5G LENA: An E2E Simulator for 5G NR Networks. Models and evaluations in licensed and unlicensed bands.

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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

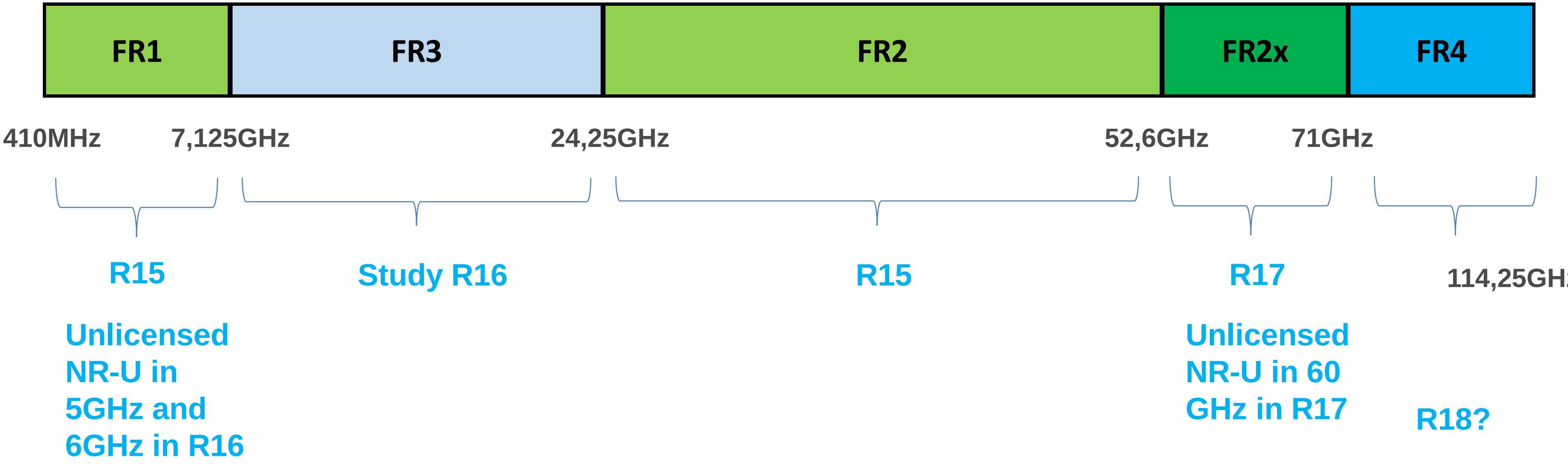
Introduction

- 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
FR3
FR2
FR2x
FR4
410MHz
7,125GHz
24,25GHz
52,6GHz
71GHz
114,25GH
R15
Study R16
R15
R17
Unlicensed NR-U in 5GHz and 6GHz in R16
Unlicensed NR-U in 60 GHz in R17
R18?

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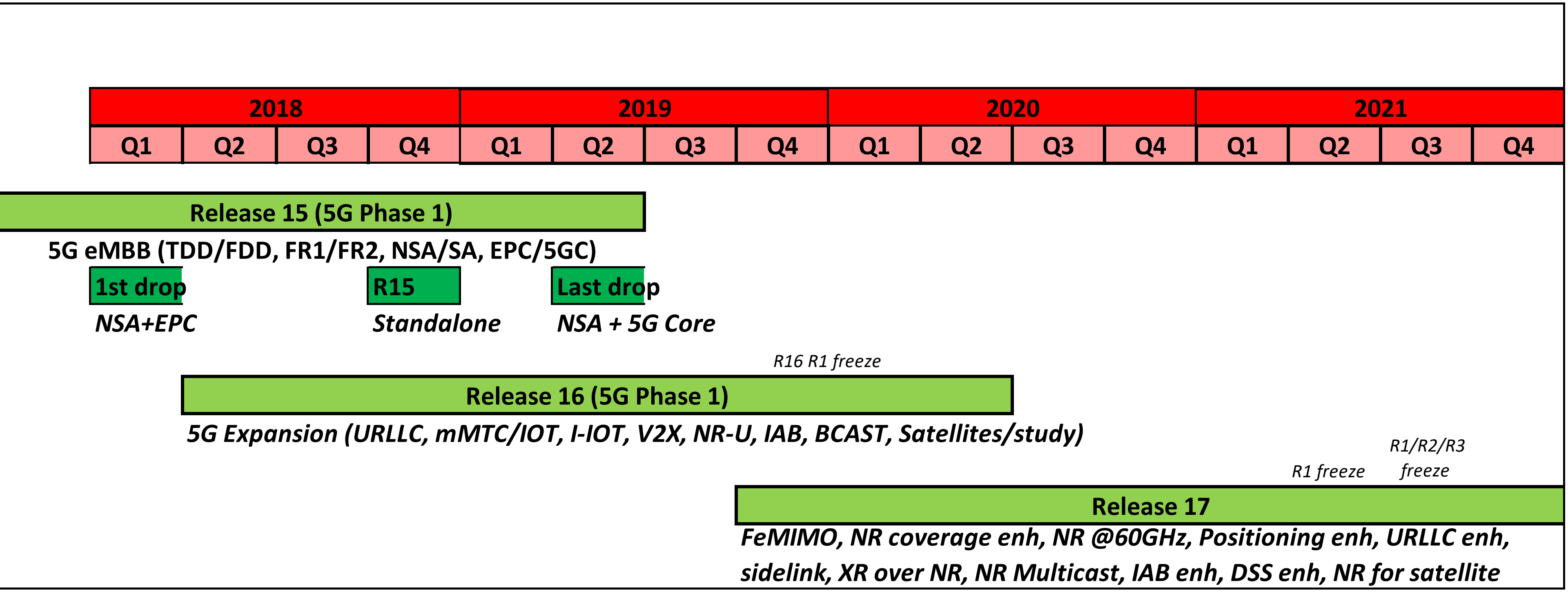
3GPP work planning and schedule

- 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



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

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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

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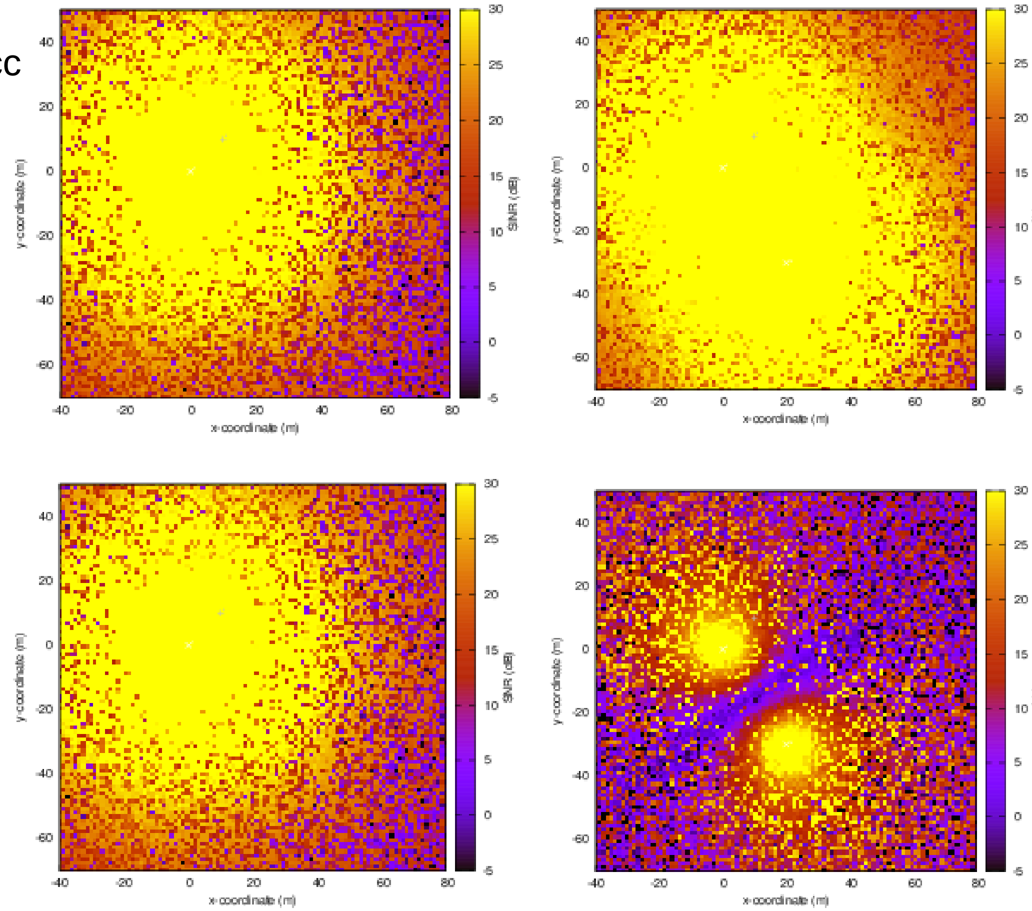
5G-LENA LTE-REM at 2GHz

- **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

1eNBs | 2 eNBs



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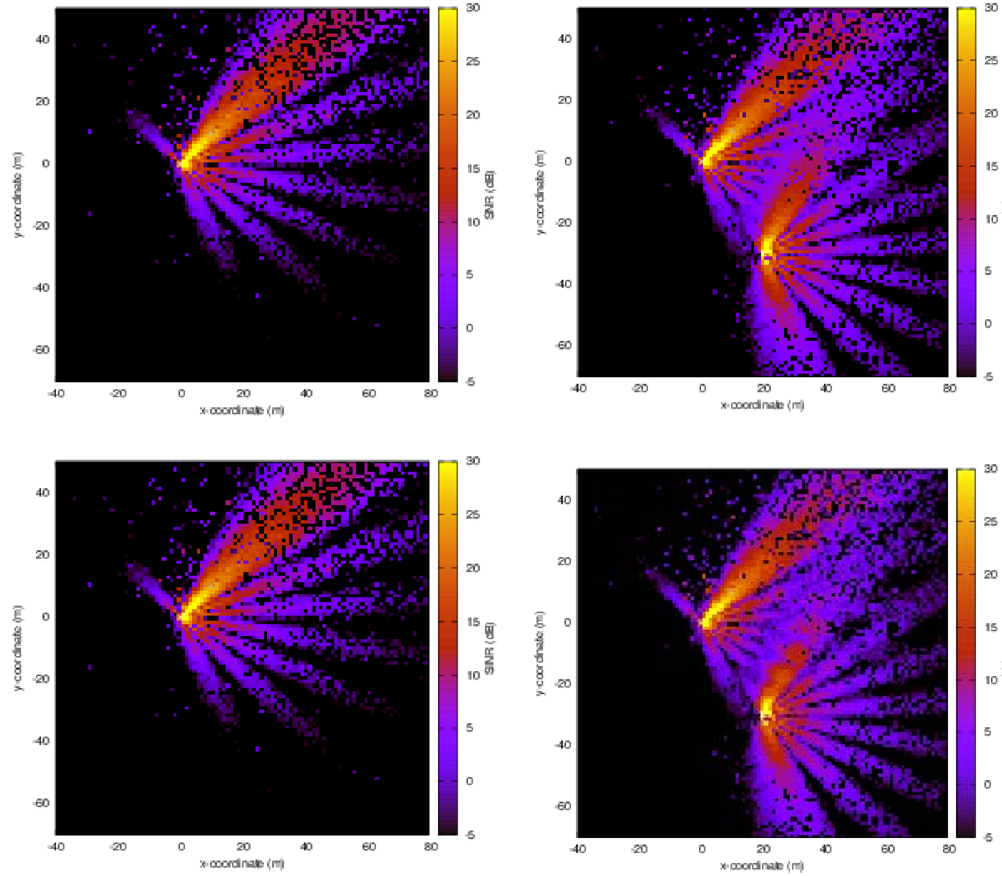
5G-LENA NR-REM at 28GHz: 1 beam example

- **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

1 gNBs

2 gNBs



5G-LENA NR-REM at 28GHz: coverage area

- **Scenario configuration:** UMa
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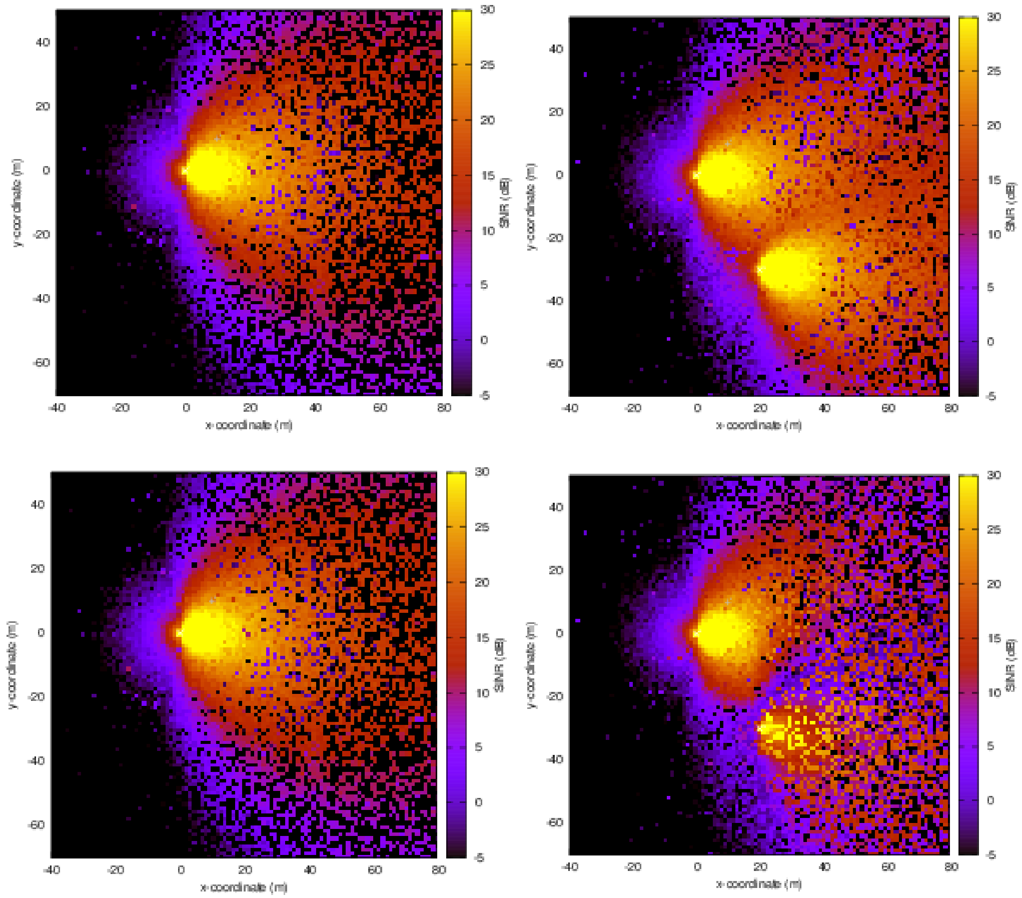
1 gNBs | 2 gNBs



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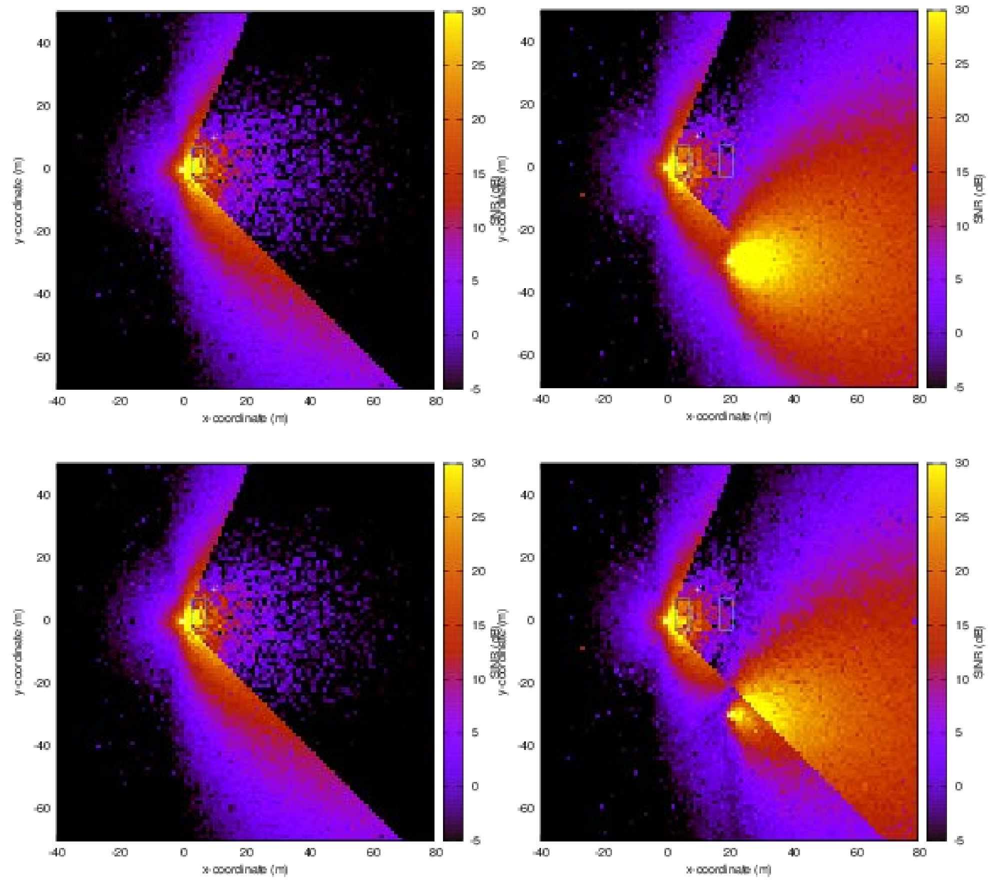
5G-LENA NR-REM at 28GHz with Buildings

1 gNBs 2 gNBs



- **Scenario configuration:** UMa
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  - Ue2 with position (25, -15, 1.5)
  - UE antenna: 1x1
  - Iso
  - Noise figure: 5 dBi
- 1building in 1 gnb case / 2 buildings in 2 gnbs case

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LTE in 4G LENA vs 5G LENA

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

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

- N. Patriciello, S. Lagen, B. Bojovic, L. Giupponi, An E2E Simulator for 5G NR Networks, Elsevier Simulation Modelling Practice and Theory (SIMPAT), vol. 96, 101933, Nov. 2019
- N. Patriciello, S. Goyal, S. Lagen, L. Giupponi, B.Bojovic, A. Demir, M. Beluri, NR-U and WiGig Coexistence in 60 GHz Bands, arXiv:2001.04779v2
- S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojovic, A. Demir, M. Beluri, New Radio beam-based Access to Unlicensed Spectrum: Design Challenges and Solutions, in IEEE Commun. Surveys and Tutorials, Oct. 2019.

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

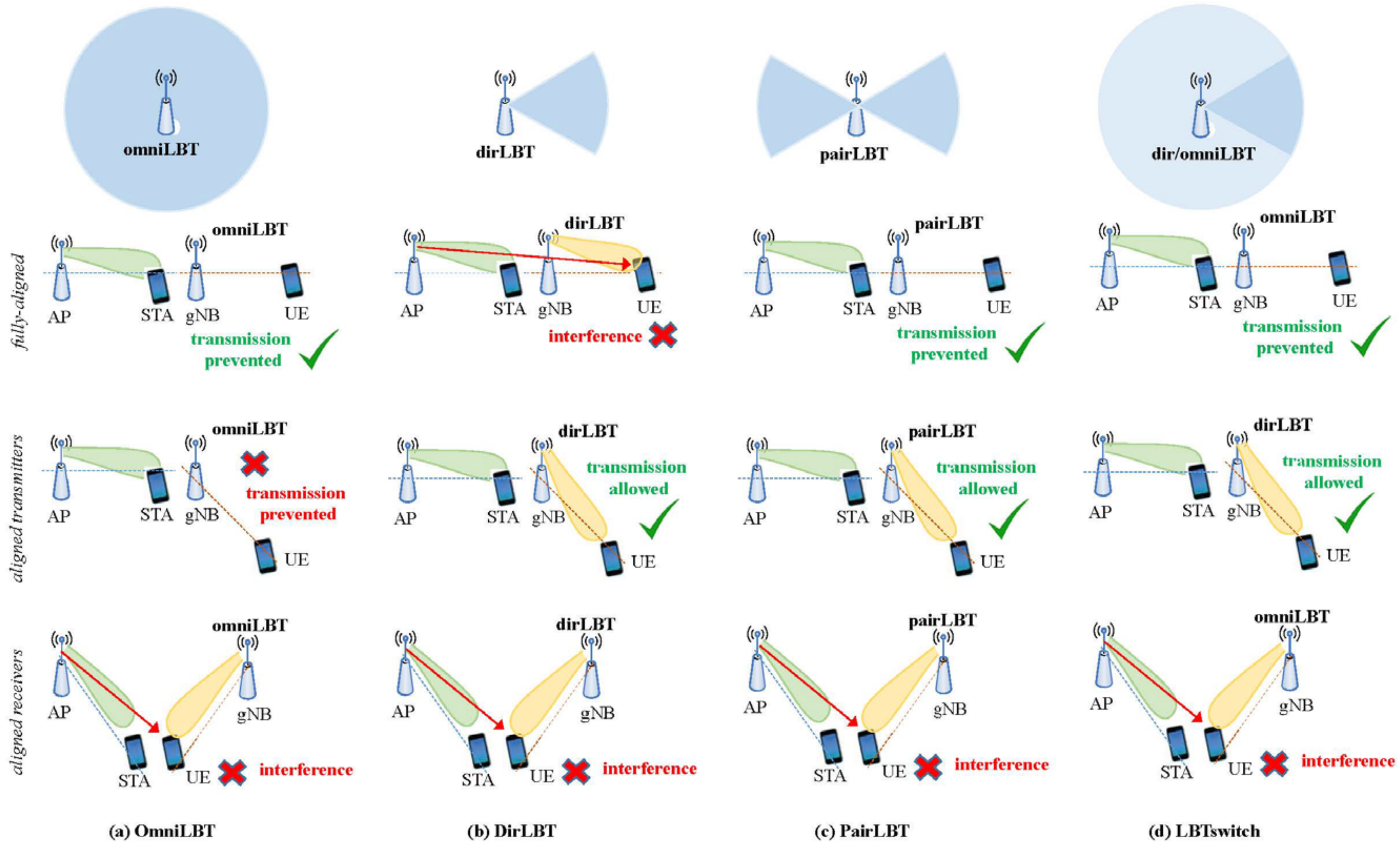
- We studied:
  - LBT for beam-based transmissions: LBT suffers from hidden and exposed node problems, which are emphasized by the directionality of transmission and reception.
  - Receiver-assisted LBT for beam-based transmissions: The receivers are in a better position to assess potential interference.
  - 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

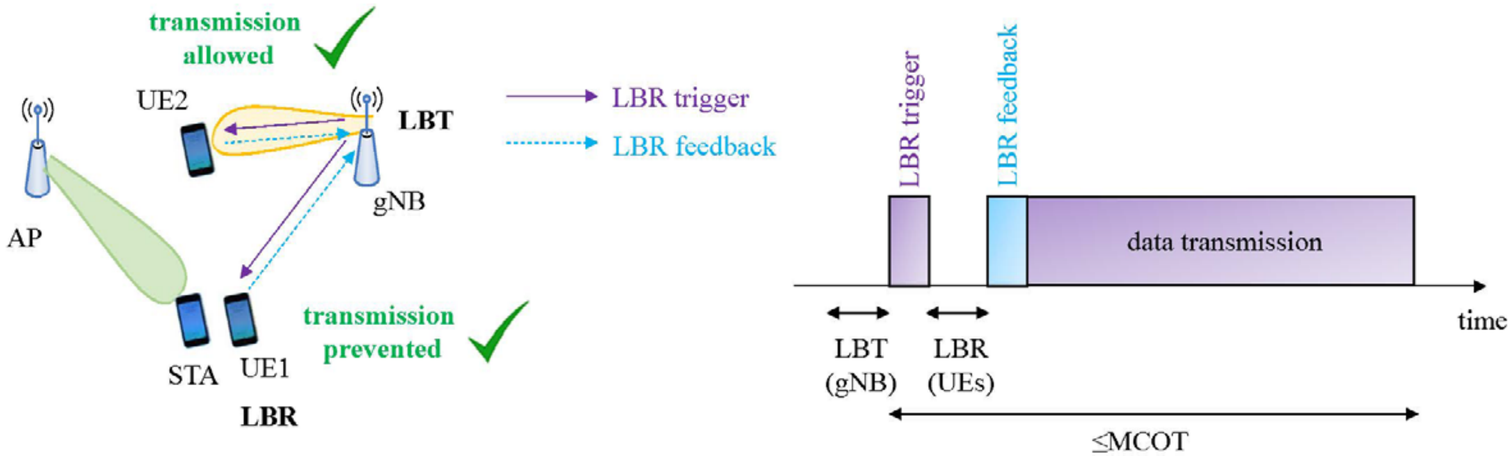
- Omnidirectional LBT: senses omnidirectionally. Under directional transmissions, it overprotects because a transmission is prevented even if a signal is detected from a direction that may not create harmful interference. (exposed node)
- Directional LBT: senses in a directional manner within the transmit beam towards the intended receiver. On-going 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, and N. Patriciello, “LBT switching procedures for new radio-based access to unlicensed spectrum,” in 2018IEEE Globecom Workshops (GC Wkshps) , pp. 1–6, Dec 2018.
- 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



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 25x25m^2 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$\times\log_2$(1+SINR), based on the SINR, and assuming ideal link adaptation

Scenario

- Directional transmission at gNBs/APs:
  - Transmit beams: 30º 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 90º.
- 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.

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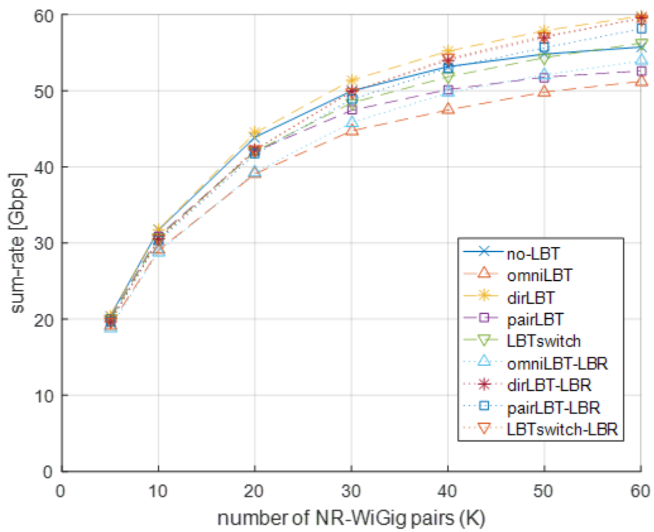
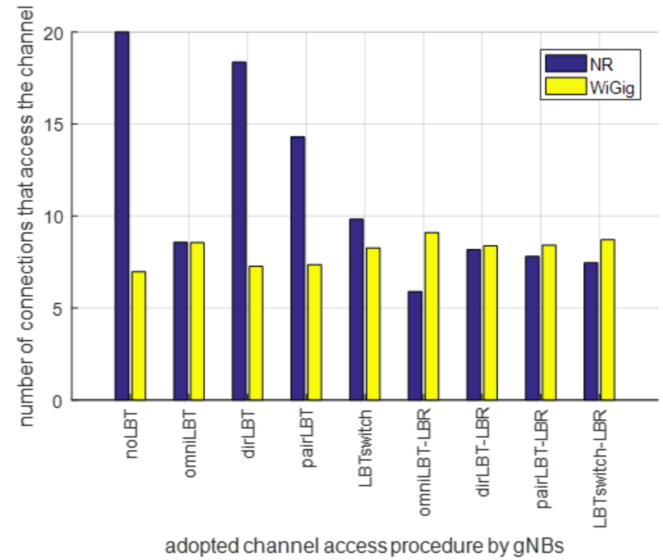
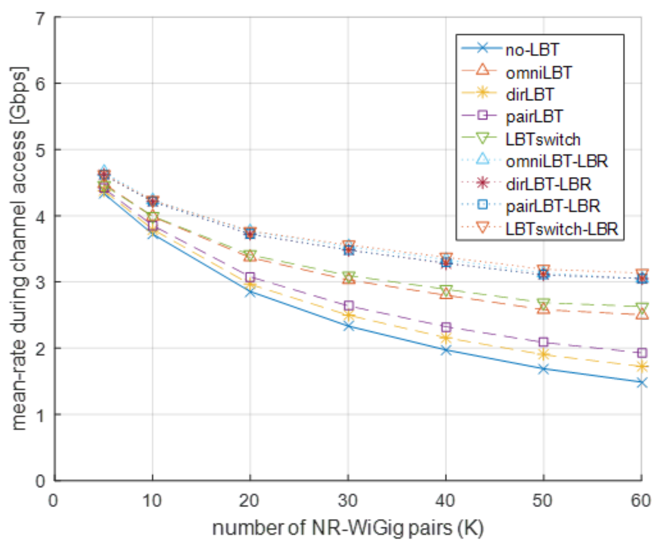
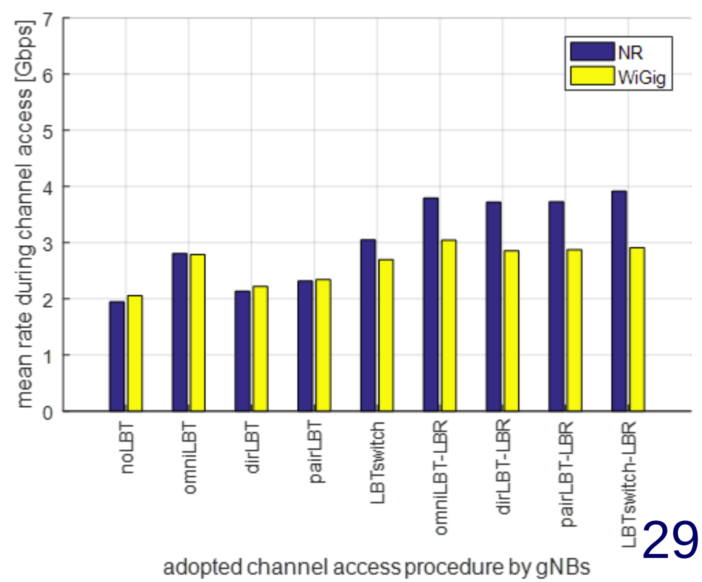
Results: omnidirectional reception at UEs/STAs

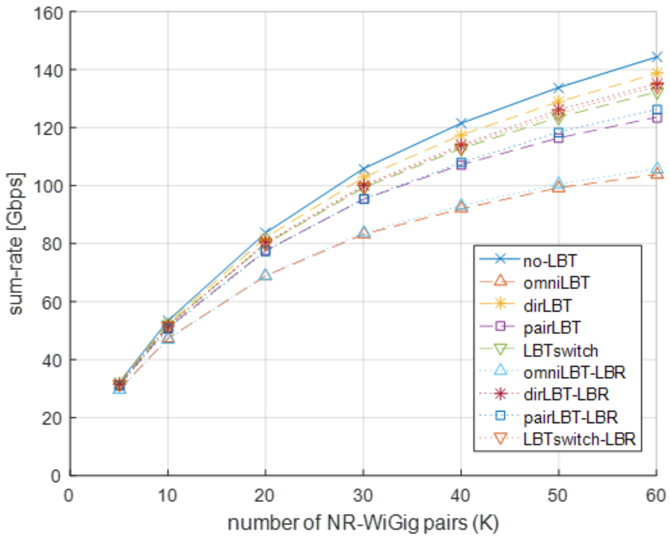


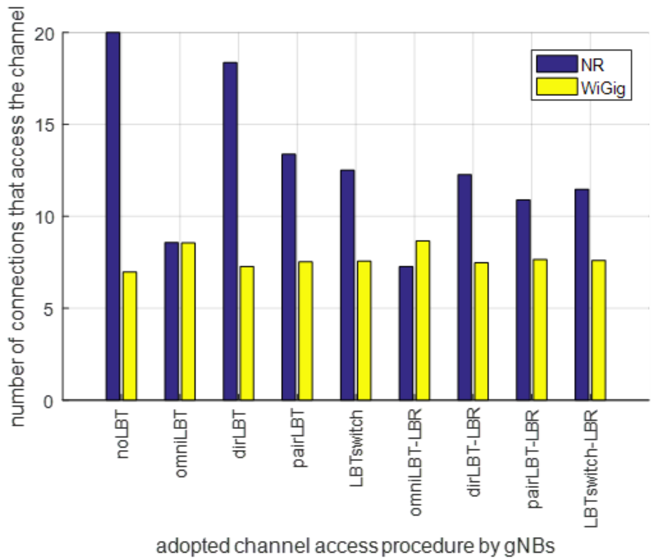


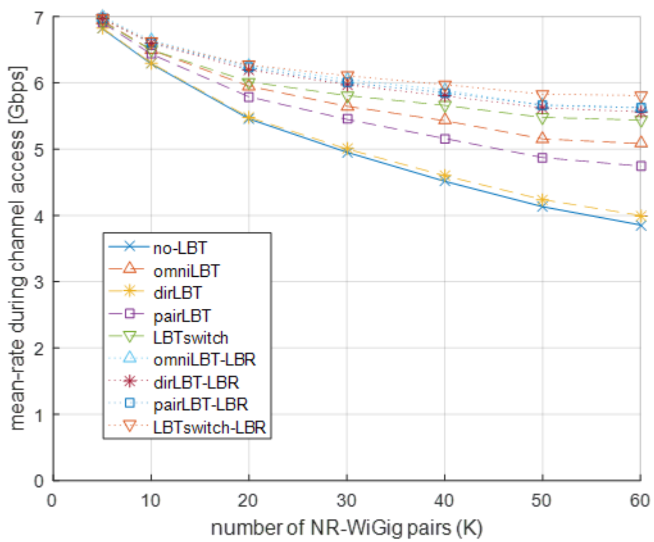


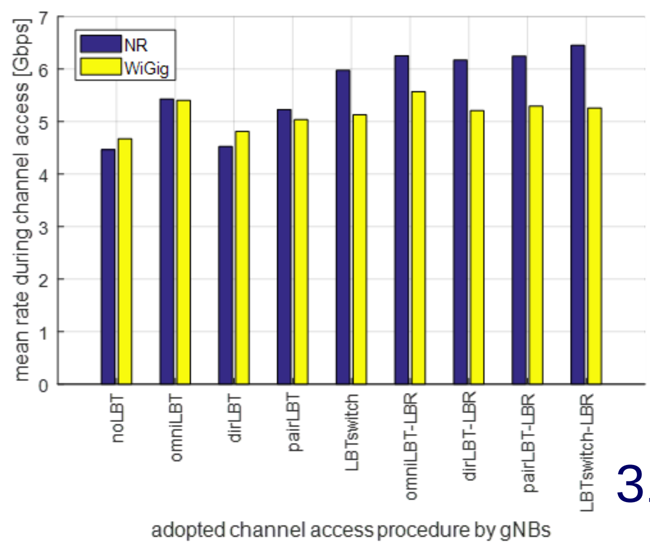


Results: Quasi-omni reception at UEs/STAs

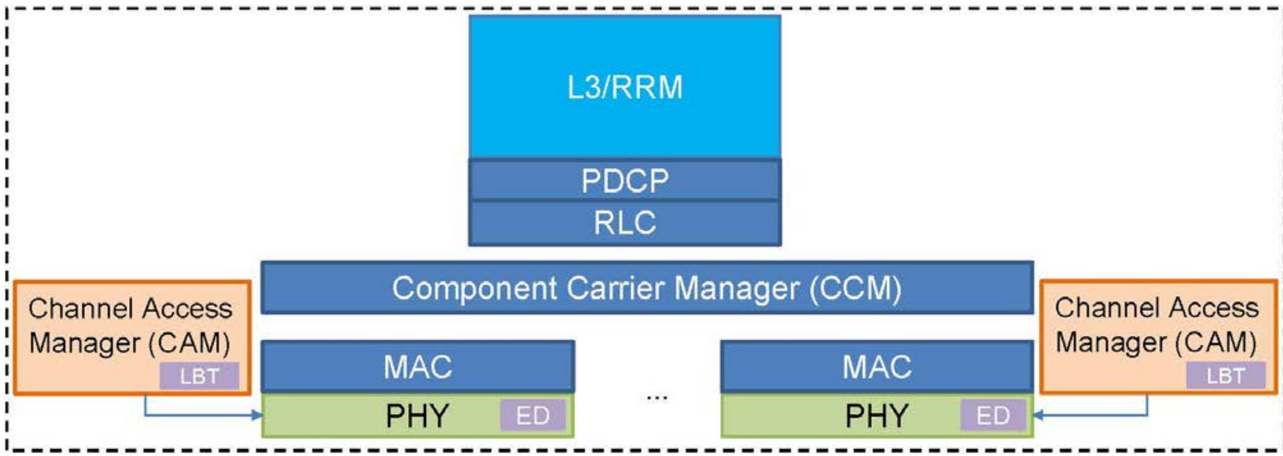




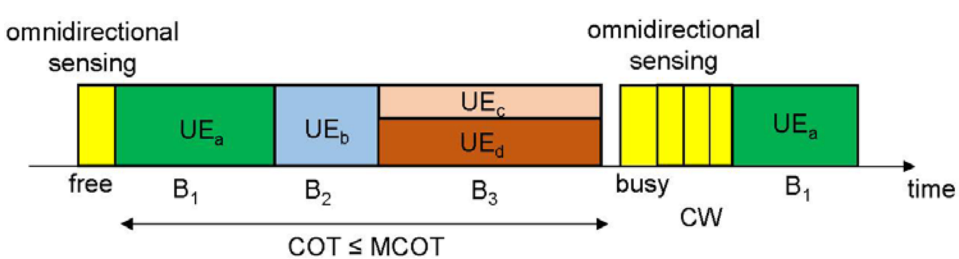




ns-3 NR-U simulator architecture



- 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



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Network simulations - models

TABLE 1: NR-U and WiGig models.

	NR-U	WiGig
Frame structure	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^{μ} slots (associated to $15\times2^{\mu}$ 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	TDD WiGig-compliant [23], [32]: - Beacon interval of 102.4 ms, including BTI, A-BFT, ATI 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 poling [32]
Antenna models	3GPP-compliant [38]: - Antenna arrays: 1 uniform planar array per AP/STA, $M\times N$ antenna elements, no polarization - Antenna elements: isotropical radiation and directional radiation are supported	3GPP-compliant [38]: - Antenna arrays: 1 uniform planar array per AP/STA, $M\times N$ antenna elements, no polarization - Antenna elements: isotropical 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 Table1 and MCS Table2 [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

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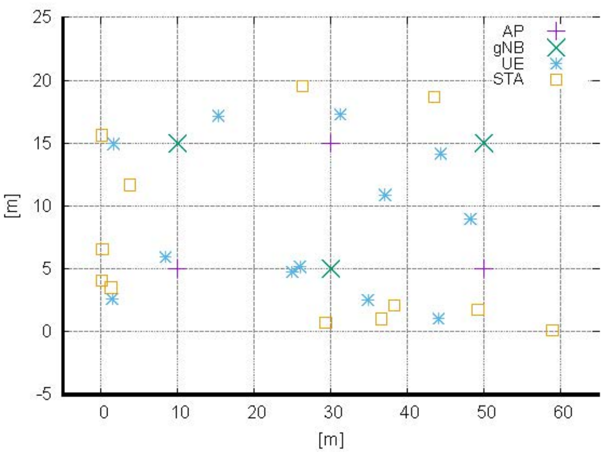
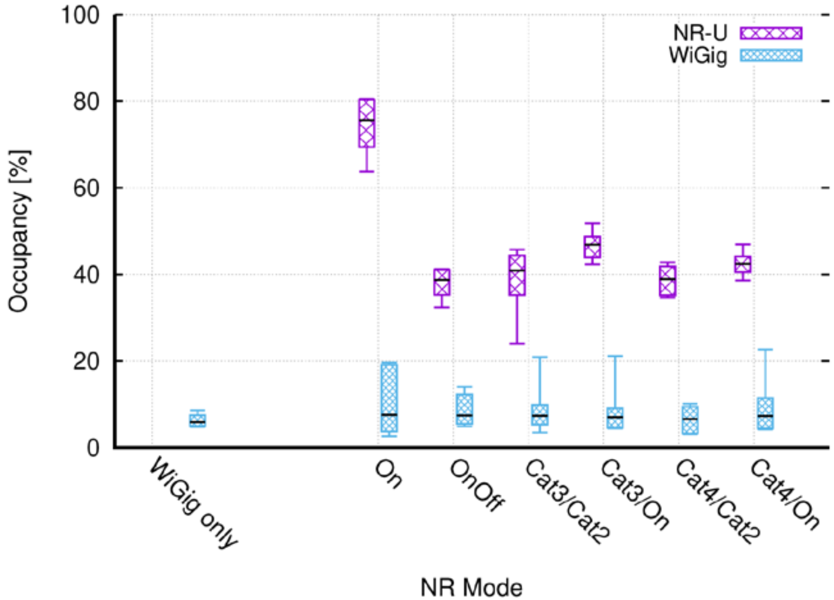


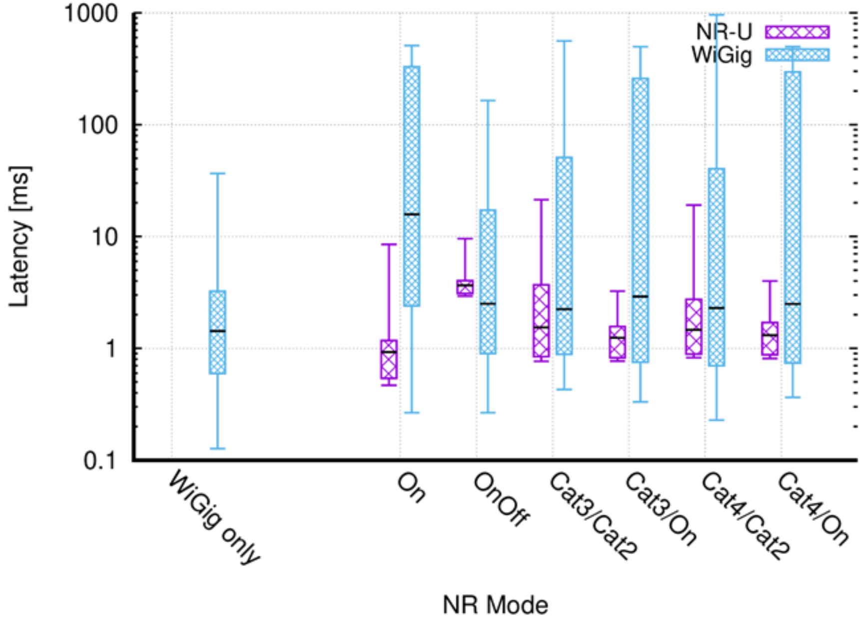
TR38.889 with reduced distances to adapt to mmWave ranges

TABLE 2: Main scenario simulation parameters

Parameter	Value (baseline)	Value (tested variations)
Deployment and propagation parameters:		
Channel model	3GPP Indoor Hotspot Mixed Office	
Deployment	2 operators, 3 base stations and 12 users per operator	
gNB/AP/UE/STA height	1.5 m	
Channel bandwidth	2.16 GHz	
Central frequency	58 GHz	
Noise power spectral density	-174 dBm/Hz	
Traffic parameters:		
Direction	downlink	
Application packet size	1000 Bytes	
Application load	10 Mbps and 50 Mbps	
Device parameters:		
gNB/AP antennas	8x8	4x4
UE/STA antennas	4x4	2x2
gNB/AP transmit power	17 dBm	
UE/STA transmit power	17 dBm	
gNB/AP noise figure	7 dB	
UE/STA noise figure	7 dB	
NR-U parameters and functionalities:		
Frame structure	SCS=120 kHz	SCS=60 kHz, SCS=240 kHz
Channel bandwidth	2.16 GHz	400 MHz, 800 MHz
Beamforming method	beam search	SVD-based
Beam reciprocity	yes	
Link adaptation	adaptive MCS (Shannon-based adaptation)	
Error model	NR PHY abstraction based on EESM [40]	
MCS table	MCS Table1	
HARQ method	HARQ-IR	
MAC	scheduled-based	
gNB CAM	Cat4 LBT	AlwaysOn, OnOff
UE CAM	Cat2 LBT	AlwaysOn, OnOff
RLC mode	RLC-UM	
RLC buffer size	999999999 Bytes	
LBT CAM:		
gNB ED threshold	-79 dBm (omniLBT)	-69 dBm, -89 dBm
UE ED threshold	-69 dBm (dirLBT)	
CCA slot duration	5 us	
defer interval during CCA	8 us	
Maximum COT	9 ms	
Cat 4 LBT minimum CWS	15	
Cat 4 LBT maximum CWS	1023	
Cat 3 LBT CWS	15	
Cat 2 LBT defer period	25 us	
DL-UL switching points	one within COT	
OnOff CAM:		
duty cycle	50%: ON and OFF periods of 9 ms	
WiGig parameters and functionalities:		
Frame structure	BI length =102.4ms, BTI length=1.2ms, 8 SS slots and 16 SSW frames per slot, no ATI	
Channel bandwidth	2.16 GHz	
Beamforming method	beam search	
Beam reciprocity	yes	
Link adaptation	adaptive MCS (Shannon-based adaptation)	
Error model	60 GHz sensitivity model	
MAC	contention-based	
RTS/CTS	disabled	
PDU and SDU aggregation	enabled	
CSMA/CA:		
AP/STA ED threshold	-79 dBm (omniLBT)	
AP/STA preamble detection threshold	-96 dBm (omniLBT)	
CCA slot duration	5 us	
defer interval during CCA	8 us	
CSMA/CA minimum CWS	15	
CSMA/CA maximum CWS	1023	

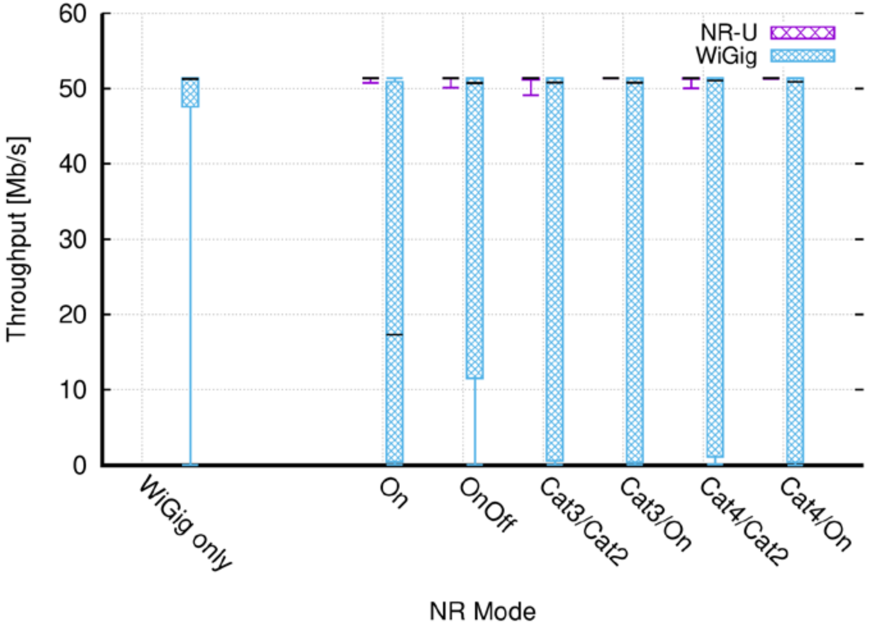
Impact of NR-U channel access

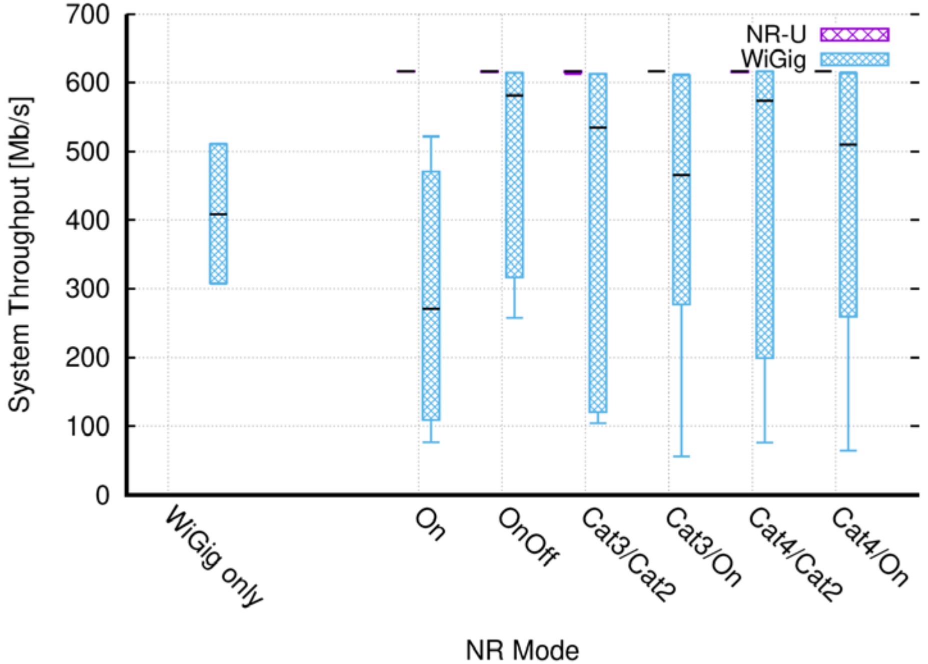




- NR-U channel occupancy is higher than WiGig's, due to symbol level granularity.
  - For SCS 120 KHz, symbol is 8,92 us, while WiGig frame on average 3,5 us.
  - Effect decreases with LBT and OnOff, since packets are accumulated in queue during OFF periods. and transmission opportunity is better used.
  - 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.

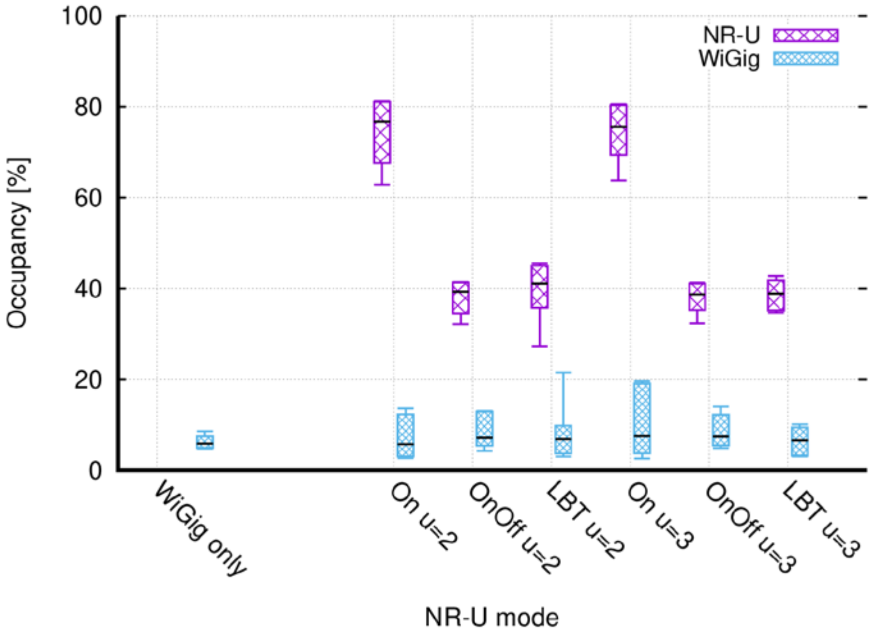
Impact of NR-U channel access

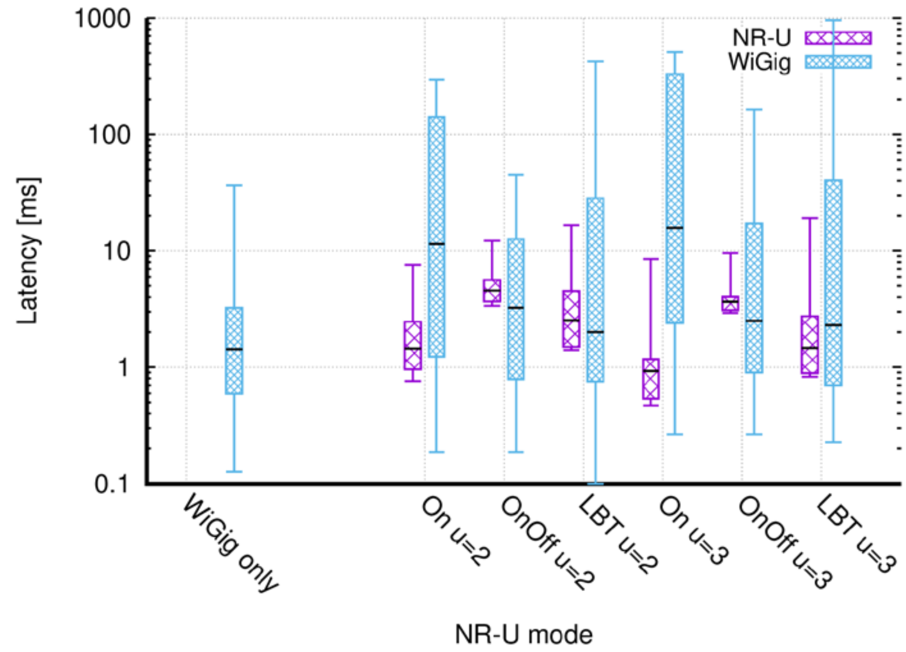




- WiGig vs WiGig: nodes see each other at -96 dBm (preamble detection).
- WiGig vs NR-U: nodes see each other at ED threshold, configured to -79 dBm.
  - More nodes (both WiGig and NR-U) gain the channel, which reduces the per node throughput, and increases the system throughput.
- Cat4/Cat2 offers the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

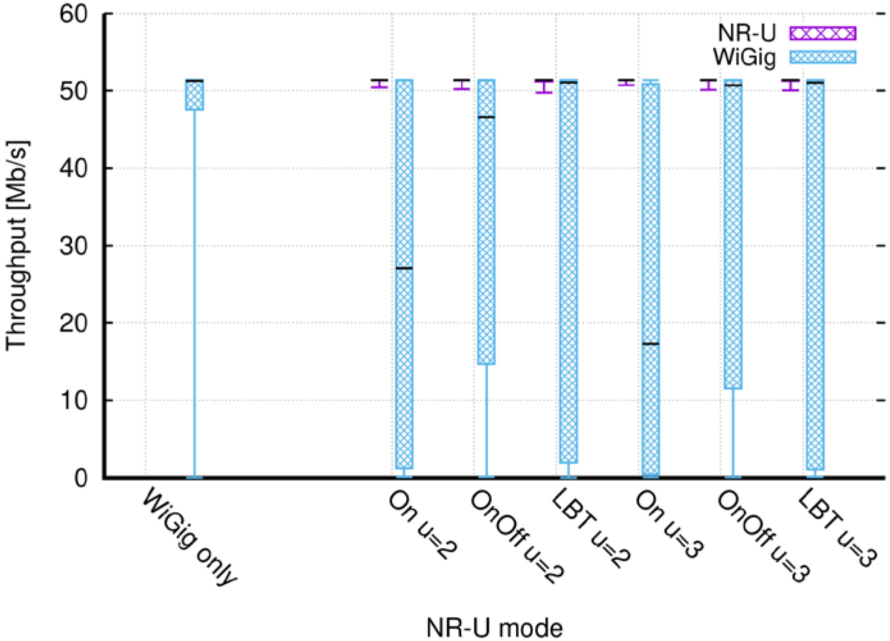
Impact of numerology

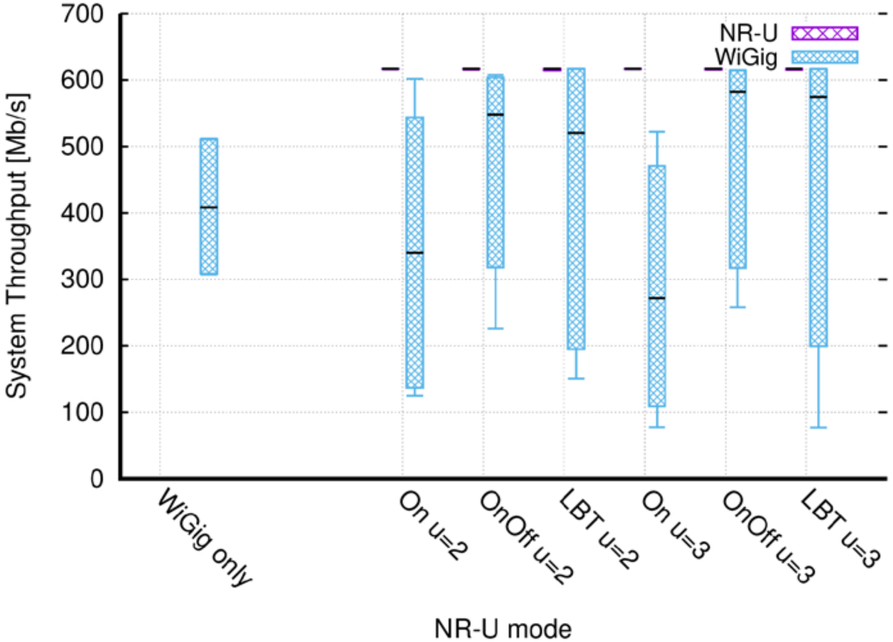




- SCS: 60, 120 KHz (we are further studying 240 KHz)
- NR-U latency goes down as expected
- Occupancy is not affected in alwaysON, but with OnOff and LBT we see a slight reduction in occupancy, because packets are aggregated and transmitted in shorter time.
- In AlwaysON case, occupancy is more bursty,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

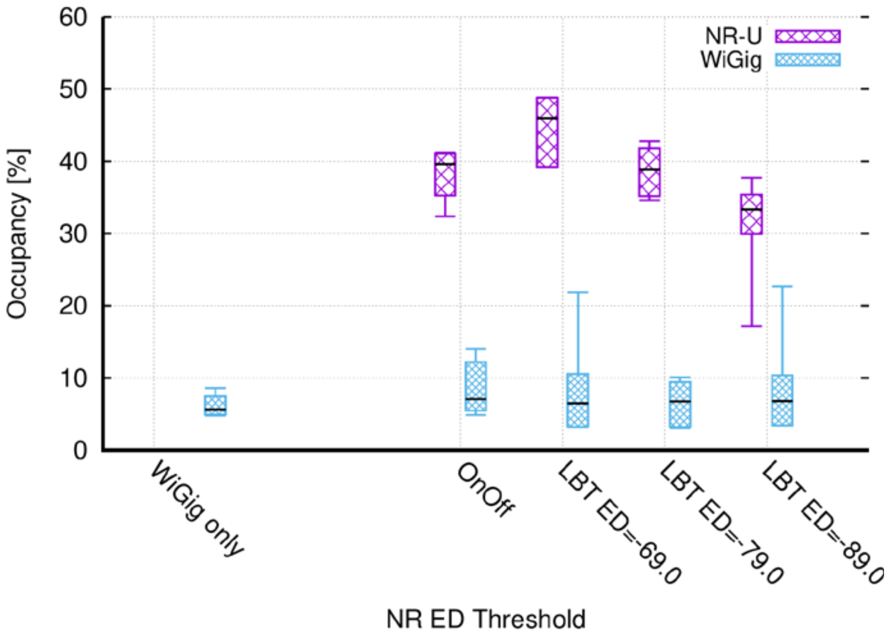
Impact of numerology

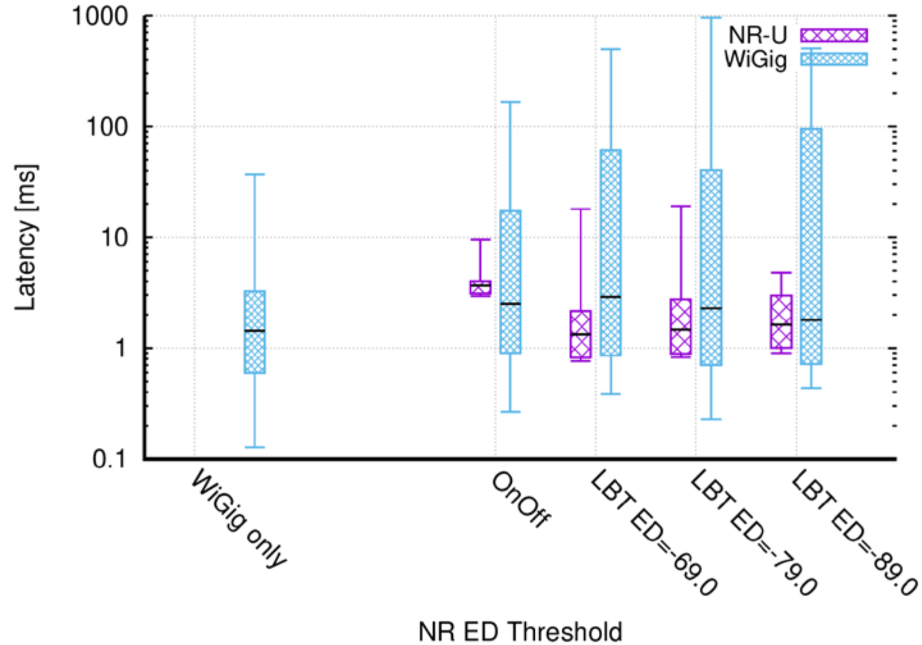




- For alwaysON, a lower numerology allows aggregation and so an access with less OFF to ON transitions. This results in better per user and system throughput.
- For OnOff and LBT, since they already naturally allow for packet aggregation during OFF periods, the higher numerology slightly improves the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

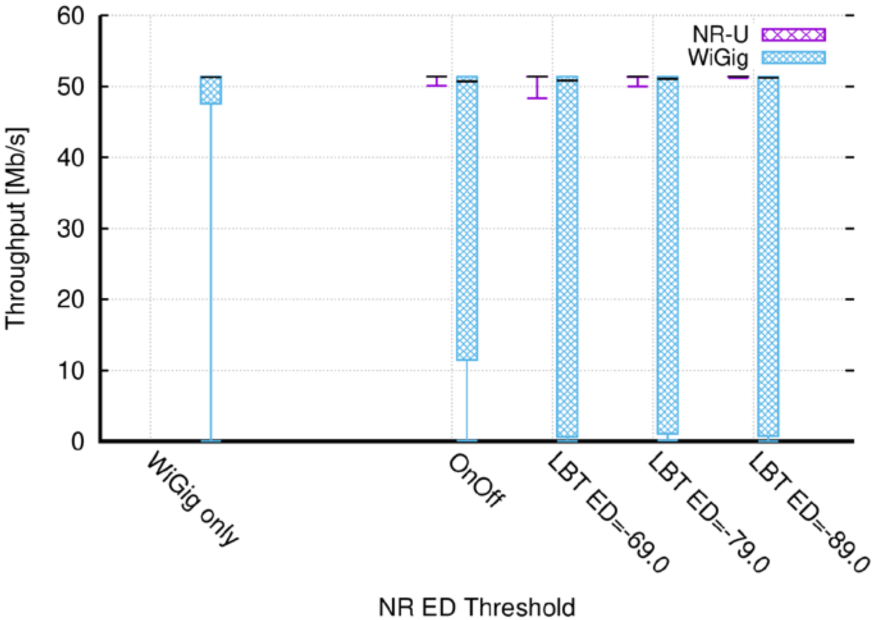
Impact of NR-U ED threshold

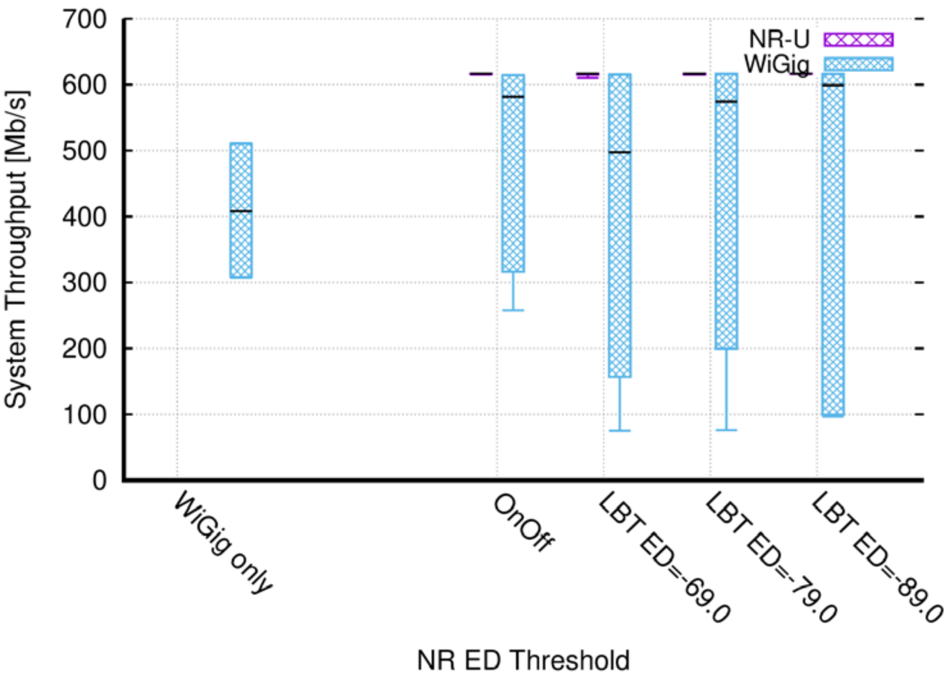




- Lower NR-U ED threshold reduces access of NR-U nodes, and so the occupancy
- This results in reduced WiGig's latency

Impact of ED threshold





- Lower NR-U ED threshold results in:
  - Improved NR-U per user throughput
  - Improved WiGig's system throughput

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Publications

Journal papers

- *N. Patriciello, S. Lagen, B. Bojovic, L. Giupponi,* **An E2E Simulator for 5G NR Networks**, Elsevier Simulation Modelling Practice and Theory (SIMPAT), vol. 96, 101933, Nov. 2019, DOI. Available here.
- *S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojovic, A. Demir, M. Beluri,* **New Radio Beam-based Access to Unlicensed Spectrum: Design Challenges and Solutions**, IEEE Communications Surveys & Tutorials, Oct. 2019, DOI. Available here.
- *N. Patriciello, S. Lagen, B. Bojovic, L. Giupponi,* **NR-U and IEEE 802.11 Technologies Coexistence in Unlicensed mmWave Spectrum: Models and Evaluation**, in IEEE Access, vol. 8, pp. 71254-71271, 2020, DOI.

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- *S. Lagen, N. Patriciello, L. Giupponi,* **Cellular and Wi-Fi in Unlicensed Spectrum: Competition leading to Convergence**, in 6G Wireless Summit, 17-20 March 2020, Levi (Finland).
- *S. Lagen, K. Wanuga, H. Elkotby, S. Goyal, N. Patriciello, L. Giupponi,* **New Radio Physical Layer Abstraction for System-Level Simulations of 5G Networks**, in Proceedings of IEEE International Conference on Communications (IEEE ICC), 7-11 June 2020, Dublin (Ireland). Available here.
- *N. Patriciello, S. Lagen, L. Giupponi, B. Bojovic,* **The impact of NR Scheduling Timings on End-to-End Delay for Uplink Traffic**, in Proceedings of IEEE Global Communications Conference (IEEE GC), 9-14 December 2019, Waikoloa (HI, USA). Available here.
- *N. Patriciello, S. Lagen, L. Giupponi, B. Bojovic,* **An Improved MAC Layer for the 5G NR ns-3 module**, in Workshop on ns-3, 19-20 June 2019, Florence (Italy). Available here.
- *N. Patriciello, S. Lagen, L. Giupponi, B. Bojovic,* **5G New Radio Numerologies and their Impact on the End-To-End Latency**, in Proceedings of IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (IEEE CAMAD), 17-19 September 2018, Barcelona (Spain), DOI. Available here.
- *S. Lagen, B. Bojovic, S. Goyal, L. Giupponi, J. Mangues,* **Subband Configuration Optimization for Multiplexing of Numerologies in 5G TDD New Radio**, in Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC), 9-12 September 2018, Bolonga (Italy), DOI. Available here.
- *B. Bojovic, S. Lagen, L. Giupponi,* **Implementation and Evaluation of Frequency Division Multiplexing of Numerologies for 5G New Radio in ns-3**, in Workshop on ns-3, 13-14 June 2018, Surathkal (India). Available here.