (RAT) for 5G
  - Inherent support for operation at high carrier frequencies (mmWave spectrum region) and wide bandwidth.
- Operation from **low to very high bands**: 0.4 – 100 Ghz
  - Release 15 till 52.6 GHz
  - Including standalone operation in unlicensed bands
  - Release 17 includes study item for operation till 71 GHz
- **Very wide** bandwidth
  - Up to 100MHz in < 7 GHz
  - Up to 400MHz in > 7 GHz
- Set of **different numerologies** for scaled, optimal operation in different frequency ranges.
- Native **forward compatibility** mechanisms
- New **channel coding**
  - LDPC (Low density parity check) for data channel
  - Polar coding for control channel
- Native support for **Low Latency & Ultra Reliability**
- Native end-to-end support for **Network Slicing**
**Bands**

- **FR1**: 410MHz to 7,125GHz
- **FR3**: Study R16
- **FR2**: 24,25GHz to 52,6GHz
- **FR2x**: 52,6GHz to 71GHz
- **FR4**: 114,25GHz

Unlicensed NR-U in 5GHz and 6GHz in R16
Unlicensed NR-U in 60 GHz in R17
R18?
3GPP work planning and schedule

- First phase of NR specs was published as part of Release 15 in 2018.
- The second phase has been released as part of Release 16 by the end of 2019.
- More extensions, agreed as part of Release 17 in December 2019, and still ongoing.

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
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<td>2021</td>
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**Release 15 (5G Phase 1)**

- 5G eMBB (TDD/FDD, FR1/FR2, NSA/SA, EPC/5GC)
  - 1st drop: NSA+EPC
  - R15: Standalone
  - Last drop: NSA + 5G Core

**Release 16 (5G Phase 1)**

- 5G Expansion (URLLC, mMTC/IOT, l-IOT, V2X, NR-U, IAB, BCAST, Satellites/study)

**Release 17**

- FeMIMO, NR coverage enh, NR @60GHz, Positioning enh,(URLLC enh, sidelink, XR over NR, NR Multicast, IAB enh, DSS enh, NR for satellite

NSA = Non StandAlone = EPC core (“Option 3”) & LTE anchor
SA = StandAlone = 5G Core (“Option 2”) & no LTE anchor
ns-3 NR module: features available in Rel-0

- Released in Feb 2019. Presented in WNS3 2019/2020
- NSA architecture: 5G RAN and 4G EPC
- Flexible and automatic configuration of the NR frame structure through multiple numerologies
- Orthogonal Frequency-Division Multiple Access (OFDMA)-based access with variable TTIs
- Restructuring and redesign of the MAC layer, including new flexible MAC schedulers that simultaneously consider time- and frequency-domain resources (resource blocks and symbols) both for Time-Division Multiple Access (TDMA) and OFDMA-based access schemes with variable TTI.
- UpLink (UL) grant-based access scheme with scheduling request and 3GPP-compliant buffer status reporting
- NR-compliant processing timings
- New Bandwidth Part (BWP) managers and the architecture to support operation through multiple BWPs
- PHY layer abstraction, considering LDPC codes for data channels
Current projects

• Currently the simulator is under development in two main directions

• **S3** in collaboration with LLNL.
  • Extension of the simulator to study coexistence in spectrum sharing scenarios in 1695-1710 MHz and 1755-1780 MHz bands
  • The aim is to evaluate the impact on military assets from LTE/NR cellular technologies.

• **NR V2X** in collaboration with NIST
  • Extension of the simulator with Rel-16 NR V2X
  • Focus on data communications
Latest releases

- **NR-U** for coexistence with WiGig in 60 GHz
- **LTE** remodelling inside 5G-LENA
  - LTE in 5G LENA now calibrated to LTE in 4G LENA
- New multicell configuration helper to configure independently each eNB/gNB in the scenario (technology, band, numerology, BWP....)
- New **REM** helper: some examples in the following
5G-LENA LTE-REM at 2GHz

- **Scenario configuration**: UMa

- **Scenario path**: nr/examples/rem-example.cc (not public yet)

- **Devices**: Left 1 gNB and 1 UE (SNR up, SINR down) Right 2 gNBs and 1 UE per gNB

- **RTDs**:
  - gNB1 (0, 0, 1.5)
  - gNB2 (20, -30, 1.5)
  - gNBs antenna: 8x8
  - **Iso**
  - Frequency = 2e9
  - Bandwidth = 20e6
  - gNB txPower: 1 dBm
  - Numerologies: gNB1 = 0

- **RRD**:
  - Ue1 with position (10, 10, 1.5)
  - Ue2 with position (25, -15, 1.5)
  - UE antenna: 1x1
  - **Iso**
  - Noise figure: 5 dBi
5G-LENA NR-REM at 28GHz: 1 beam example

- **Scenario configuration:** UMa
- **Scenario path:** nr/examples/rem-example.cc (not public yet)
- **Devices:** Left 1 gNB and 1 UE (SNR up, SINR down) Right 2 gNBs and 1 UE per gNB
- **RTDs:**
  - gNB1 (0, 0, 1.5)
  - gNB2 (20, -30, 1.5)
  - gNBs antenna: 8x8
- **3GPP**
  - Frequency = 28e9
  - Bandwidth = 100e6
  - gNB txPower: 1 dBm
  - Numerologies: gNB1 = 4
- **RRD:**
  - Ue1 with position (10, 10, 1.5)
  - Ue2 with position (25, -15, 1.5)
  - UE antenna: 1x1
  - Iso
  - Noise figure: 5 dBi
Scenario configuration: UMa

Scenario path: nr/examples/rem-example.cc (not public yet)

Devices: Left 1 gNB and 1 UE (SNR up, SINR down)
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- gNB1 (0, 0, 1.5)
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  - Numerologies: gNB1 = 4

RRD:
- Ue1 with position (10, 10, 1.5)
- Ue2 with position (25, -15, 1.5)
- UE antenna: 1x1
- Iso
- Noise figure: 5 dBi
5G-LENA NR-REM at 28GHz with Buildings

- **Scenario configuration:** UMa

- **Scenario path:** nr/examples/rem-example.cc (not public yet)

- **Devices:** Left 1 gNB and 1 UE  
  (SNR up, SINR down)  
  Right 2 gNBs and 1 UE per gNB

- **RTDs:**
  - gNB1 (0, 0, 1.5)
  - gNB2 (20, -30, 1.5)
  - gNBs antenna: 8x8
  - 3GPP
    - Frequency = 28e9
    - Bandwidth = 100e6
    - gNB txPower: 1 dBm
    - Numerologies: gNB1 = 4

- **RRD:**
  - Ue1 with position (10, 10, 1.5)
  - Ue2 with position (25, -15, 1.5)
  - UE antenna: 1x1
  - Iso
  - Noise figure: 5 dBi

- 1 building in 1 gNB case / 2 buildings in 2 gNBs case
# LTE in 4G LENA vs 5G LENA

<table>
<thead>
<tr>
<th></th>
<th>LTE in 4G LENA</th>
<th>LTE in 5G LENA</th>
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<tbody>
<tr>
<td>Duplexing modes</td>
<td>FDD</td>
<td>TDD and FDD</td>
</tr>
<tr>
<td>SINR computation</td>
<td>Based on PDCCH or mixed</td>
<td>Based on PDSCH</td>
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<tr>
<td>CQI feedback</td>
<td>Wideband and inband CQI</td>
<td>wideband</td>
</tr>
<tr>
<td>PHY DL error control models</td>
<td>available</td>
<td>not available yet (ongoing)</td>
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<tr>
<td>Basic PF/RR schedulers</td>
<td>Do not consider data available in RLC queue</td>
<td>Do consider data available in RLC queue</td>
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<tr>
<td>AMC</td>
<td>“Piro” model or “Vienna” model</td>
<td>“Piro” model or “Vienna” model</td>
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<tr>
<td>PHY data error models</td>
<td>TS36.213</td>
<td>TS36.213</td>
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<tr>
<td>Processing times</td>
<td>L1L2CtrlLatency UL_PUSCH_TTIS_DELAY</td>
<td>N1 and N2 to be configured appropriately</td>
</tr>
<tr>
<td>HARQ</td>
<td>IR, 8 processes</td>
<td>IR, CC, to configure 8 processes</td>
</tr>
<tr>
<td>RRC</td>
<td>Ideal/real, HO management, RLF</td>
<td>Only ideal, RLF unavailable, no mobility</td>
</tr>
<tr>
<td>SR and MAC PDU</td>
<td>simplified</td>
<td>Standard compliant</td>
</tr>
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</table>
Soon to be released

- Realistic Beamforming
- SRS modelling and Control error model
- RRC enhancements
- Improved X2/Xn interface
- ICIC
- UL power control
- Mobility and HO management
**NR-V2X**

- Long term collaboration with NIST, first in LTE D2D and now in NR V2X
- Based on grant from fall 2019 to spring 2021
- Objectives:
  - Extend 5G-LENA simulator with NR V2X capabilities
  - NR V2X evaluations on high fidelity, full stack network simulator
- Output:
  - Open source network simulator for NR V2X evaluations
  - First release planned for 2Q 2021
**NR-V2X**

- V2X extensions for NR in development, based on standardization in 3GPP Release 16
- Available features
  - Broadcast, groupcast, unicast.
  - FR1 (numerologies 0, 1, 2), FR2 (numerologies 2, 3).
  - Out-of-coverage scenario (in-coverage scenario).
  - Mode 2 resource allocation (UE selected), Mode 1 (gNB scheduled).
  - Omnidirectional tx/rx for SL.
  - Sensing based and random based semi-persistent scheduler (basic service messages), per packet scheduling
  - Time multiplexing of PSCCH and PSSCH, frequency multiplexing
  - Blind retransmissions, no feedback. HARQ, feedback channel (PSFCH)
Coexistence @60 GHz

• Collaboration with ID started due to our previous experience with studies on coexistence at 5GHz, which we carried out with WFA and Spidercloud
• More than 2 years of collaboration between spring 2017 and fall 2019.
• Objectives
  • Design operation of NR-U at 60 GHz, considering coexistence with WiGig
  • Multi-RAT NR-WiGig evaluations on high fidelity, full stack network simulator
• Outputs
  • Open source network simulator for NR/NR-U/WiGig evaluations
  • Publications, patents, knowledge generation

NR-U system design

- We started analyzing the spectrum allocation and regulatory requirements
  - At the time we identified 60 GHz having similar requirement to 5 GHz band, wrt LBT (Listen Before Talk).
  - **MCOT** (Maximum Channel Occupancy Time) is 9 ms at 60 GHz, while at 5GHz depends on the channel access priority class.
  - Max **EIRP** (Equivalent Isotropically Radiated Power) is limited to 40 dB and **PSD** (Power Spectral Density) to 23 dBm/MHz
  - **OCB** (Occupied Channel Bandwidth) defined as the bandwidth with 99% of signal power, in 60% should be between 80 and 100% of Nominal Channel Bandwidth (NCB)
  - Frequency Reuse (**FR**)
  - Dynamic Frequency Selection (**DFS**)
NR-U system design

• The design focused on:

  • **Channel access procedure**: LBT procedure may not be as useful as it was in omnidirectional scenarios.
  • **COT structure**: it can be optimized for unlicensed-based access in TDD systems to meet the MCOT limit while reducing the access delay and enabling fast DL-UL responses when needed.
  • **Initial access procedure**: need to be rethought to meet regulation, and to mitigate LBT impact on latency.
  • **HARQ procedure**: similar to above.
  • **MAC scheduling**: Impact of processing delays on the scheduler and relations with channel access procedure.

• We will only focus on channel access due to time limits
Channel Access procedures

- We studied:

  - **LBT for beam-based transmissions**: LBT suffers from hidden and exposed node problems, which are emphasized by the directionality of transmission and reception.
  - **Receiver-assisted LBT for beam-based transmissions**: The receivers are in a better position to assess potential interference.
  - **Intra-RAT tight frequency reuse**: LBT operation based solely on ED is uncoordinated inherently, it may result in unnecessary blocking among different nodes of the same RAT.
  - **Congestion Window Size (CWS) adjustment for beam-based transmissions**: NACKs do not necessarily reflect collisions and introduce delays into the CWS update procedure. Under beam-based transmission, collisions may be due to interference coming from other directions.
**LBT for Beam-based Transmissions**

- **Omnidirectional LBT:** senses omnidirectionally. Under directional transmissions, it overprotects because a transmission is prevented even if a signal is detected from a direction that may not create harmful interference. (exposed node)
- **Directional LBT:** senses in a directional manner within the transmit beam towards the intended receiver. Ongoing nearby transmissions might not be detected, and directional hidden node problems may cause interference.
- **Paired LBT:** performs directional sensing in paired directions, i.e., in the transmitting direction and its opposite direction(s).
- **LBT switch:** switches the type of carrier sense between omnidirectional and directional, based on the beamwidth configuration and density of neighboring nodes, HARQ feedbacks, UE measurements, etc.

- S. Lagen, L. Giupponi, B. Bojovic, A. Demir, and M. Beluri, “Paired listen before talk for multi-rat coexistence in unlicensed mmwave bands,” in 2018 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 1–6, May 2018.
LBT for Beam-based Transmissions

(a) OmniLBT  
(b) DirLBT  
(c) PairLBT  
(d) LBTswitch
Receiver-Assisted LBT for Beam-based Transmissions

• Similar to WiFi RTS/CTS, LBR (Listen Before Receive)
• The gNB triggers the UE to perform carrier sense, and only if the UE responds, the gNB can initiate the transmission.

S. Lagen and L. Giupponi, “Listen before receive for coexistence in unlicensed mmwave bands,” in 2018 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6, April 2018. BEST CONFERENCE PAPER AWARD
Initial evaluation: Scenario

- NR-WiGig coexistence scenario, composed of 20 NR connections (gNB-UE) and 20 WiGig connections (AP-STA). There is a total of K=40 connections, but we also vary K through simulations.
- Dense indoor network deployment, for which the pair connections are randomly deployed in a 25x25m² area.
- Downlink-only evaluation:
  - Carrier freq: fc=60 GHz, bandwidth: BW=1 GHz, IEEE 802.11ad pathloss model
  - Transmit power: Ptx=10 dBm, noise PSD: -174 dBm/Hz
  - Normalized energy detection threshold: -74 dBm
- Channel access procedures:
  - APs use omniLBT
  - gNBs can adopt different procedures: no-LBT, omniLBT, dirLBT, pairLBT, or LBTswitch
  - We also combine these strategies with LBR
- We do not emulate backoff processes, and simply consider how many connections can get access to the shared channel and the obtained QoS, measured through the “rate”:
  - rate=BW×log₂(1+SINR), based on the SINR, and assuming ideal link adaptation
Scenario

- Directional transmission at gNBs/APs:
  - Transmit beams: $30^\circ$ beamwidth and 10 dB mainlobe gain.

- Two reception configurations are used at UEs/STAs:
  - Omnidirectional reception
  - Quasi-omnidirectional reception → the receive beam gain at UEs/STAs is fixed to 7 dB with a receive mainlobe beamwidth of $90^\circ$.

- KPIs:
  - Sum-rate: “capacity”
  - Mean-rate during channel access: “QoS” per device, measured globally and separately for NR and WiGig pairs.
  - Number of NR and WiGig pairs that get access to the channel: “channel access success rate”, fairness, measured separately for NR and WiGig pairs.
Results: omnidirectional reception at UEs/STAs
Results: Quasi-omni reception at UEs/STAs
ns-3 NR-U simulator architecture

- Based on Rel. 15 NR, with LBT addition
- LBT is performed after MAC is executed, when data are ready at PHY to be sent
- Multiple CAM are supported: ON, OnOff, LBT Cat 1, 2, 3, 4 at gNB, Cat 1, 2 at UE
- Focus on omnidirectional LBT
# Network simulations - models

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<tr>
<th>Frame structure</th>
<th>NR-U</th>
<th>WiGig</th>
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<tr>
<td>TDD NR-compliant frame structure with slots and OFDM symbols of numerology-dependent length [1], [31]: - frame: 10 ms, subframe: 1 ms - each subframe has 2^m slots (associated to 15 × 2^m kHz SCS) - numerologies μ=0,1,2,3,4 are supported - each slot is composed of 14 OFDM symbols - 1st symbol: DL control, 14th symbol: UL control, 2nd to 13th symbols flexibly allocated to DL and UL data</td>
<td>TDD WiGig-compliant [23], [32]: - Beacon interval of 102.4 ms, including BTI, A-BFT, AIT and DTI phases - Beacon Transmission Interval (BTI) of 1.2 ms - Association Beamforming Training (A-BFT), composed of 8 slots and 16 frames per slot - Announcement Transmission Interval (ATI): currently deactivated - Data Transmission Interval (DTI) of 98 ms: currently based on contention, but also supports contention-free and polling [32]</td>
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| Antenna models | 3GPP-compliant [38]: - Antenna arrays: 1 uniform planar array per AP/STA, M × N antenna elements, no polarization - Antenna elements: isotropic radiation and directional radiation are supported | 3GPP-compliant [38]: - Antenna arrays: 1 uniform planar array per AP/STA, M × N antenna elements, no polarization - Antenna elements: isotropic radiation and directional radiation are supported |

| Beamforming methods | Two methods are available: beam-search method and singular value decomposition (SVD)-based method [39]. Both are ideal in the sense that no resources are used for beam training. | Beam-search method, implemented with a real training through BTI phase (to train AP beam) and A-BFT phase (to train STA beam) [32] |

| DL/UL data/control channels | - DL/UL data: transmitted and received directionally - DL control: sent quasi-omnidirectionally from gNBs and received directionally at UEs - UL control: sent directionally from UEs and received quasi-omnidirectionally at gNBs | - DL/UL data: transmitted and received directionally - DL control: sent directionally from APs and received quasi-omnidirectionally at STAs - UL control: sent directionally from STAs and received quasi-omnidirectionally at APs |

| Error models | - NR PHY abstraction for DL and UL data channels [40] including support for MCS Table 1 and MCS Table 2 [41], LDPC coding and block segmentation [42] - No error model for DL/UL control | - 60 GHz sensitivity error model for DL/UL data and control frames |

| Modulation | OFDM | Both single carrier and OFDM |
| Channel Coding | LDPC | LDPC |
| MCS | QPSK, 16-QAM, 64-QAM, 256-QAM | BPSK, QPSK, 16-QAM, 64-QAM |
| HARQ | - NR PHY abstraction for HARQ including support for HARQ-IR and HARQ-CC | Not supported by the standard |
| Retransmissions | Up to 4 with retransmission combining | Up to 7 without retransmission combining |
| MAC | Scheduled-based access: - In DL, OFDMA and TDMA accesses are supported with round-robin, proportional-fair and maximum rate rules for the MAC scheduler - In UL, TDMA access is supported | Contention-based access for DL and UL |
| Link adaptation | Two adaptive modulation and coding schemes are supported: Error model and Shannon bound | Link adaptation based on the Shannon bound |
| Operational modes | Standalone NR-U and Carrier Aggregation NR-U | Standalone WiGig |
| Channel access | LBT, OnOff, AlwaysOn | CSMA/CA |
Scenario

TR38.889 with reduced distances to adapt to mmWave ranges
Impact of NR-U channel access

- NR-U channel occupancy is higher than WiGig’s, due to symbol level granularity.
  - For SCS 120 KHz, symbol is 8.92 us, while WiGig frame on average 3.5 us.
  - Effect decreases with LBT and OnOff, since packets are accumulated in queue during OFF periods, and transmission opportunity is better used.
  - The more conservative the LBT, the lower the occupancy.
- Higher occupancy makes that WiGig stats when coexisting with NR-U have more variability, also in terms of latency.
Impact of NR-U channel access

- WiGig vs WiGig: nodes see each other at -96 dBm (preamble detection).
- WiGig vs NR-U: nodes see each other at ED threshold, configured to -79 dBm.
  - More nodes (both WiGig and NR-U) gain the channel, which reduces the per node throughput, and increases the system throughput.
- Cat4/Cat2 offers the best system throughput performance, comparable to duty cycling.
- Always On access does not coexist properly, a coexistence mechanism is needed.
Impact of numerology

- SCS: 60, 120 KHz (we are further studying 240 KHz)
- NR-U latency goes down as expected
- Occupancy is not affected in alwaysON, but with OnOff and LBT we see a slight reduction in occupancy, because packets are aggregated and transmitted in shorter time.
- In AlwaysON case, occupancy is more bursty, this affects dispersion of latency and occupancy of WiGig
Impact of numerology

- For alwaysON, a lower numerology allows aggregation and so an access with less OFF to ON transitions. This results in better per user and system throughput.
- For OnOff and LBT, since they already naturally allow for packet aggregation during OFF periods, the higher numerology slightly improves the throughput, due to reduced transmission times.
Impact of NR-U ED threshold

- Lower NR-U ED threshold reduces access of NR-U nodes, and so the occupancy.
- This results in reduced WiGig’s latency.
Impact of ED threshold

• Lower NR-U ED threshold results in:
  • Improved NR-U per user throughput
  • Improved WiGig’s system throughput
Ns-3 team at CTTC

Lorenza Giupponi
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Sandra Lagen
Katerina Koutlia
Manuel Requena
Publications

Journal papers

Publications

Conference papers


