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5G-LENA NR MODULE OVERVIEW

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ORGANIZATION (1/2)

- **09:30 – 10:30**
  - **Part I: The theoretical part**
    - Introduction
    - Architecture, design, and the protocol stack
    - PHY/MAC features
    - Calibration
    - NR-U extension
    - NR module helpers

ORGANIZATION (2/2)

- **11:00 – 11:30 UTC**
  - **Part II: The practical part**
    - A hands-on session using a typical NR module example
    - NR module learning resources
    - Contributing to NR module
    - Publications

NR MODULE PART I: THEORETICAL PART

- NR Module Introduction
  - History
  - General Overview
- NR Module Design
  - End-to-end and DATA/CTRL Plane Architecture
  - NR PHY Layer
  - NR MAC Layer
- NR-U
- NR Module Calibration
- NR Module Helpers

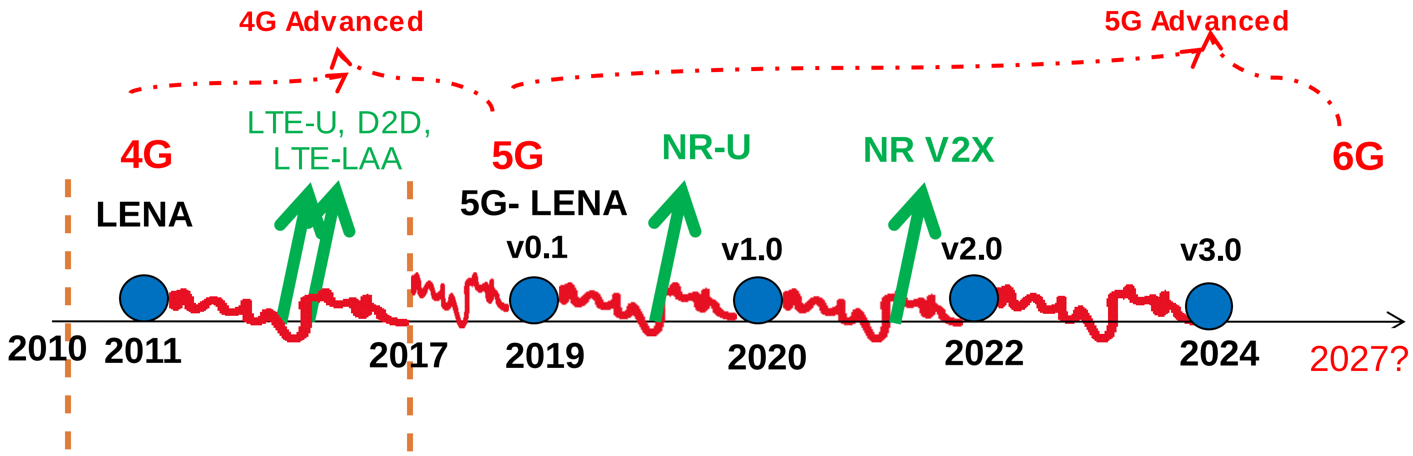
5G-LENA SIMULATOR

- 5G-LENA is an open-source end-to-end network simulator
- Designed as **a pluggable module to ns-3** network simulator
- Allows to simulate 5G NR technology with **high-fidelity standard-compliant protocols calibrated** with 3GPP results
- **A common open-source software platform for academy and industry**
- Allows to evaluate R&D solutions **before** industrial or real-network implementation

https://5g-lena.cttc.es

https://www.nsnam.org/

LENA AND 5G-LENA HISTORY

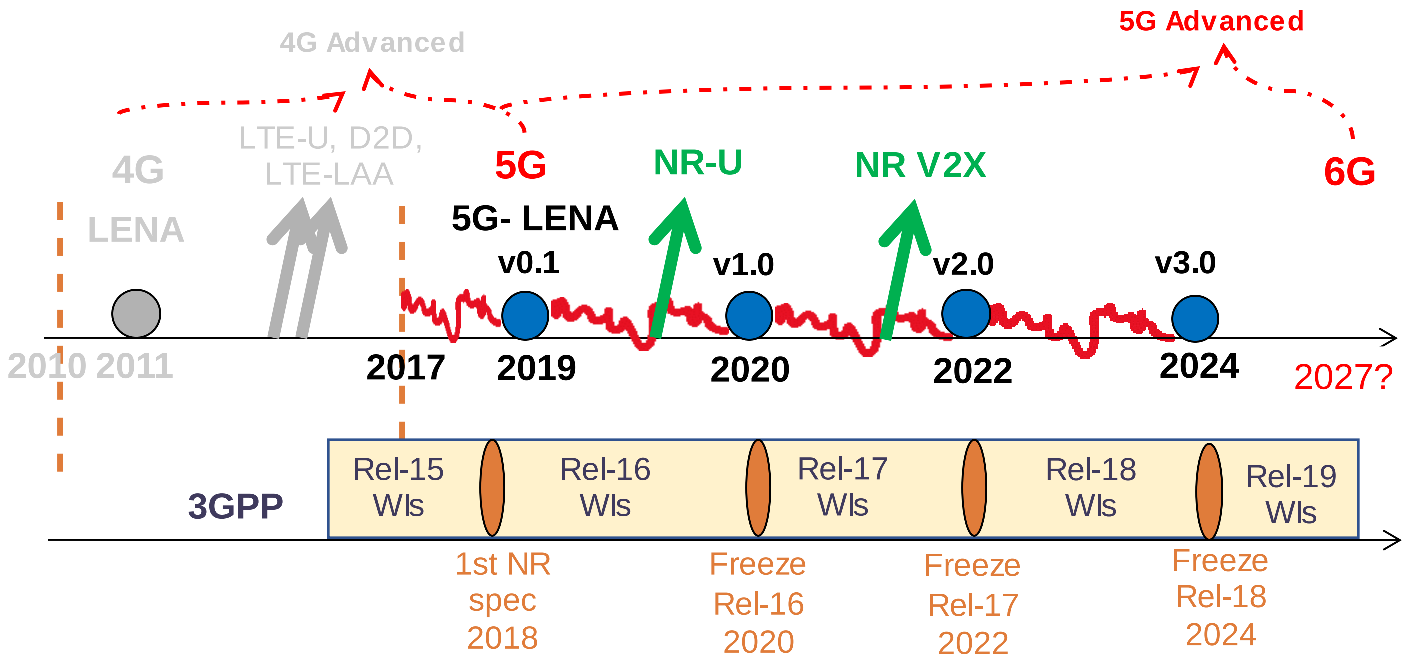


2010, LENA:

- **CTTC** gets contracted by **Ubiquisys (Cisco)** to develop an **LTE module of ns-3** (aka LENA)

Ubiquisys

LENA AND 5G-LENA HISTORY



2017, 5G-LENA:

- CTTC project with **InterDigital** to develop the **3GPP compliant nr module for ns-3**, aka as **5G-LENA**
- Forked from **mmWave** module

interdigital

5G-LENA: INDUSTRIAL PROJECTS

- ns-3 LENA and 5G-LENA have been developed over more a decade of a dedicated **collaborations with major telecom companies**

5G-LENA: INDUSTRIAL PROJECTS

- **InterDigital** (2017-2019)
  - The first release of **5G-LENA module** in 2019
  - The first release of **NR-U module** in 2020
- **LLNL** Lawrence Livermore National Lab (US dept. Defense) (2019-2021)
  - **Uplink Power Control, REM maps**, **LENA vs 5G-LENA calibration** added to 5G-LENA and released as open-source
- **NIST** National Institute of Standards and Tech (US dept. Commerce) (2020-2021)
  - The first release of **NR V2X module**
- **Huawei (2020-2021)**
  - Fronthaul compression control, O-RAN architecture
- **Meta** (2021-2022)
  - DP-MIMO
  - 5G-LENA improvements for **AR/VR**, Released in 2023
- **Different private colaborations** (2022-2024)
  - 5G-LENA improvements for **SU-MIMO** (4 streams/UE, 32 antenna ports), Enhancement released in 2023 and 2024

OPENSIM RU VISION

- Collaborative research through open-source
- Common and open-source software platforms
- We release the major part of our developments and findings
- Strong commitment with the ns-3 community

- Advances in RAN, RRM
- 3GPP/IEEE coexistence
- SON for O-RAN
- Analytical problem formulation and solving

- Design
- Development
- Validation
- Calibration
- Evaluations

ns-3 and 5G-LENA advancements

CTTC OPENSIM RESEARCH UNIT TEAM

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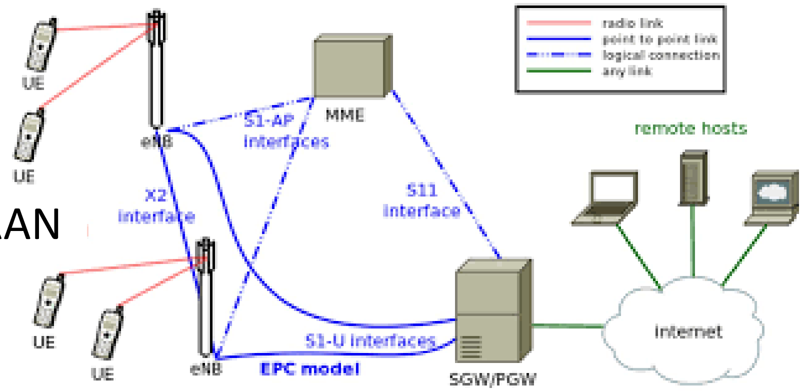
Zoraze Ali

FEATURES AND ASSUMPTIONS (1/4)

- NSA architecture: 5G RAN and 4G EPC
- Realistic Data Plane Protocol stack model
  - Realistic RLC, PDCP, S1-U, X2-U
  - Allows for end-to-end QoS/QoE evaluations
- Simplified Control Plane model: S1-AP, X2-C, S5 and S11 models
- Simplified EPC: One MME, one SGW and PGW

NR 5G RAN



FEATURES AND ASSUMPTIONS (2/4)

- Support for FDM of numerologies through different BWPs
- BWP/CC managers and architecture to support operation through multiple BWPs/CCs
- Schedulers: PF, RR, MR and QoS
- UL grant-based access scheme with scheduling request and 3GPP-compliant buffer status reporting
- NR-compliant processing timings (K1, K2)

FEATURES AND ASSUMPTIONS (3/4)

- Flexible and automatic configuration of the NR frame structure through multiple numerologies
- Duplexing schemes: TDD/FDD
- OFDMA and TDMA-based access modes with variable TTIs
  - Time domain granularity: OFDM symbol
  - Frequency domain granularity: Resource Block
- PHY layer abstraction:
  - Considering LDPC codes for data channels
  - PHY abstraction for DL and UL CTRL channels: No error model.

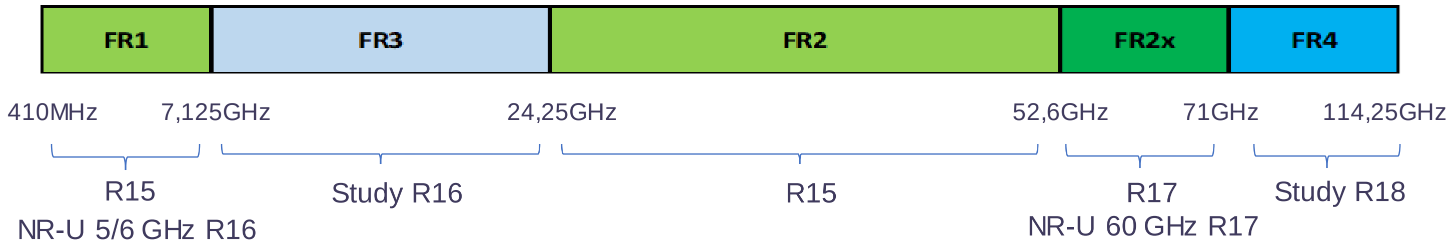
FEATURES AND ASSUMPTIONS (4/4)

- 2 ideal beamforming methods (no real BF overhead)
  - Beam-search method
  - LOS-path method
- Realistic beamforming:
  - For TDD systems
  - Based on SRS reception
  - An abstraction model estimates the channel matrix
- SU-MIMO
  - Since 5G-LENA 3.0 3GPP compliant codebook-based Type I MIMO

*B. Bojovic, Z. Ali, S. Lagen, **ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO**, in Workshop on ns-3, June 2022.*

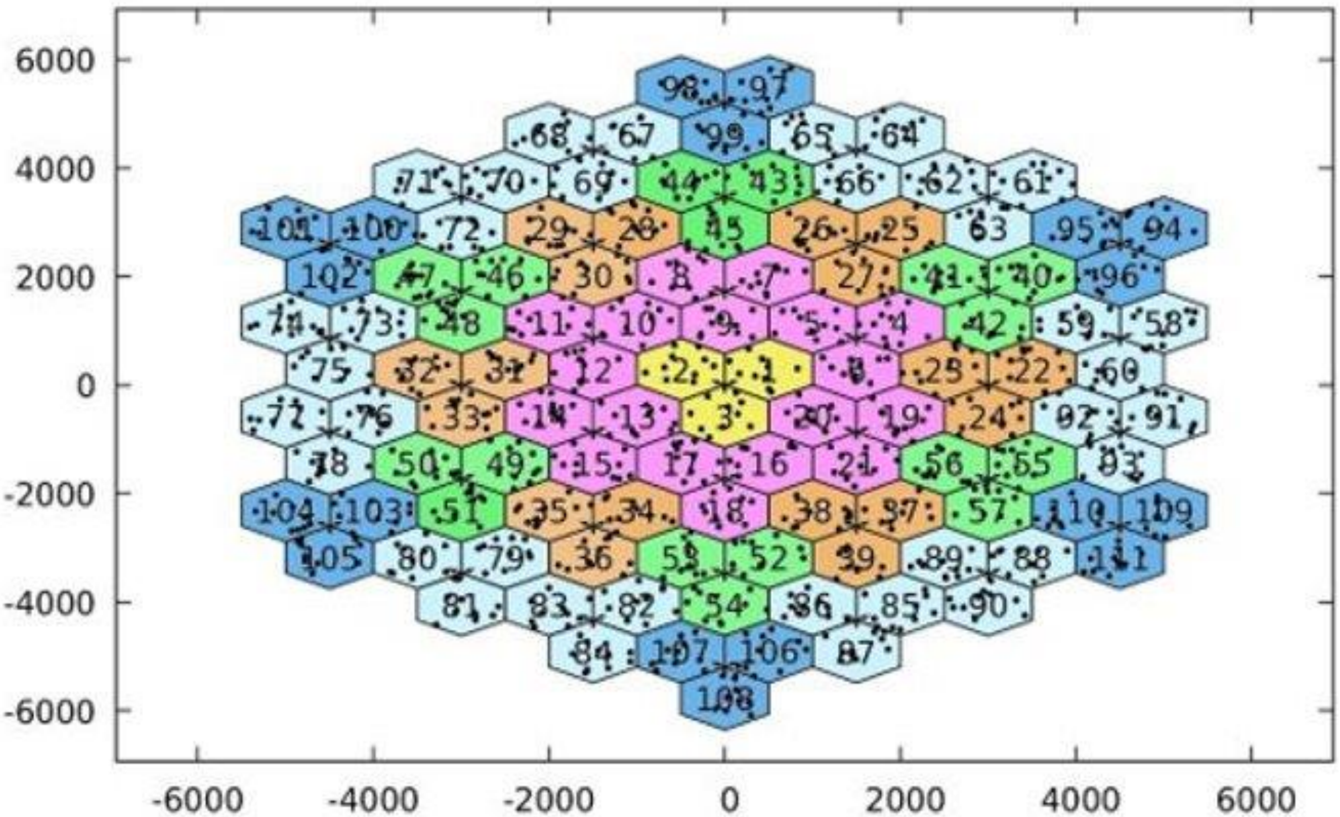
5G-LENA FREQUENCY BANDS

- Flexible to work from 400 MHz to 100 GHz, using the 3GPP SCM [TR 38.901]
- We have tested NR in FR1 and FR2, and also NR-U in 60GHz and 5/6GHz



- ns-3 GSoC 2024 project: "**5G nr module benchmark and analysis for distinct channel models**", Joao Albuquerque:
  - it will be possible to use 5G-LENA with NYU channel model, which supports up to 150 GHz

AN EXAMPLE OF A LARGE-SCALE SCENARIO



0 rings = 1 site
1 rings = 7 sites
2 rings = 13 sites
3 rings = 19 sites
4 rings = 31 sites
5 rings = 37 sites

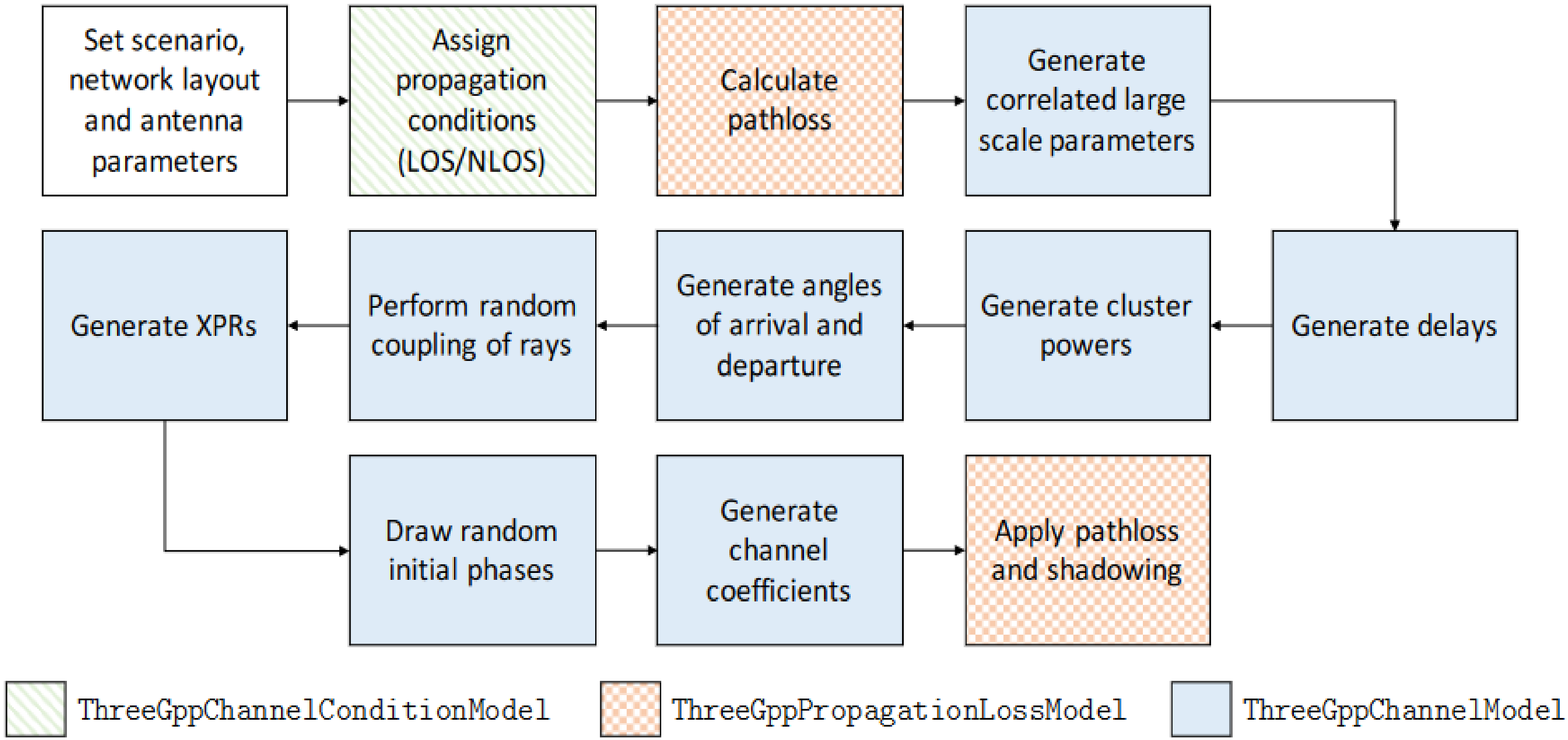
Example:
5 rings
37 sites
111 gNBs
1110 UEs

5G-LENA 3GPP TR 38.901 CHANNEL MODEL

- 0.5-100 GHz freq. Range
- Scenarios:
  - InH Office-Open
  - InH Office-Mixed
  - Rural Macro
  - Urban Macro
  - Urban Micro Street-Canyon
  - V2V-Highway
  - V2V-Urban
- LOS and NLOS conditions as per 3GPP, but can be enforced

T. Zugno, M. Polese, N. Patriciello, B. Bojovic, S. Lagen, M. Zorzi, ***Implementation of A Spatial Channel Model for ns-3****, in Workshop on ns-3, June 2020.*
T. Zugno, M. Drago, S. Lagen, Z. Ali, M. Zorzi, ***Extending the ns-3 Spatial Channel Model for Vehicular Scenarios****, in Workshop on ns-3, June 2021.*

3GPP CHANNEL MODEL GENERATION PROCEDURE



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NR END-TO-END ARCHITECTURE OVERVIEW

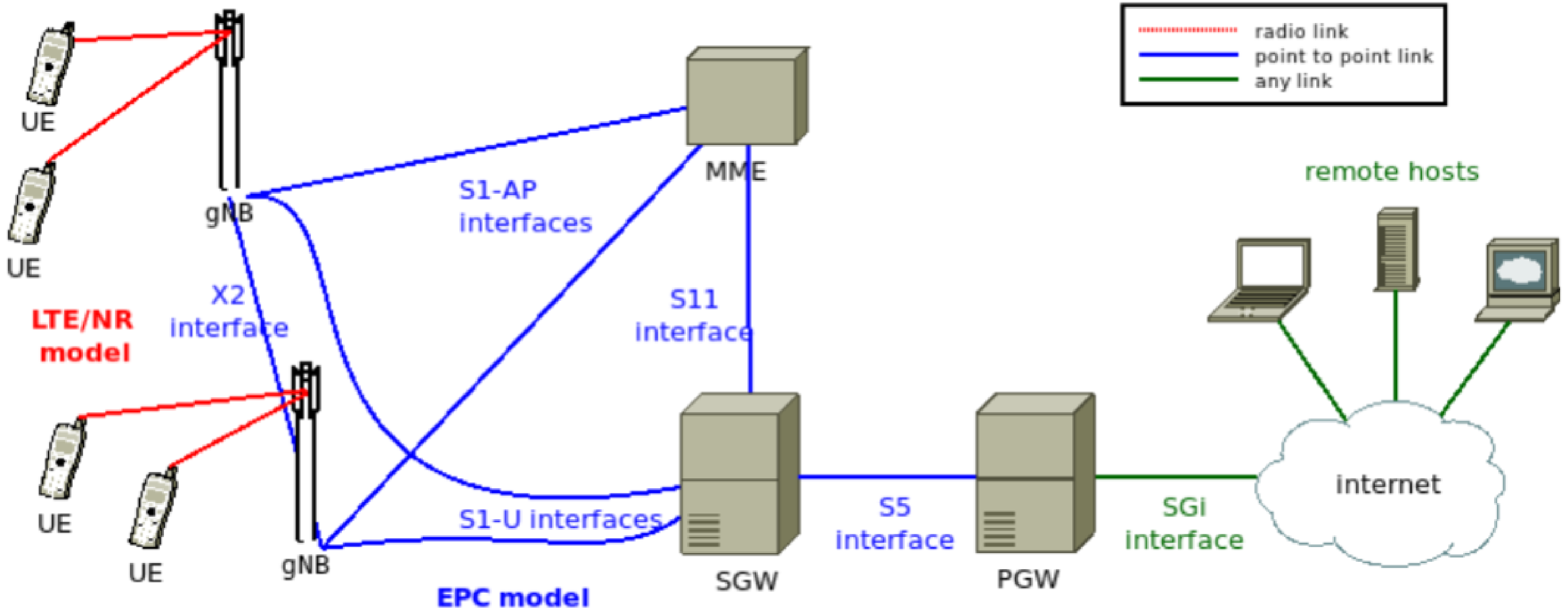
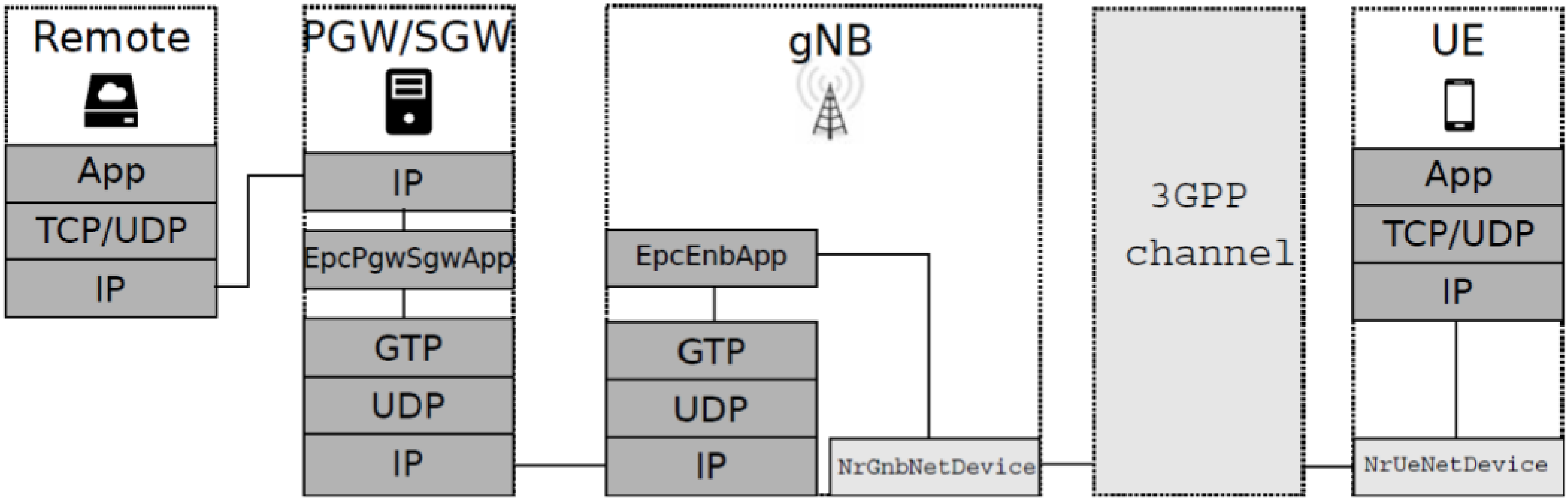


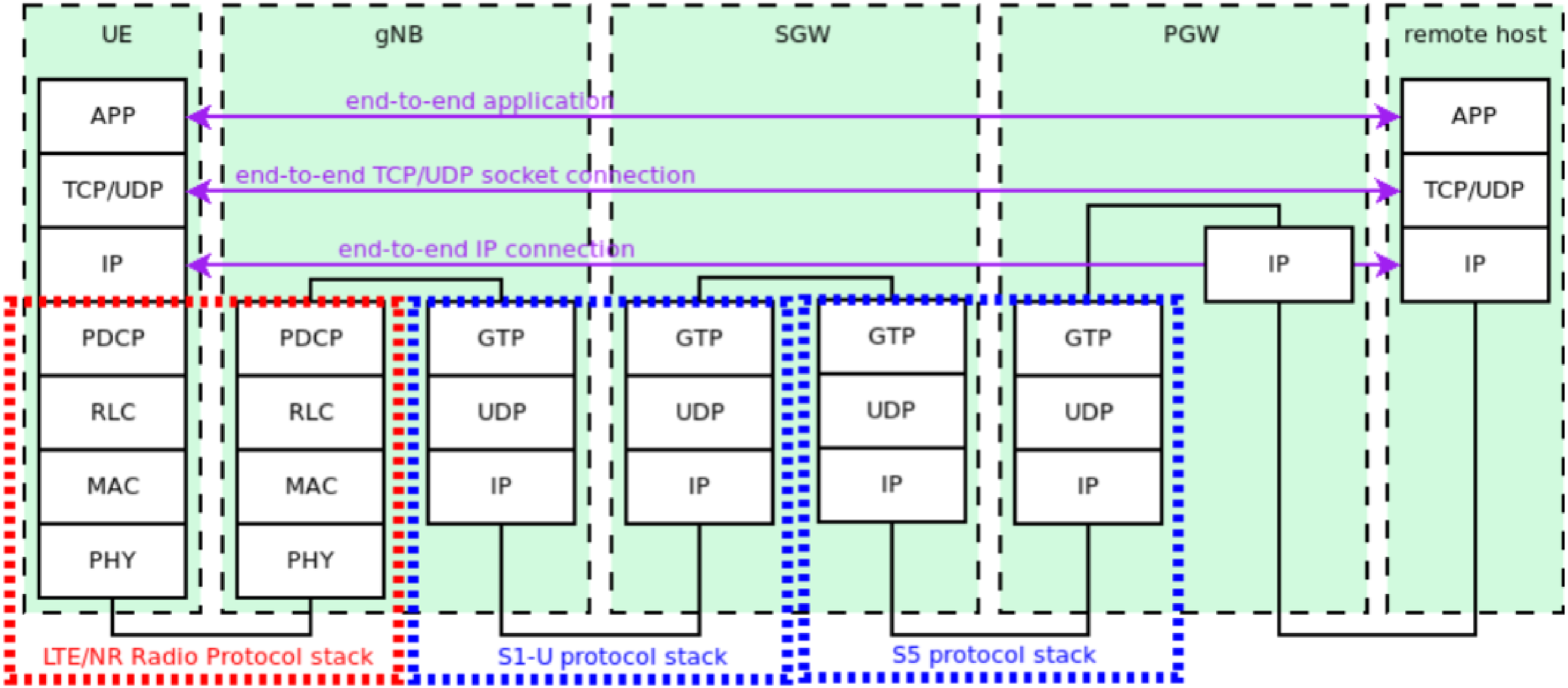
Figure: End-to-end overview

NR END-TO-END ARCHITECTURE OVERVIEW

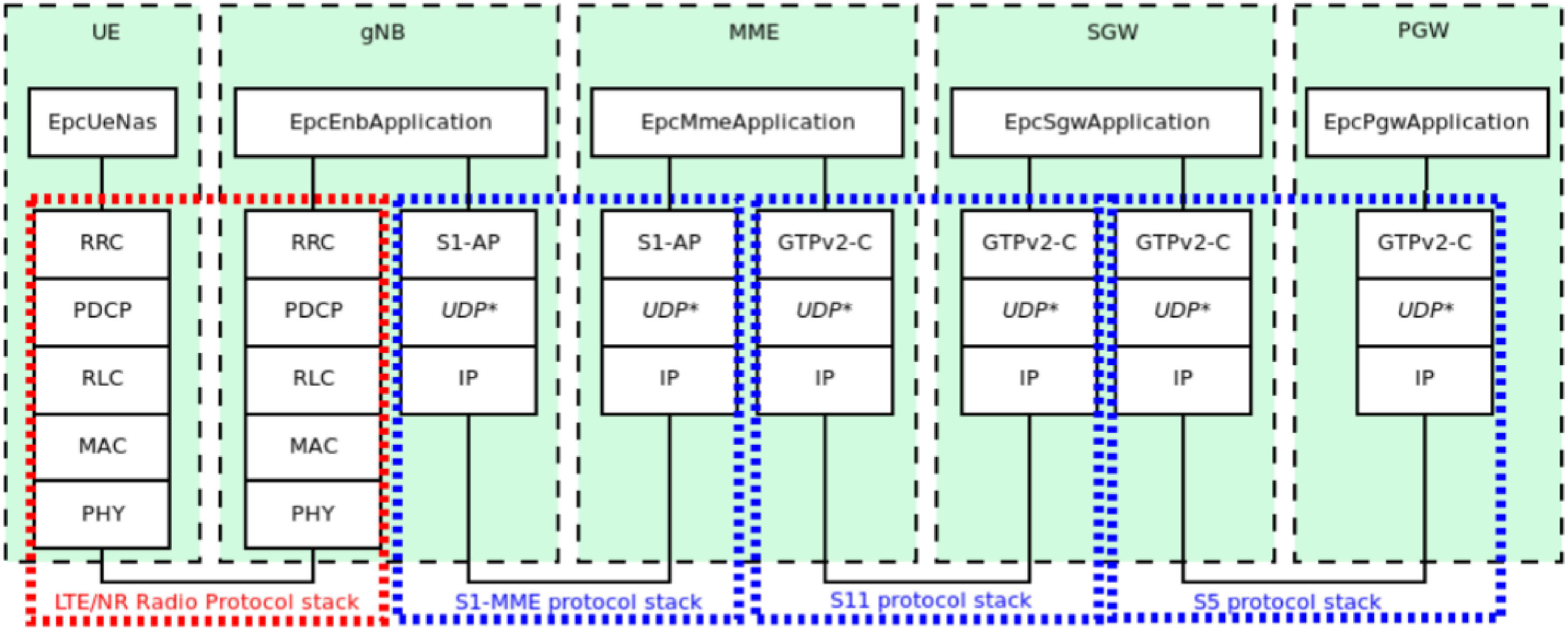


LTE/NR DATA PLANE PROTOCOL STACK

- Currently, the NR module relies on LTE modules for layers above MAC (RLC, PDCP, NAS, RRC and EPC)
- New PHY and MAC



LTE/NR CTRL PLANE PROTOCOL STACK

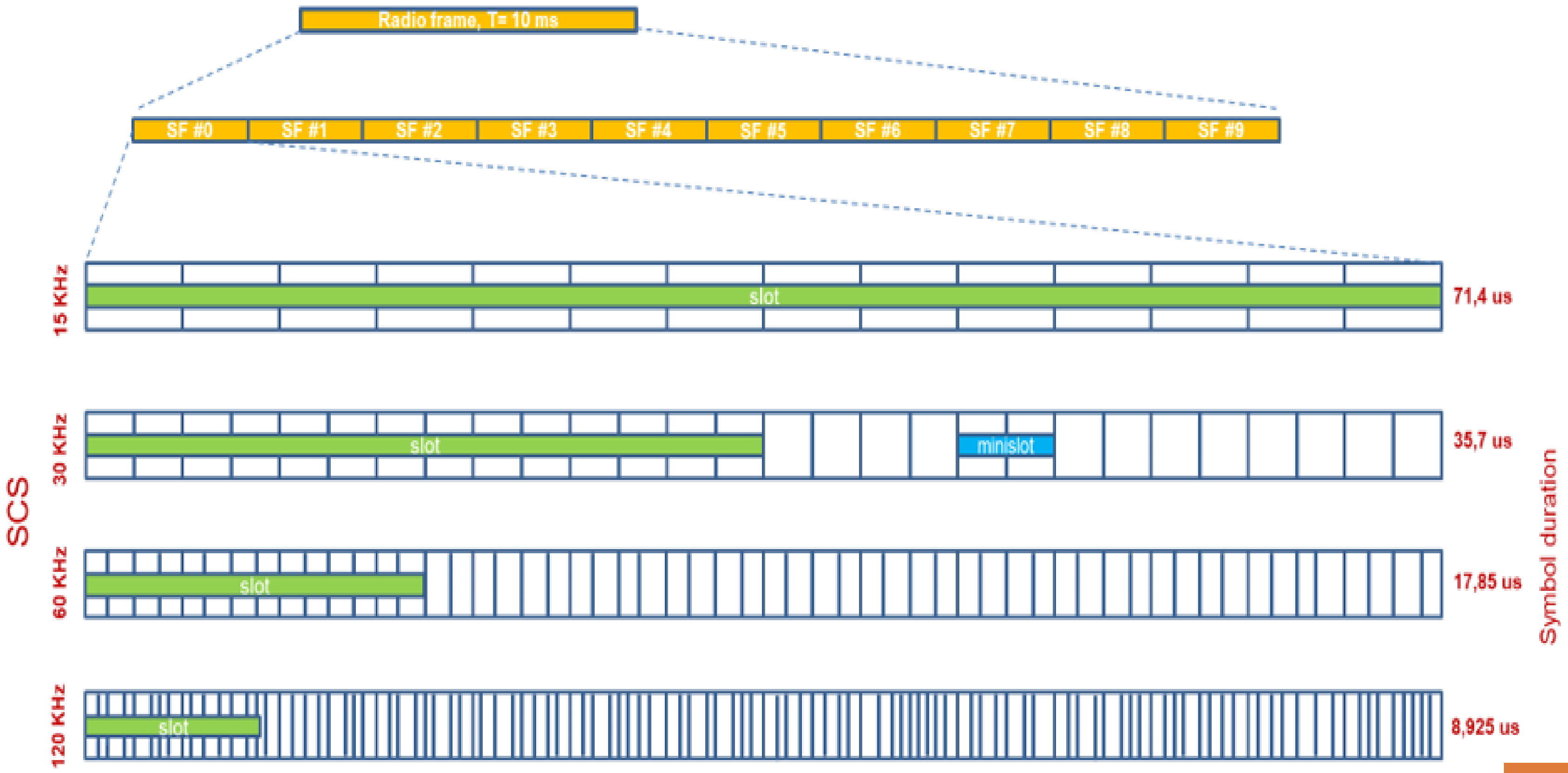


NR PHY LAYER

- Frame structure model and numerologies
- Duplexing schemes
- BWPs and FDM of numerologies
- CQI feedback
- Power allocation
- Interference model
- Spectrum model
- Abstraction model for error modeling
- Antenna model
- Beamforming model
- SRS transmission and reception
- Uplink power control
- HARQ
- SU-MIMO

NR PHY: FRAME STRUCTURE MODEL AND NUMEROLOGIES

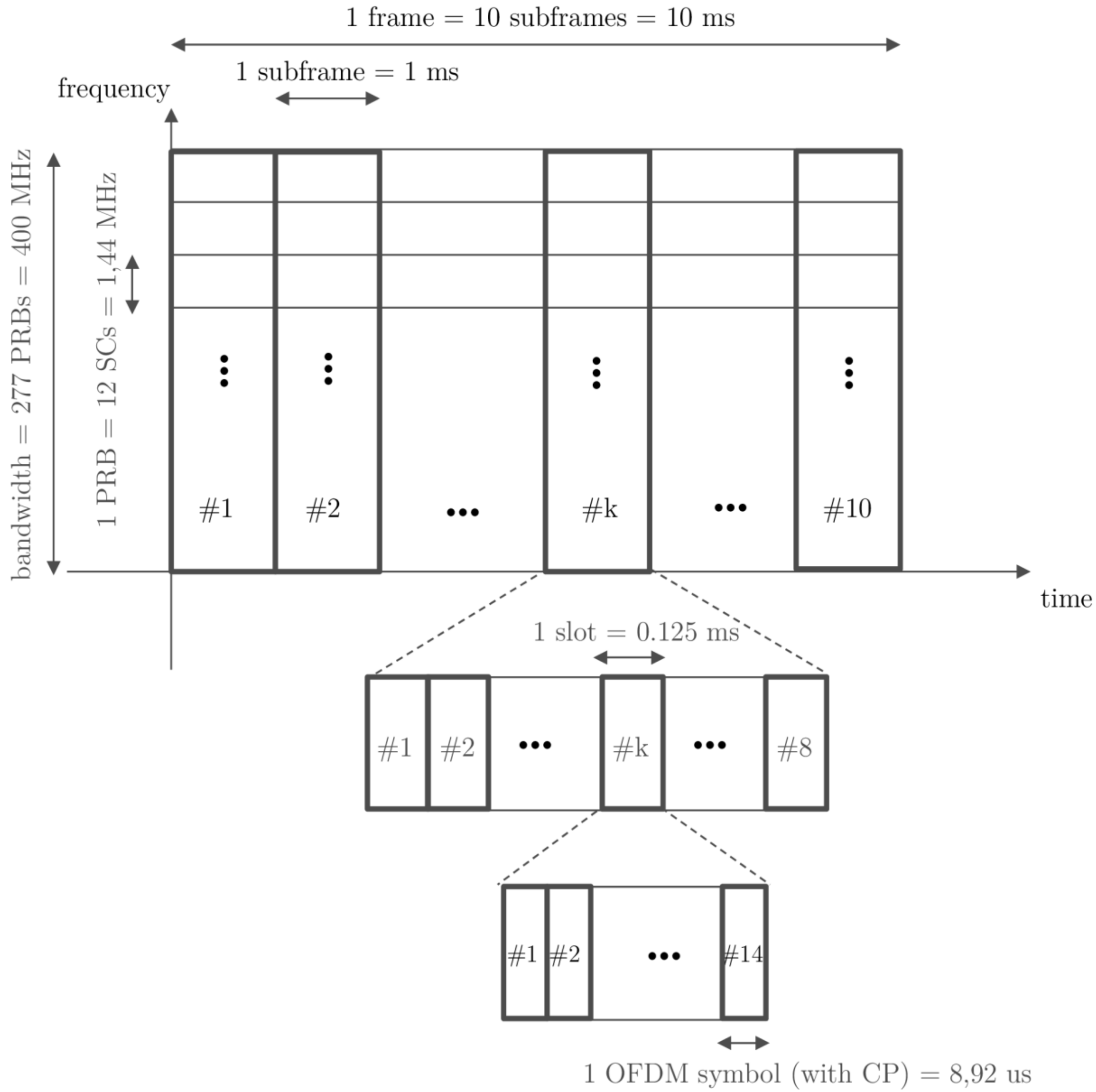
- In 5G NR, the subcarrier spacing (SCS) can range from 15 kHz to 480 kHz
- Flexible numerology results in flexible time/freq-slot structure
- 6 frame structures are currently included in the NR module



NR PHY: FRAME STRUCTURE MODEL AND NUMEROLOGIES

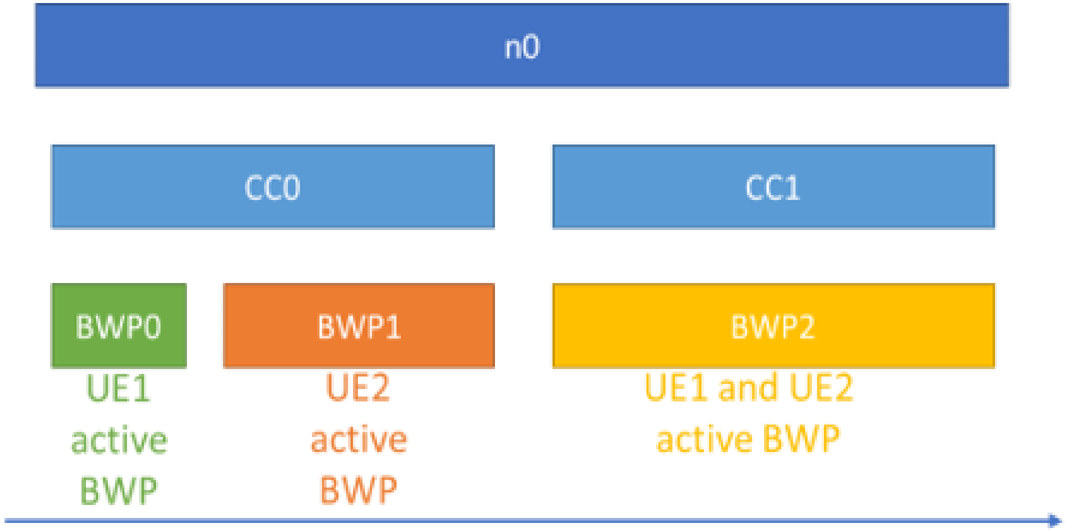
Numerology	0	1	2	3	4	5
Frame length	10ms					
Subframes per frame	10					
Subframe length	1ms					
Slots per subframe	1	2	4	8	16	32
Slot length	1ms	500us	250us	125us	62.5us	31.25us
OFDM symbols per slot	14					
OFDM symbol length	**71.42us**	**35.71us**	**17.85us**	**8.92us**	**4.46us**	**2.23us**
Subcarriers in a PRB	12					
Subcarrier spacing	**15kHz**	**30kHz**	**60kHz**	**120kHz**	**240kHz**	**480kHz**
PRB width	180kHz	360kHz	720kHz	1.44MHz	2.88MHz	5.76MHz

NR PHY: FRAME STRUCTURE EXAMPLE



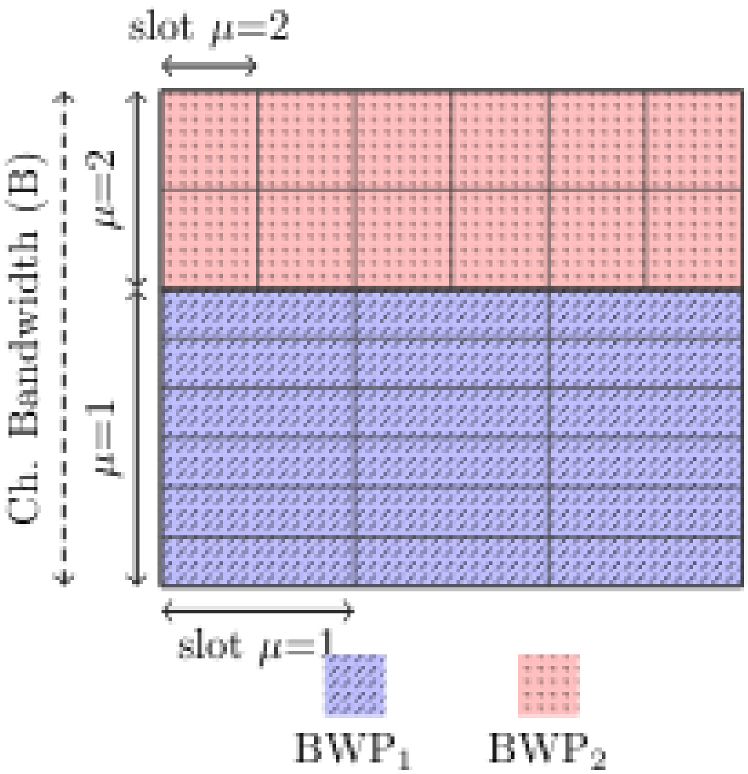
NR PHY: DUPLEXING SCHEMES

- FDD and TDD duplexing modes are supported:
  - Frequency domain granularity: Resource Block (RB)
  - Time domain granularity: Symbol
- FDD/TDD configuration per BWP
- The gNB can simultaneously transmit and receive through different BWPs
- The UE is active in a single BWP at a time (default BWP manager)



NR PHY: FDM OF NUMEROLOGIES

- To address the trade-off between latency and throughput for different types of traffic
- The user can configure FDM bands statically before the simulation starts
- Run time reconfigurations would require RRC improvements



NR PHY: TDD

- UL and DL configured through a TDD pattern
- TDD pattern represented by a vector of **slot** types
- Supported slot types:
  - DL-only (“D”)
  - UL-only (“U”)
  - Flexible (“F”)
  - Special (“S”)
- Example: [D D D F U]

NR PHY: FDD

- Assumes usage of two paired bandwidth parts: one dedicated to for DL data and CTRL, and the other for the UL data and CTRL

- Paired BWPs have to be configured with the same numerology

- The user should configure each bandwidth part with a DL-only or UL-only pattern, for example:
  - DDDDDD
  - UUUUUU

- A link between the two bandwidth parts should be configured for the correct routing of the control messages

- As an example, the HARQ feedback for a DL transmission will be uploaded through the UL-only bandwidth part, but it applies to the DL-only bandwidth part

NR PHY: CQI FEEDBACK

- CQI is reported by the UE and is used for MCS selection at the gNB for DL data transmissions
- 5G-LENA supports CQI Table1 and Table2 (i.e., Table 5.2.2.1-1 and Table 5.2.2.1-2 from TS 38.214)
- 5G-LENA supports the generation of wideband CQI that is computed based on the data channel (PDSCH)
- Such value represents the average state of the RBs that have been used (neglecting RBs with 0 transmitted power)
- The AMC module maps the SINR measurement to a CQI index
- CQI is computed for each PDSCH reception and reported after it

NR PHY: POWER ALLOCATION

- The NR module supports two types/models for power allocation:
  - uniform power allocation **over the whole BW**, i.e., power per RB is fixed
  - uniform power allocation over **the active RBs,** i.e., power per RB depends on the number of the active RBs
- If an RB is not allocated to any data transmission, the transmitted power over it is 0, and no interference is generated in that RB
- Implemented in: **nr-spectrum-value-helper.h/cc**
- Configurable through the attribute **PowerAllocationType** of **NrGnbPhy** and **NrUePhy** classes

NR PHY: INTERFERENCE MODEL

- The interference model is based on the Gaussian interference models, according to which the overall interference is the sum of powers of interfering signals
- The interference model calculates the SNR, the SINR, and the RSSI
- SINR computation is based on PDSCH
- Implemented in: ***nr-interference.h/cc***

NR PHY: SPECTRUM MODEL

- The spectrum module handles the signal propagation through the wireless channel
- Each BWP is modeled through a separate instance of the spectrum channel
- Each NR device will have as many PHY instances as it supports BWPs
- NR module support for the ns-3 spectrum is implemented in: ***nr-spectrum-phy.h/cc***
- In FDD system, the PHY instance attaches as a listener only to the channel instance on which the device is listening
- In TDD system, the same device can transmit and receive through the same spectrum channel instance

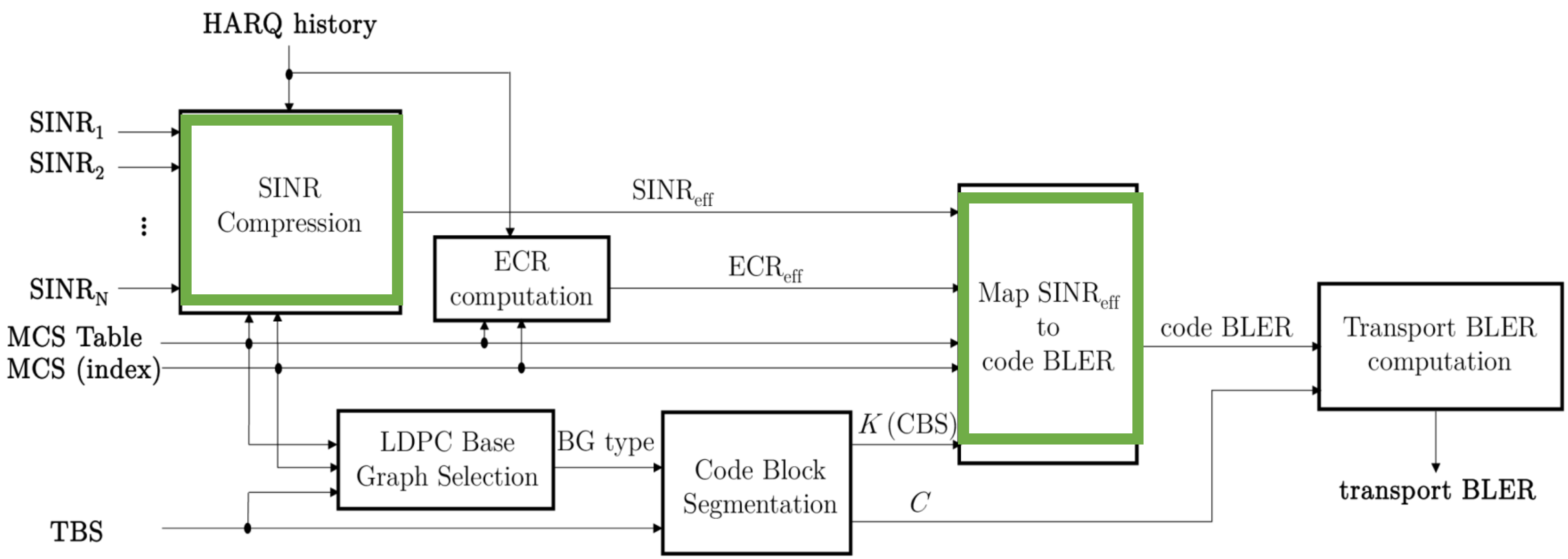
*B. Bojovic, Z. Ali, S. Lagen, **ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO**, in Workshop on ns-3, June 2022.*

NR PHY: ANTENNA MODEL

- Uniform planar arrays (UPA) specified by the number of antennas in each dimension, by the number of horizontal and vertical ports, and if it is dual-polarized
- Antenna elements:
  - Isotropical radiation, or
  - Directional radiation (based on the 3GPP model, using vertical and horizontal radiation patterns in TR 38.901)

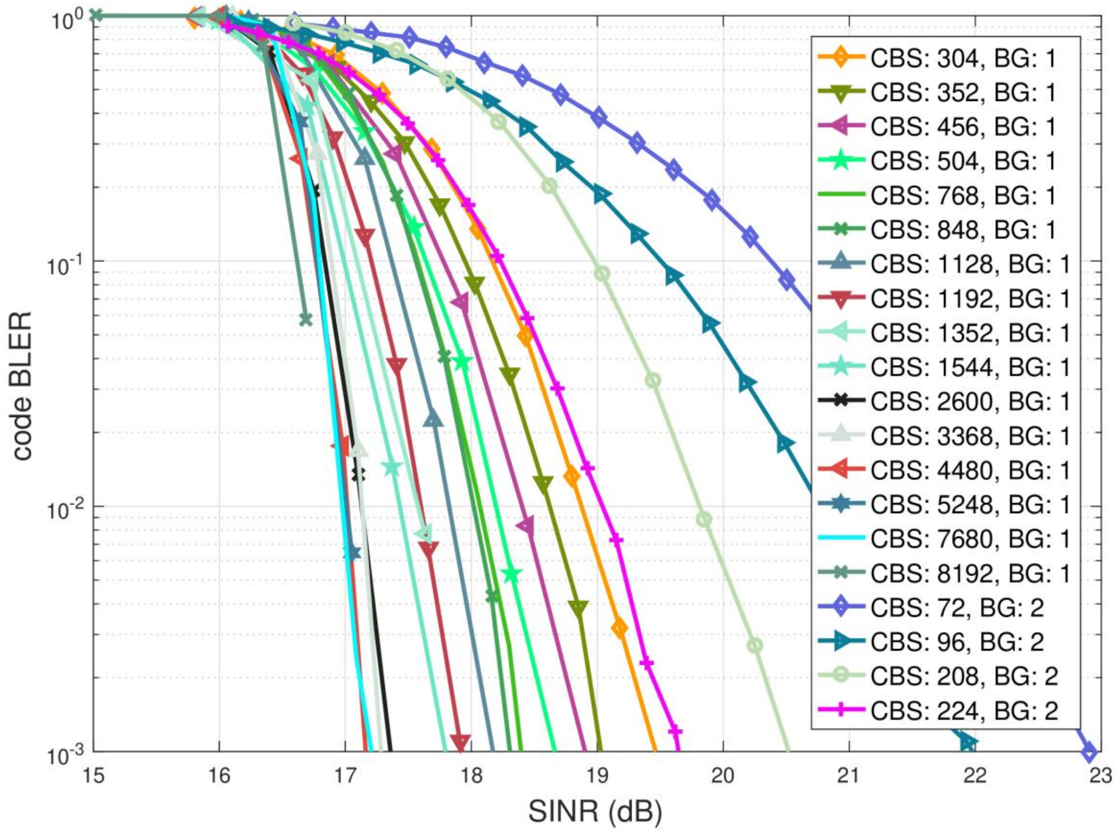
NR PHY: ABSTRACTION MODEL FOR ERROR MODELING

- L2SM abstraction based on the Exponential Effective SNR Metric (EESM)
- BLER-SINR curves provided by InterDigital:
  - MCS table 1 (64QAM) and MCS table 2 (256QAM), as per TS 38.214
  - LDPC BG1 and BG2, and
- BG selection and block segmentation for LDPC as per TS 38.212



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 ICC, 7-11 June 2020, Dublin (Ireland).*

NR PHY: BLER-SINR CURVES



- Example: MCS23 of MCS Table 1
- Look up tables available in: **ns-3-dev/src/nr/model/nr-eesm-t1.cc** and **nr-eesm-t2.cc**

NR PHY: BEAMFORMING MODEL

- Beamforming of the UPA is specified by means of the beamforming (BF) vector
- Multiple antennas are used to concentrate the radiated power towards the receiver's location
- NR module supports ideal and realistic analog BF methods
- All these methods are **analog BF methods**
- However, the ns-3 BF vectors are ready to support hybrid and digital BF

B. Bojovic, S. Lagen, L. Giupponi, ***Realistic beamforming design using SRS-based channel estimate for ns-3 5G-LENA module****, in Workshop on ns-3, June 2021.*

NR PHY: BEAMFORMING MODEL

Ideal BF methods:

- no physical resource is employed
- ideal channel state acquisition is assumed
- computed offline, i.e., no real training, no BF overhead.
- Ideal BF methods supported by the NR module are:
  - **Beam-search method**
  - **LOS-path method**

B. Bojovic, S. Lagen, L. Giupponi, ***Realistic beamforming design using SRS-based channel estimate for ns-3 5G-LENA module****, in Workshop on ns-3, June 2021.*

NR PHY: BEAMFORMING MODEL

Realistic BF:

- For TDD systems, based on SRS reception
- An abstraction model estimates the channel matrix

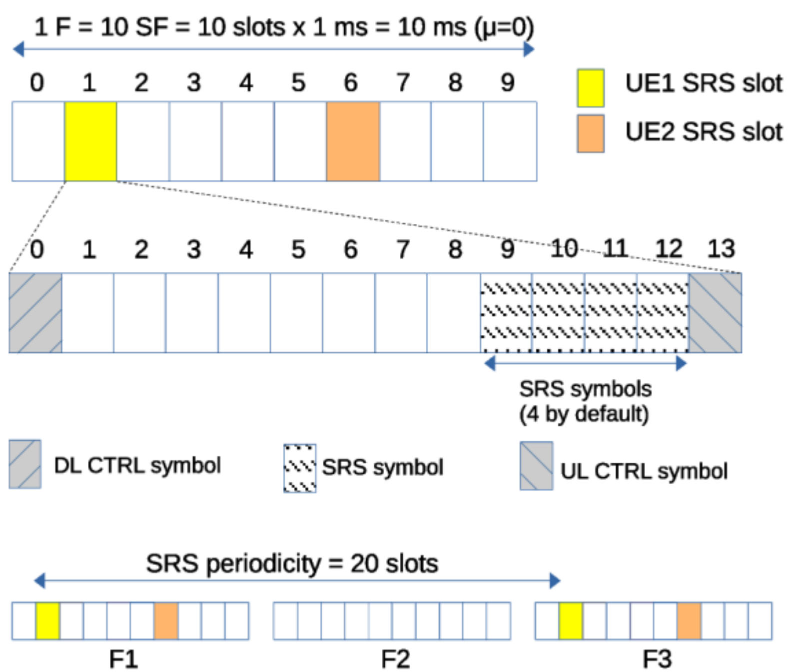
B. Bojovic, S. Lagen, L. Giupponi, ***Realistic beamforming design using SRS-based channel estimate for ns-3 5G-LENA module****, in Workshop on ns-3, June 2021.*

NR PHY: SRS TRANSMISSION AND RECEPTION

- SRS typically spans over 1, 2 or 4 consecutive OFDM symbols at the end of the NR slot
- All subcarriers are used for SRS transmission
- Scheduling-based SRS
- SRS scheduling is implemented in: ***nr-mac-scheduler-srs-default.h/cc***

NR PHY: SRS TRANSMISSION AND RECEPTION

- Example of SRS transmissions of 2 UEs
- 1 UE SRS per slot in 5G-LENA due to granularity in freq
- SRS periodicity equal to 20 slots
- Numerology considered is μ = 0
- F stands for frame and SF for subframe



NR PHY: UPLINK POWER CONTROL

- Uplink Power Control (ULPC) allows to adjust the transmission power of a UE
- Plays a critical role in reducing inter-cell Interference
- NR uplink power control implementation supports both TS 36.213 for 4G LTE, and TS 38.213 for 5G NR
- The uplink power control supports the open and closed UL PC for:
  - PUSCH
  - SRS
  - PUCCH
- Implemented in: ***nr-ue-power-control.cc***

NR PHY: UPLINK POWER CONTROL

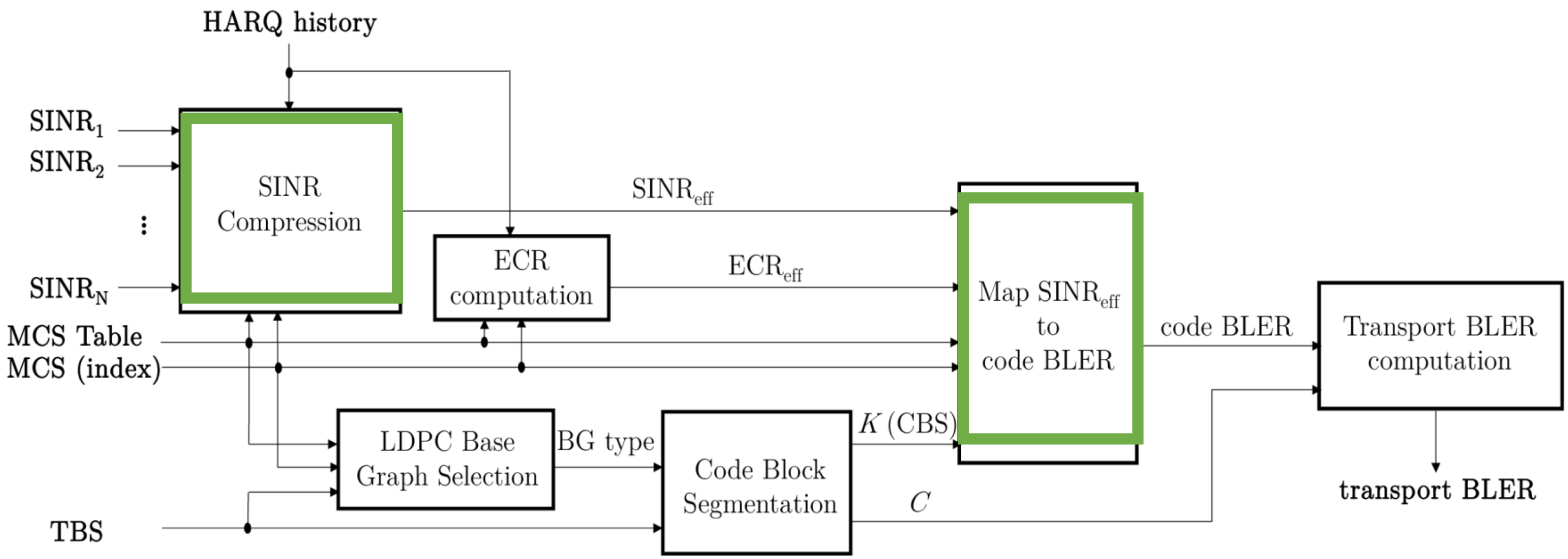
- In the open loop the UE transmission power depends on the estimation of the downlink path loss
- In closed loop, the gNB can control the UE transmission power by means of explicit TPC included in the DCI
- In closed Loop, two modes are available:
  - **the absolute mode**
  - **the accumulation mode**

NR PHY: HARQ

- A configurable number of HARQ processes
- HARQ is integrated in the error model and supports up to 4 redundancy versions (RV) per each HARQ block
- The retransmission maintains the MCS and number of allocated resource element groups of the original blocks

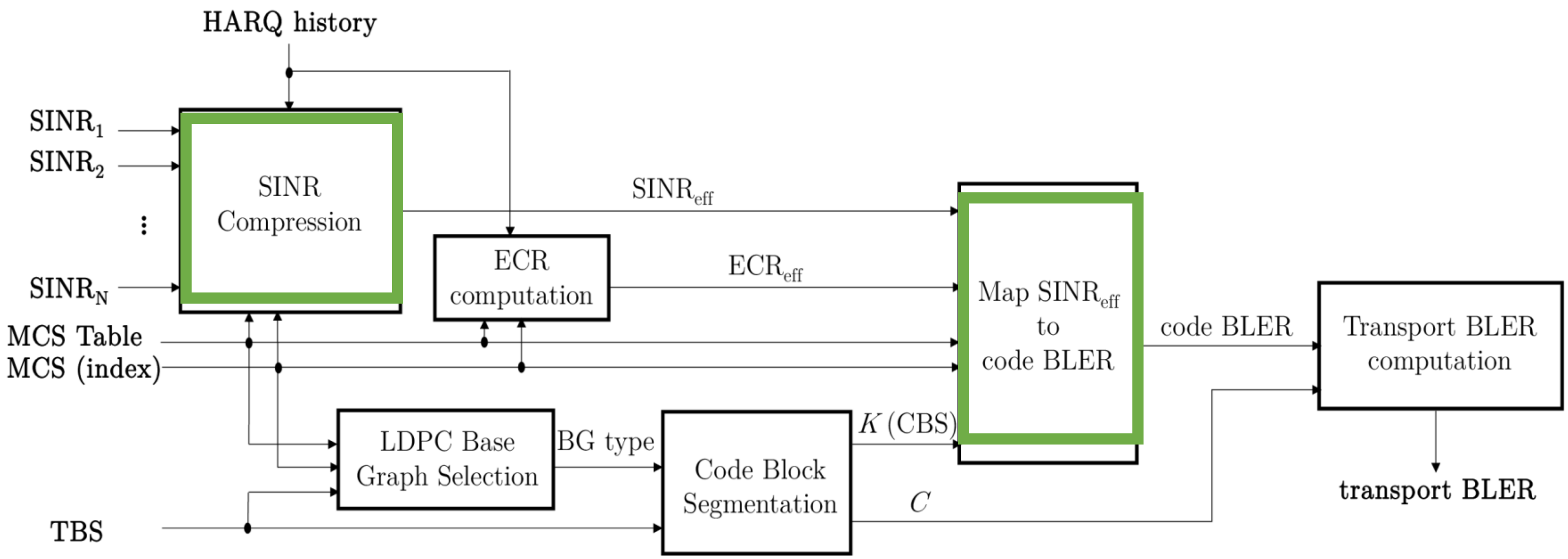
NR PHY: HARQ

- Two methods for PHY abstraction for HARQ:
  - HARQ-IR changes the effective SINR and the ECR
  - HARQ-CC changes the effective SINR



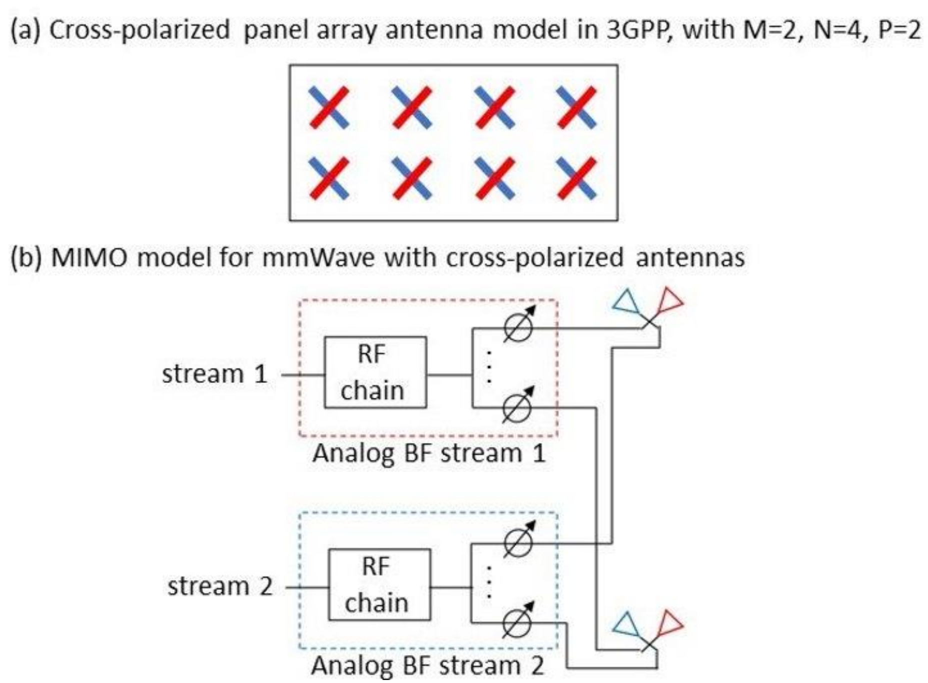
NR PHY: HARQ

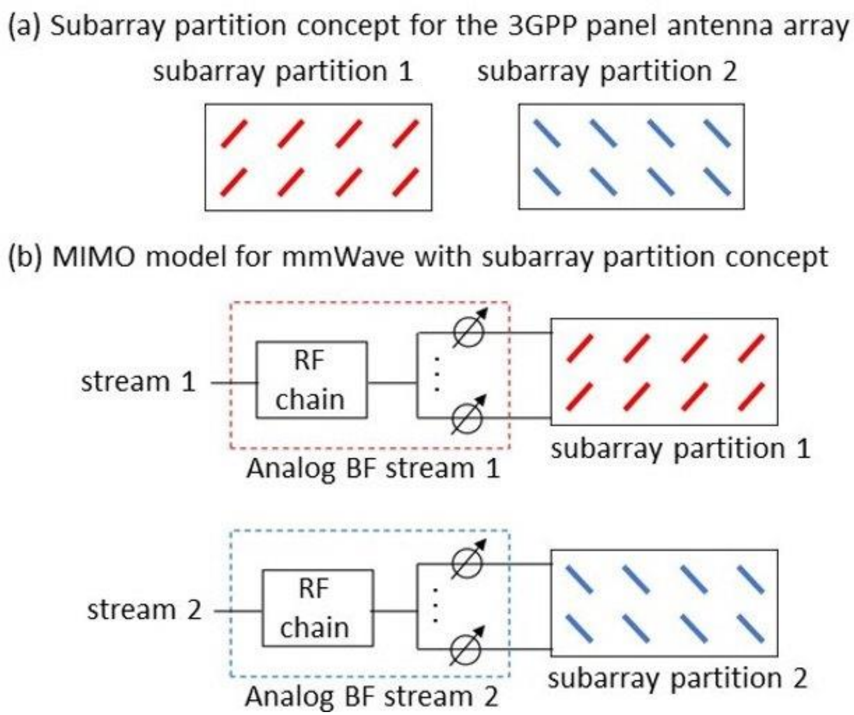
- We consider the bits to be combined, to enable flexible NR scheduling decisions in time/freq domains.
- Implemented in: ***nr-eesm-cc.h/cc, nr-eesm-cc-t1.h/cc, nr-eesm-cc-t2.h/cc, nr-eesm-error-model.h/cc, nr-eesm-ir.h/cc, nr-eesm-ir-t1.h/cc, nr-eesm-ir-t2.h/cc***



NR PHY: SU-MIMO (OLD IMPLEMENTATION)

- Dual-Polarized MIMO model is supported, exploiting dual-polarized antennas, under line-of-sight conditions:
  - Up to 2 streams per user, rank indicator reporting and rank adaptation algorithms





*B. Bojovic, Z. Ali, S. Lagen, **ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO**, in Workshop on ns-3, June 2022.*

NR PHY: SU-MIMO (NEW IMPLEMENTATION)

- 3GPP-compliant SU-MIMO simulation model TS38.214
- Hybrid beamforming spatial multiplexing + beamforming in analog and digital domain
- Closed-loop MIMO feedback including precoding and rank (PMI and RI)
- Type-I codebook-based precoding: W = W1 * W2
- CSI computation based on PDSCH
- An exhaustive search is used for PMI/RI selection
- 5G-LENA 3.0 up to 2 ports (2 streams)
- Soon: up to 32 antenna ports and 4 streams

NR MAC LAYER

- OFDMA and TDMA resource allocation
- Scheduler
- Timing relations
- BWP Manager
- Adaptive modulation and coding
- Transport block model
- Notching
- SU-MIMO

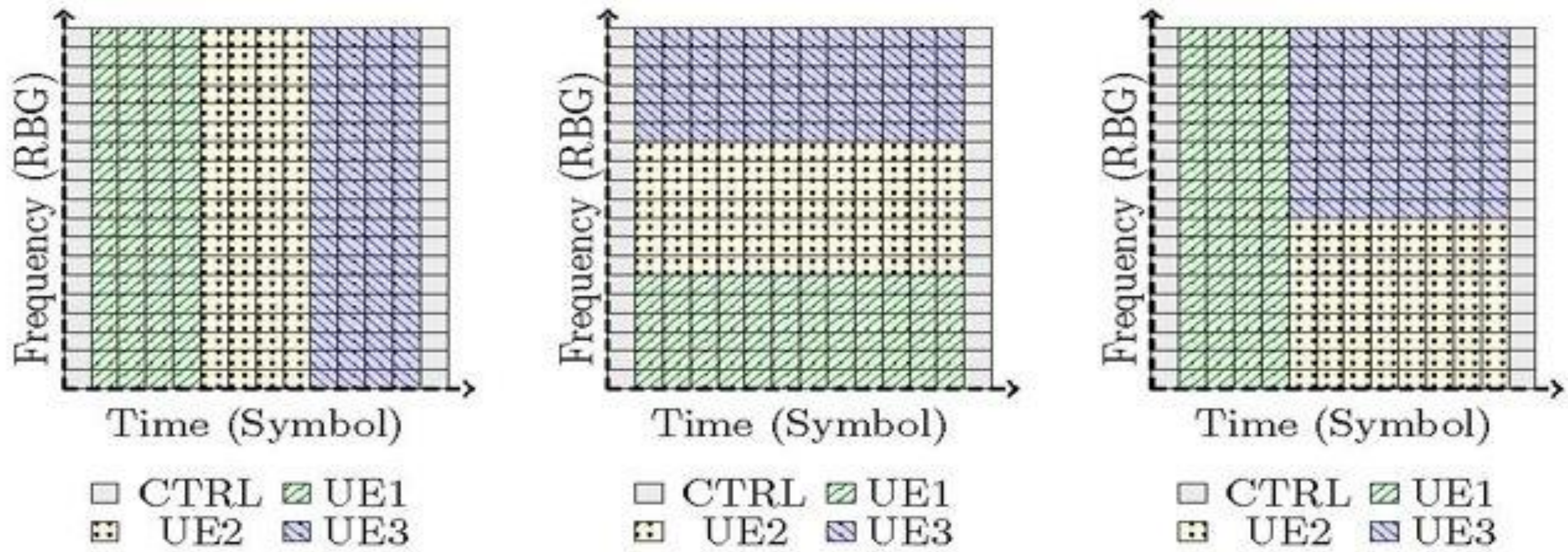
NR MAC: OFDMA AND TDMA

- Support of both OFDMA and TDMA in UL and DL:
- Single-beam capability:
  - Only a single receive or transmit beam can be used at any given time instant
  - UEs that are served by different beams cannot be scheduled at the same time
  - Inside the same beam, UEs can be differentiated in frequency
- Variable TTI:
  - number of allocated symbols to one user is variable, based on the scheduler allocation, and not fixed as in LTE

NR MAC: OFDMA AND TDMA

- Depending on the SCS and the operational band, RBs are grouped into RBGs
- RBGs: 2, 4, 8, or 16 RBs based on Table 5.1.2.2.1-1 [TS 38.214]
- For decoding: the scheduler generates a bitmask sent to the UE through the DCI
- The length of the bitmask is the number of RBGs, to indicate the RBGs assigned to the UE
    - In TDMA the bitmask has all bits set to 1
    - In OFDMA, 1s are only set to RBGs where the UE has to listen

NR MAC: OFDMA AND TDMA



(a) Pure TDMA scheme. (b) Pure OFDMA scheme. (c) OFDMA with variable TTI scheme.

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).*

NR MAC: ADAPTIVE MODULATION AND CODING (AMC)

- Two AMC models for link adaptation:
  - Error model-based:
    - The MCS index is selected to meet a target transport BLER (e.g., 0.1)
  - Shannon-based:
    - Chooses the highest MCS that gives a spectral efficiency lower than the one provided by the Shannon rate
- The MCS can be fixed to a predefined value, both for DL and UL transmissions

NR MAC: BWP MANAGER

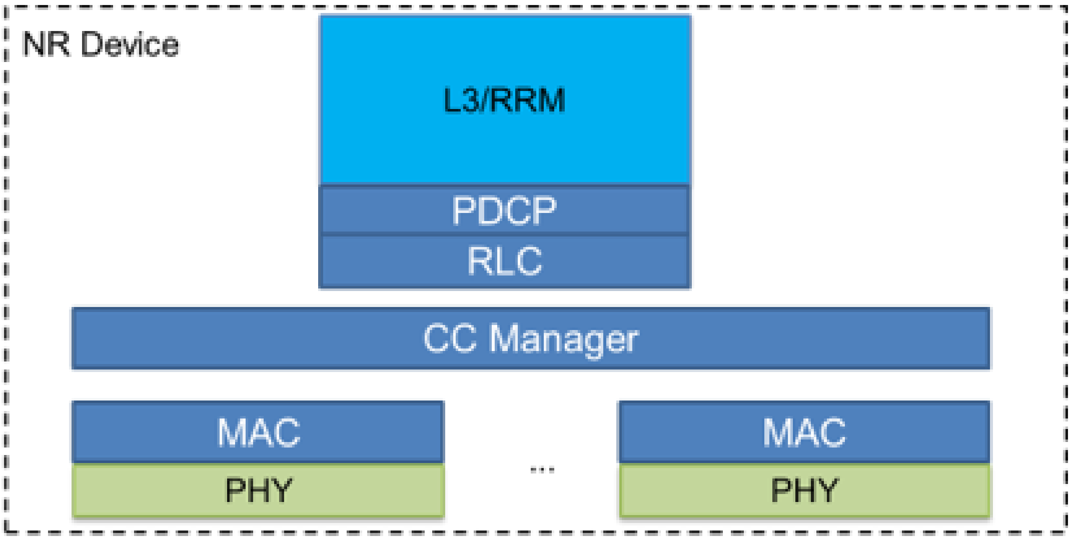
- Model can be used for FDM of numerologies: orthogonal allocation of multiple BWPs, or carrier Aggregation (multiple CCs)
- Each BWP has its own MAC and PHY instances
- Each BWP can be configured differently: MAC scheduler, PHY parameters (i.e., BW, numerology, power, etc), TDD pattern,...
- Each BWP has its own control and data channels
- HARQ processes are maintained per BWP.
- There is at least 1 BWP which is considered as primary and SIB/MIB are sent through it to enable UEs attachment
- The BWP configuration is static during the simulation

*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).*

NR MAC: BWP MANAGER

BWP/CC manager:

- Allocates flows to BWP based on their QCI (FDM of numerologies strategy for multiple BWPs)
- Other rules/algorthims for CC manager can be implemented.



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).*

NR MAC: TRANSPORT BLOCK AND MAC PDU

- The model multiplexes RLC PDUs onto MAC PDUs
- Only one MAC PDU can be transmitted per TB per MAC entity
- Differently from LTE module models, we progressed towards a real model of MAC headers and control elements (CE)
- The Buffer Status Report is modeled as a MAC CE

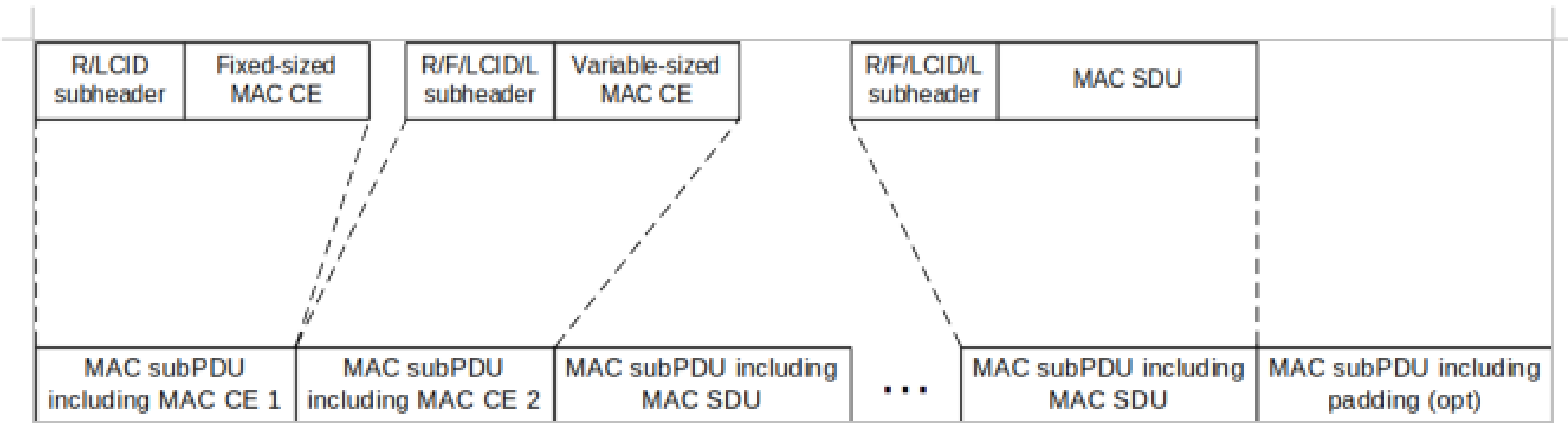


Figure 6.1.2-4: Example of a DL MAC PDU

NR MAC: TRANSPORT BLOCK SIZE

- The TBS is based on TS 38.214, Section 5.1.3.2 (DL) and 6.1.4.2 (UL).
- TBS is computed as follows:

$$N_{info} = R \times Q \times n_s \times n_{rb} \times (12 - n_{refSc})$$

  - R is the Effective Code Rate (ECR) of selected MCS
  - Q is the modulation order
  - ns is the number of allocated OFDM symbols
  - nrb is the number of allocated RBs
  - nrefSc is the number of reference subcarriers carrying DMRS (Demodulation reference signal) per RB
- The CRC attachment to the TB is subtracted (24 bits)

NR MAC: SCHEDULING

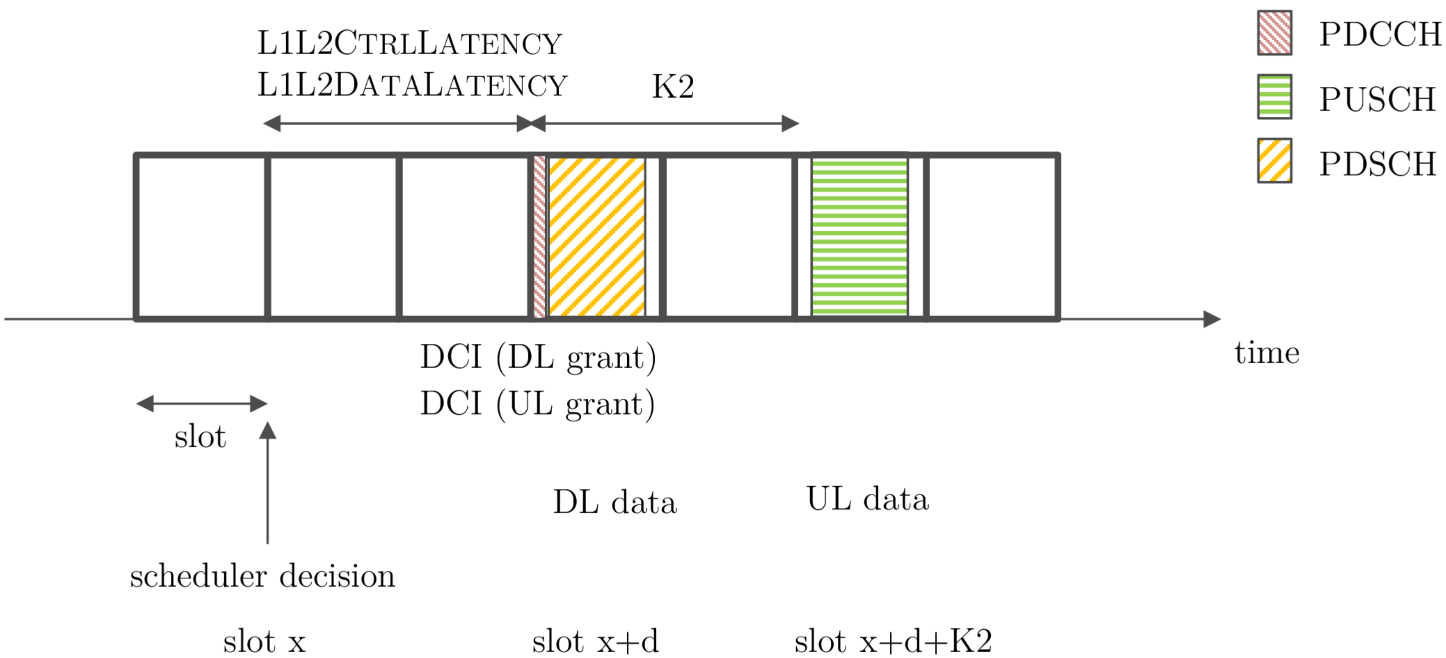
- Dynamic scheduled based access for DL (as LTE)
- UL grant-based (as LTE)
- HARQ has priority over new data transmissions
- UL has priority over DL
- Scheduling algorithms supported: PF/RR/MR/QoS
- Different types of scheduling:
  - OFDMA – symbols divided among beams
  - TDMA – symbols divided among active UEs

NR MAC: SCHEDULING

- The main output of a scheduler functionality is a list of DCIs for a specific slot including:
  - The transmission starting symbol
  - the duration (in number of symbols)
  - RBG bitmask, in which a value of 1 in the position x represents a transmission in the RBG number x.
- The core class of the NR module schedulers design is ***NrMacSchedulerNs3***
- Schedulers API follows the FemtoForum specification for LTE MAC Scheduler Interface

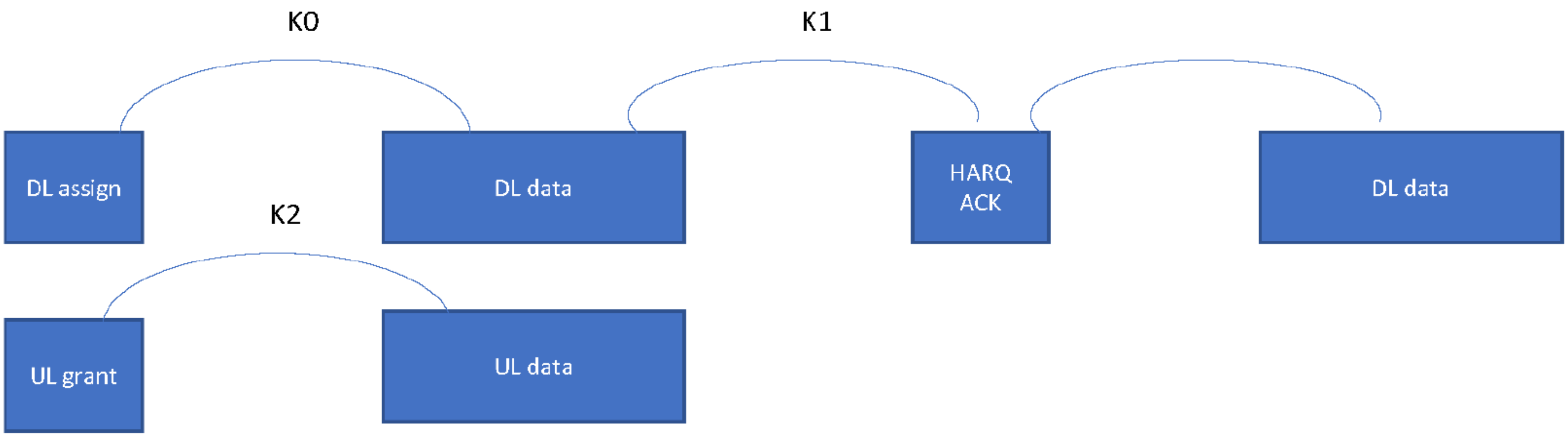
NR MAC: TIMING RELATIONS

- At slot **X** scheduler takes decisions for :
  - DL slot **X + L1L2CtrlLatency**, and
  - UL slot **X + L1L2CtrlLatency + K2**
- Flexible scheduling and DL HARQ feedback timings as specified in [TS 38.213], [TS 38.214]: **K0, K1,** and **K2**



NR MAC: TIMING RELATIONS

- **K0**: Delay in slots between DL DCI reception at UE side and corresponding DL Data (PDSCH) reception
- **K1**: Delay in slots between DL Data (PDSCH) reception at UE side and corresponding ACK/NACK transmission in UL
- **K2**: Delay in slots between UL DCI reception at UE (in DL) and UL Data (PUSCH) transmission.



NR MAC: TIMING RELATIONS

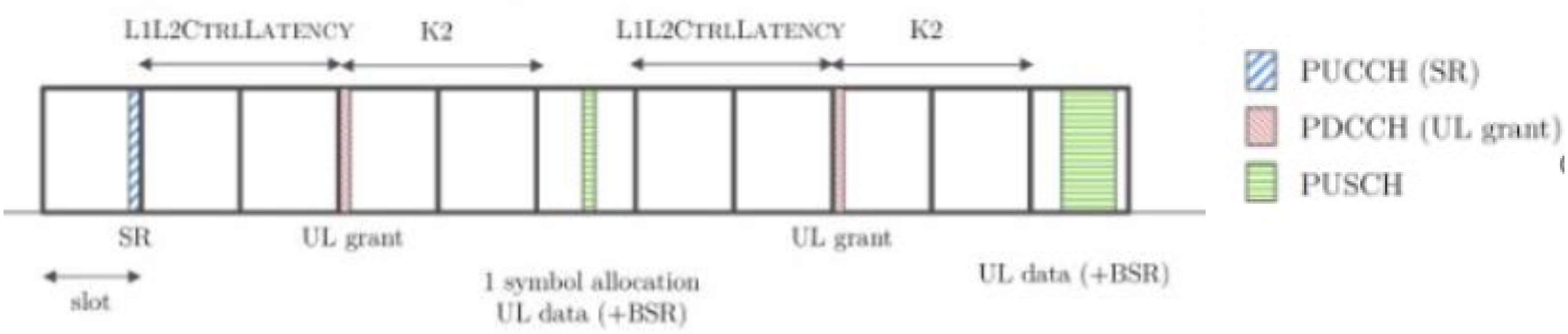
- The values of the K0, K1, K2 depend on:
  - the corresponding processing timings of the UE (N0, N1, N2), i.e., its processing capabilities to decode the DL DCI, DL DATA, UL DCI, and encode HARQ feedback, and UL DATA (see 3GPP R1-1721515)
  - the technology (LTE/NR) and numerology
  - the duplexing mode (FDD/TDD) and in case of TDD, on the configuration (pattern)
- When the eNB/gNB calculates the scheduling timings (K0, K1, K2), it communicates its values to the UE through the DCI

NR MAC: TIMING RELATIONS

	N0		N1		N2	
	Default Value	Typical Values	Default Value	Typical Values	Default Value	Typical Values
NR TDD	0	0, 1 [38.214 - Table 5.1.2.1.1-2] Often considered as int {0-32}	4	0-15 [Indicated by 38.213 - Table 9.2.3-2]	2	1-6 [38.214 - Table 6.1.2.1.1-2] Often considered as int {0-32}
NR FDD	0	0, 1 [38.214 - Table 5.1.2.1.1-2] Often considered as int {0-32}	4	0-15 [Indicated by 38.213 - Table 9.2.3-2]	2	1-6 [38.214 - Table 6.1.2.1.1-2] Often considered as int {0-32}
LTE TDD	0	0 [Not defined, so corresponds to 0]	4	Depends on TDD pattern K1 ≥ 4 [36.213 - Table 10.1.3-1]	2	K2 ≥ 4 [36-213 - Table 8-2]
LTE FDD	0	0 [Not defined, so corresponds to 0]	4	4 [36.213 - Table 7.3.1-2]	2	4 [36.213 - Section 8.0]

NR MAC: UL SCHEDULING REQUEST (SR)

- The MAC scheduler receives SR and schedules resources in UL after **L1L2 + K2**
- The UE receives UL DCI after **L1L2** and uses additional K2 slots to prepare the data plus the BSR
- At **L1L2 + K2 + 1** the gNB MAC scheduler has received the BSR and prepares the allocation for the UE to transmit such data at **L1L2 + K2 + 1 + L1L2 + K2**



K2 = 2 slots

NR MAC: NOTCHING

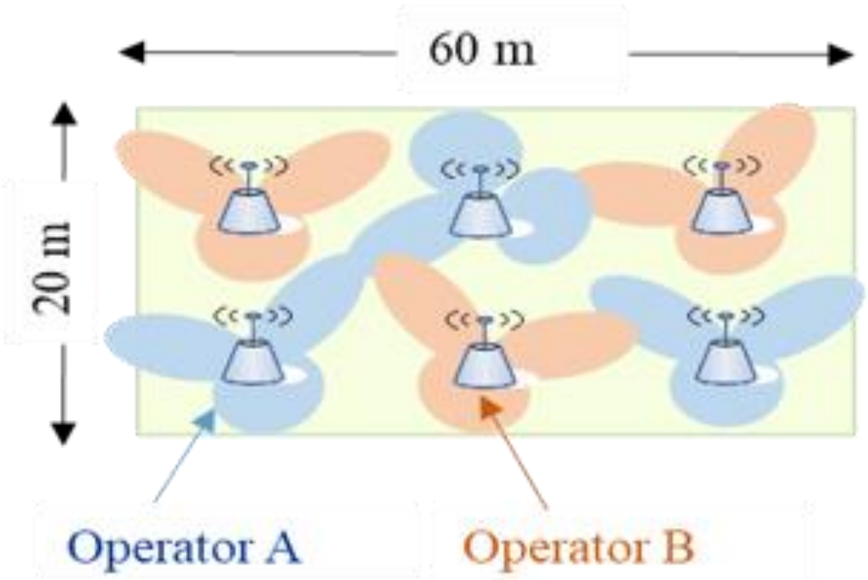
- UL Frequency Avoidance (UFA), aka as spectrum notching
- Notching is a technique that restricts the usage of certain Resource Block Groups (RBGs) for UL transmissions referred to as “notched” RBGs
- The UFA feature is implemented on top of the TDMA/OFDMA scheduler classes:
  - ***NrMacSchedulerTdma*** and
  - ***NrMacSchedulerOfdma***
- Based on the notching mask, the scheduler performs scheduling, i.e., skips the notched RBGs

NR MAC: NOTCHING

- The notching bitmask:
  - Defines the resources per gNB that can and cannot be assigned for its DL and/or UL transmissions
  - Comprised by 1s (normal RBGs) and 0s (notched RBGs)
  - The index of the position of each bit inside the mask corresponds to each RBG index
  - The length depends on the BW
  - An example: 1 1 1 1 1 0 1 1 1 1 1 0 0 0 0 1 1 1 1 0 1 1 1 1

NR-U EXTENSION

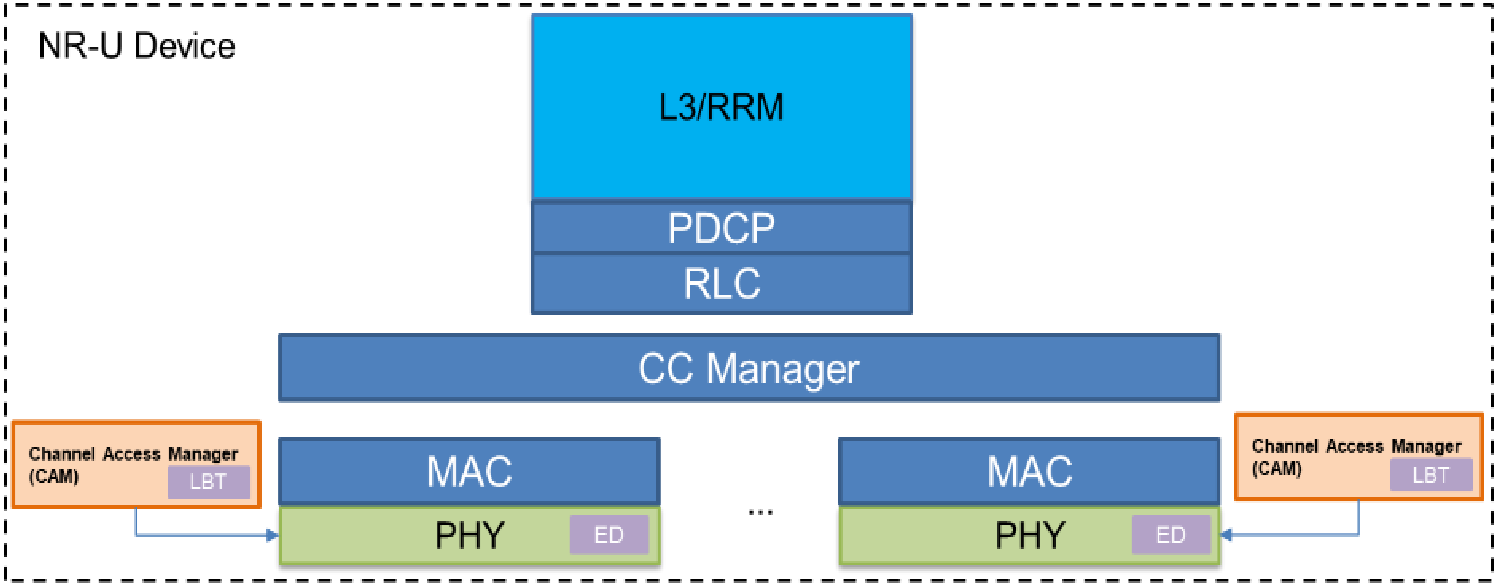
- Collaboration with Interdigital
- More than 2 years of collaboration between 2017 and 2019
- Implement and study NR-U and WiGig coexistence at 60 GHz



*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.*
*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 Commun. Surveys & Tutorials, Oct. 2019*

NR-U EXTENSION

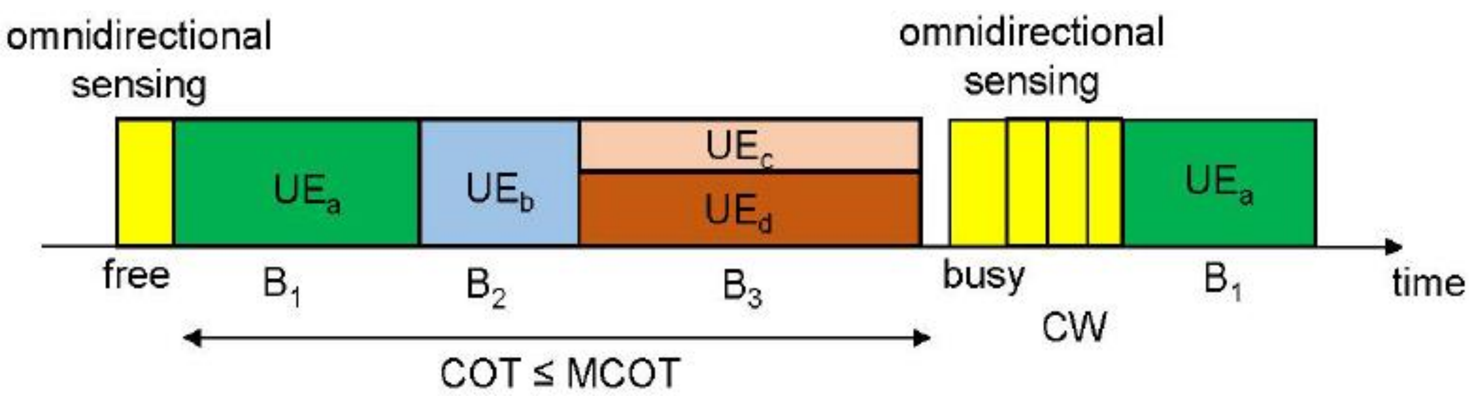
- Open-source network simulator for NR/NR-U/WiGig evaluations
- Publications, patents, knowledge generation



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.*
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 Commun. Surveys & Tutorials, Oct. 2019*

NR-U EXTENSION: FEATURES

- LBT after MAC
- CAM: AlwaysOn, OnOff, LBT (Cat2, Cat3, Cat4)
- NR-U and WiGig coexistence at 60 GHz
- Energy detection (omni)



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.*
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 Commun. Surveys & Tutorials, Oct. 2019*

NR V2X EXTENSION

- Collaboration with NIST (US)
- Features developed in the first release of NR-V2X (1):
  - 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

(1) Z. Ali, S. Lagen, L. Giupponi, R. Rouil, ***3GPP NR V2X Mode 2: Overview, Models and System-level Evaluation****, IEEE Access, vol. 9, pp. 89554-89579, June 2021*
(2) T. Zugno, M. Drago, S. Lagen, Z. Ali, M. Zorzi, ***Extending the ns-3 Spatial Channel Model for Vehicular Scenarios****, in Workshop on ns-3, June 2021*

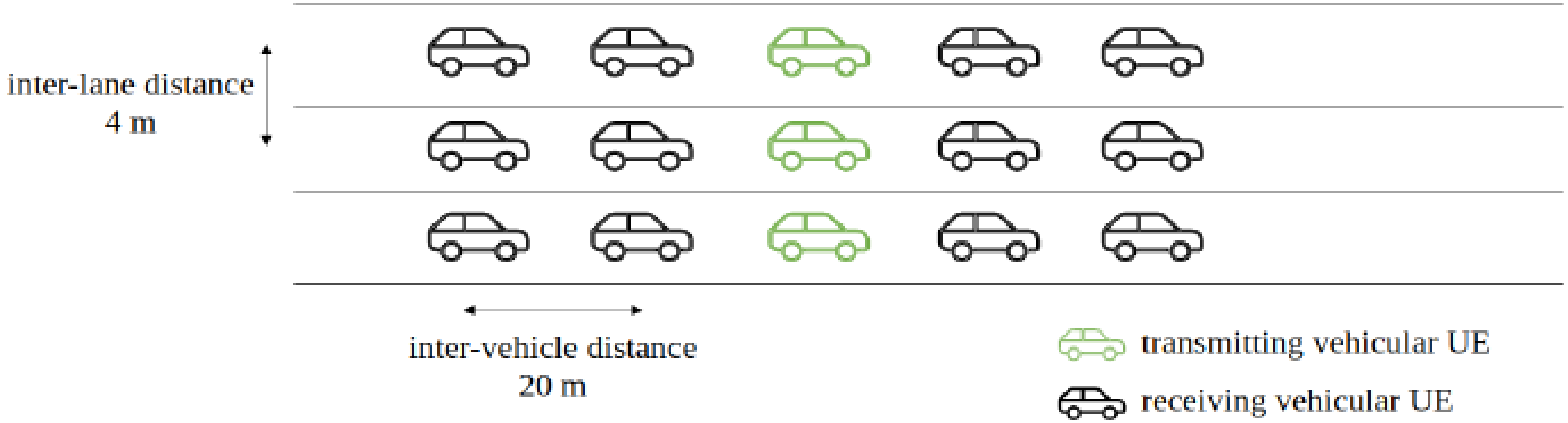
NR V2X EXTENSION

- Collaboration with NIST (US)
- Features developed in the first release of NR-V2X (2):
  - Time multiplexing of PSCCH and PSSCH, frequency multiplexing
  - Blind retransmissions, no feedback. HARQ, feedback channel (PSFCH)
- Using ns-3-dev propagation models for V2V-highway and V2V-urban 3GPP TR37.885 (2)

(1) Z. Ali, S. Lagen, L. Giupponi, R. Rouil, ***3GPP NR V2X Mode 2: Overview, Models and System-level Evaluation****, IEEE Access, vol. 9, pp. 89554-89579, June 2021*
(2) T. Zugno, M. Drago, S. Lagen, Z. Ali, M. Zorzi, ***Extending the ns-3 Spatial Channel Model for Vehicular Scenarios****, in Workshop on ns-3, June 2021*

NR V2X EXTENSION

- An example of the scenario that can be simulated by using NR-V2X



(1) Z. Ali, S. Lagen, L. Giupponi, R. Rouil, ***3GPP NR V2X Mode 2: Overview, Models and System-level Evaluation****, IEEE Access, vol. 9, pp. 89554-89579, June 2021*
(2) T. Zugno, M. Drago, S. Lagen, Z. Ali, M. Zorzi, ***Extending the ns-3 Spatial Channel Model for Vehicular Scenarios****, in Workshop on ns-3, June 2021*

NR-U EXTENSION: LBT AND ED

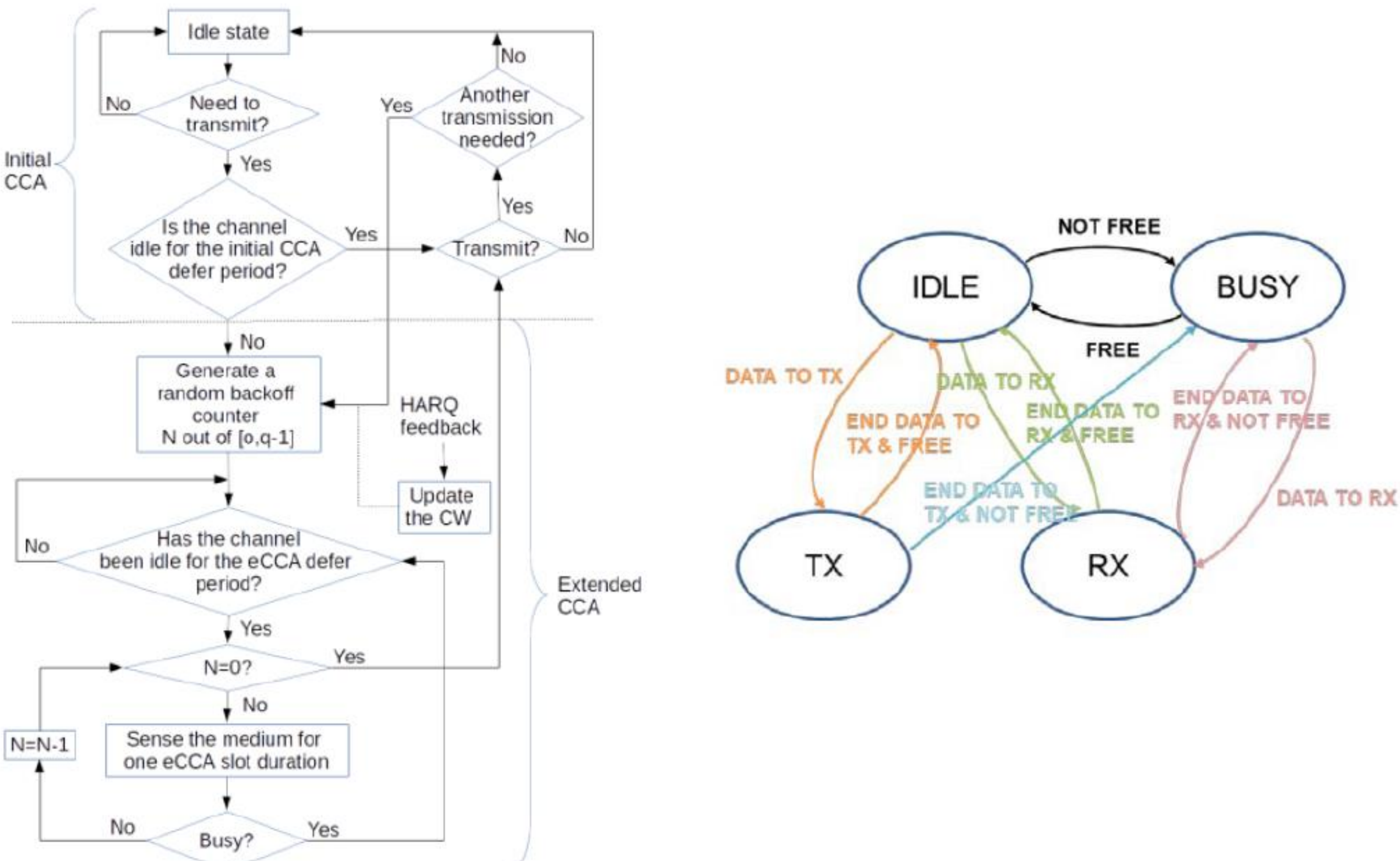
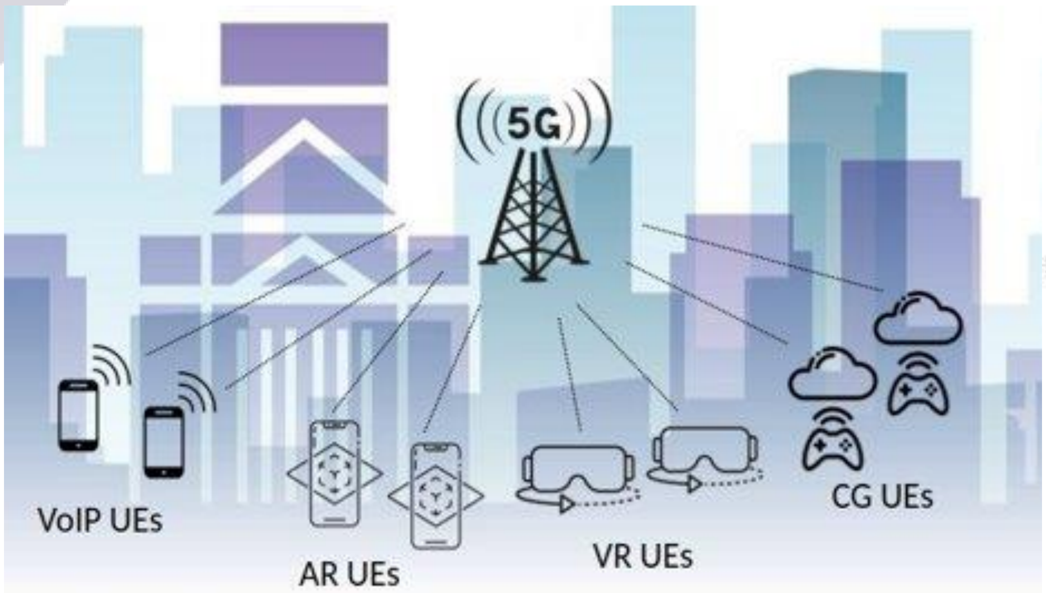
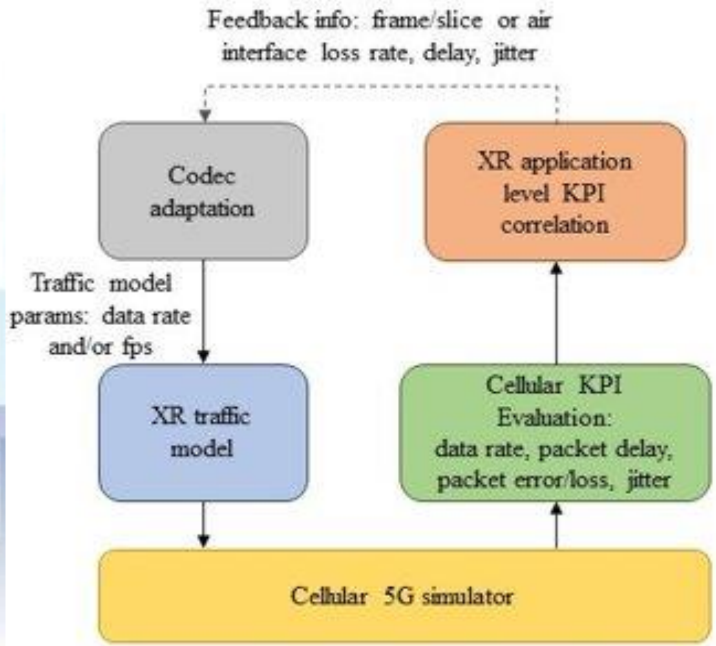


Figure: Listen Before Talk

XR (AR, VR, CG) IN 5G-LENA THANKS TO META

Collaboration with Facebook/Meta (US)





1) B. Bojovic, S. Lagen, K. Koutlia, X. Zhang, P. Wang, L. Yu, ***Enhancing 5G QoS Management for XR Traffic Through XR Loopback Mechanism****, in IEEE Journal on Selected Areas in Communications, vol. 41, no. 6, pp. 1772-1786, June 2023.*

(2) K. Koutlia, B. Bojovic, S. Lagen, X. Zhang, P. Wang, J. Liu, ***System Analysis of QoS Schedulers for XR Traffic in 5G NR****, Elsevier Simulation Modelling Practice and Theory 125 (2023), 102745.*

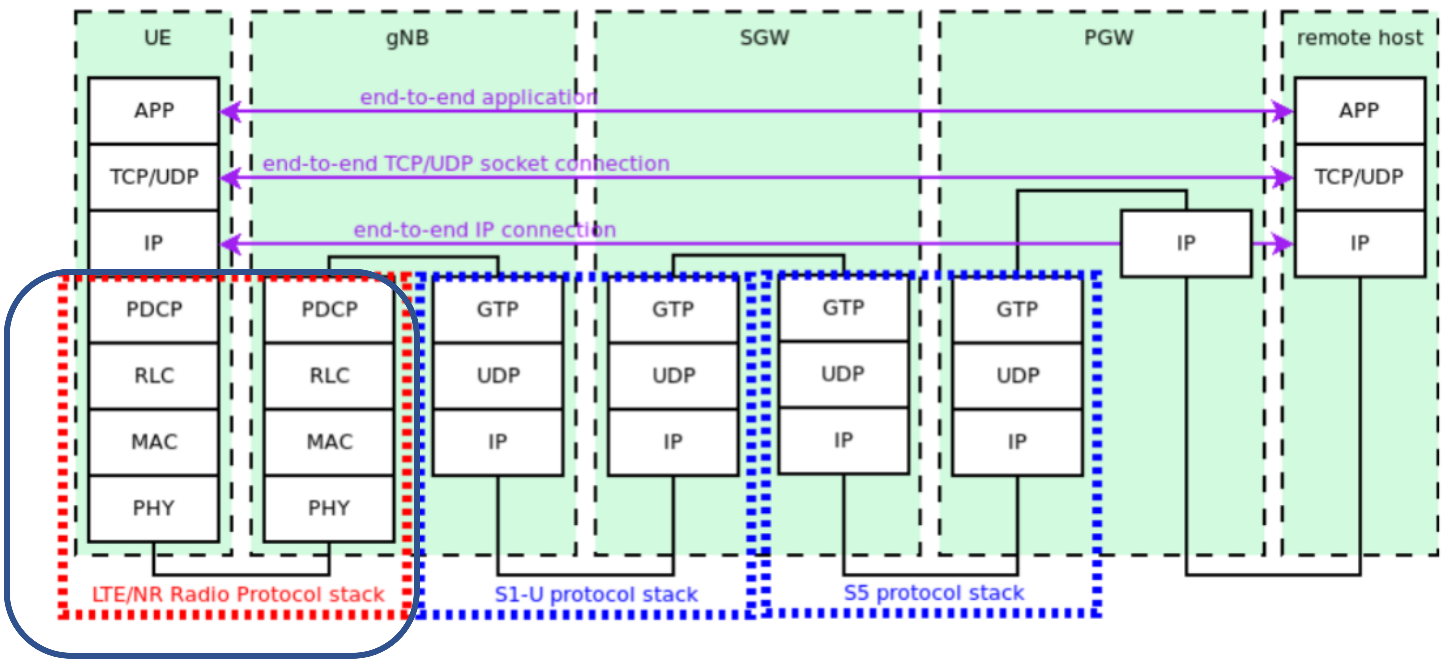
(3) S. Lagen, B. Bojovic, K. Koutlia, X. Zhang, P. Wang, Q. Qu, ***QoS Management for XR Traffic in 5G NR: A Multi-Layer System View & End-to-End Evaluation****, in IEEE Communications Magazine, May 2023.*

XR (AR, VR, CG) IN 5G-LENA THANKS TO META

- Collaboration with Facebook/Meta (US)
- Released in 5G-LENA and ns-3 as open-source in 2023:
  - NGMN traffic models: Video streaming, HTTP Web browsing, Voice over IP, FTP, Downlink/uplink gaming
  - 3GPP XR traffic models:
    - Augmented Reality: 3 streams (video, audio/data, pose/control)
    - Virtual Reality: 1/2 DL streams (video, audio/data), 1 UL stream (pose/control)
    - Cloud Gaming: 1/2 DL streams (video, audio/data), 1 UL stream (pose/control)
  - 1x1 vs Mx1 mapping architectures at UPF (core) and SDAP (RAN)
  - PDCP packet discarding (timers)
  - QoS schedulers and logical channel assignments based on QoS
- Not released fully: XR loopback adaptation algorithms

HELPERS: NrHelper

- The central helper in the NR module. Why is needed?
- Creating/building the protocol stack for the gNB and UE devices could be tedious and error-prone. Also, manually connecting all the stack layers, with the right set of APIs, would be nearly impossible for the users of the NR module

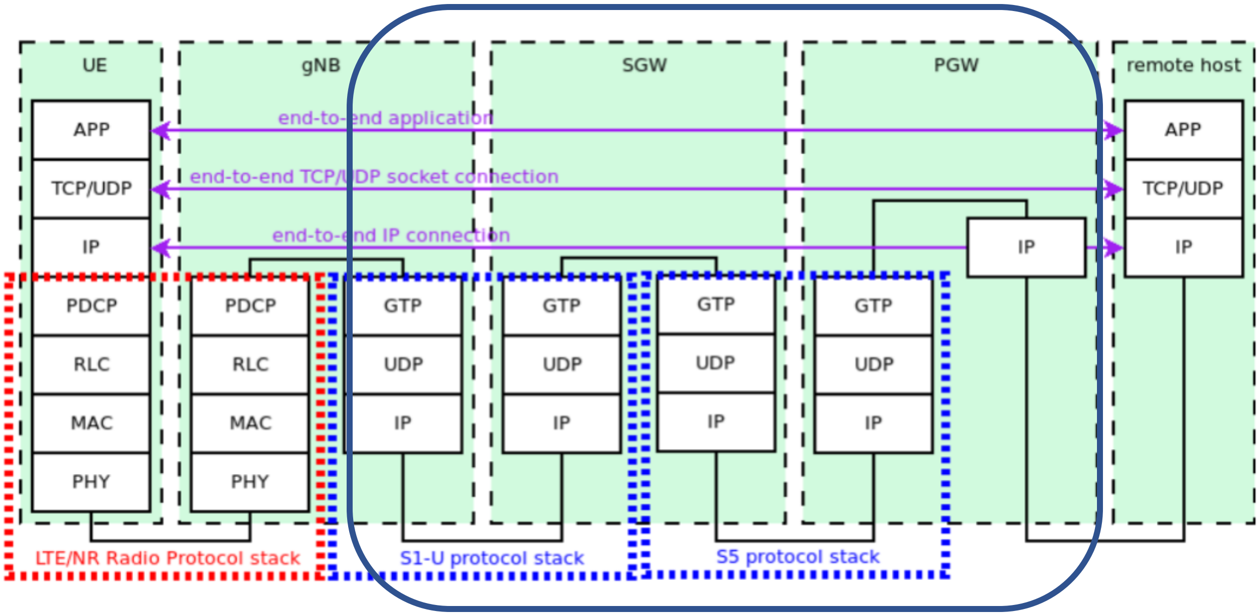


HELPERS: NrHelper

- NrHelper helps user with tasks such as:
  - Create NR UE and gNB devices
  - Attach them
  - Creating the necessary channel class and 3GPP pathloss, fading, and channel condition model for UE and gNB communications (see InitializeOperationBand function)
  - Obtain a pointer to a specific device to perform necessary configurations
  - Assign random stream for your scenario including assigning random stream for all the protocols stack random variables
  - Enable/disable simulation traces by the layer of the protocol stack

HELPERS: EpcHelper

- The core network implementation from the ns-3 LTE module
- For easier creation of the core network there is a helper in the LTE module called ***PointToPointEpcHelper*** whose child classes, such as the ***NrPointToPointEpcHelper*** for the NR module, allows creation of the network between the gNBs and the PGW/SGW



HELPERS: EpcHelper

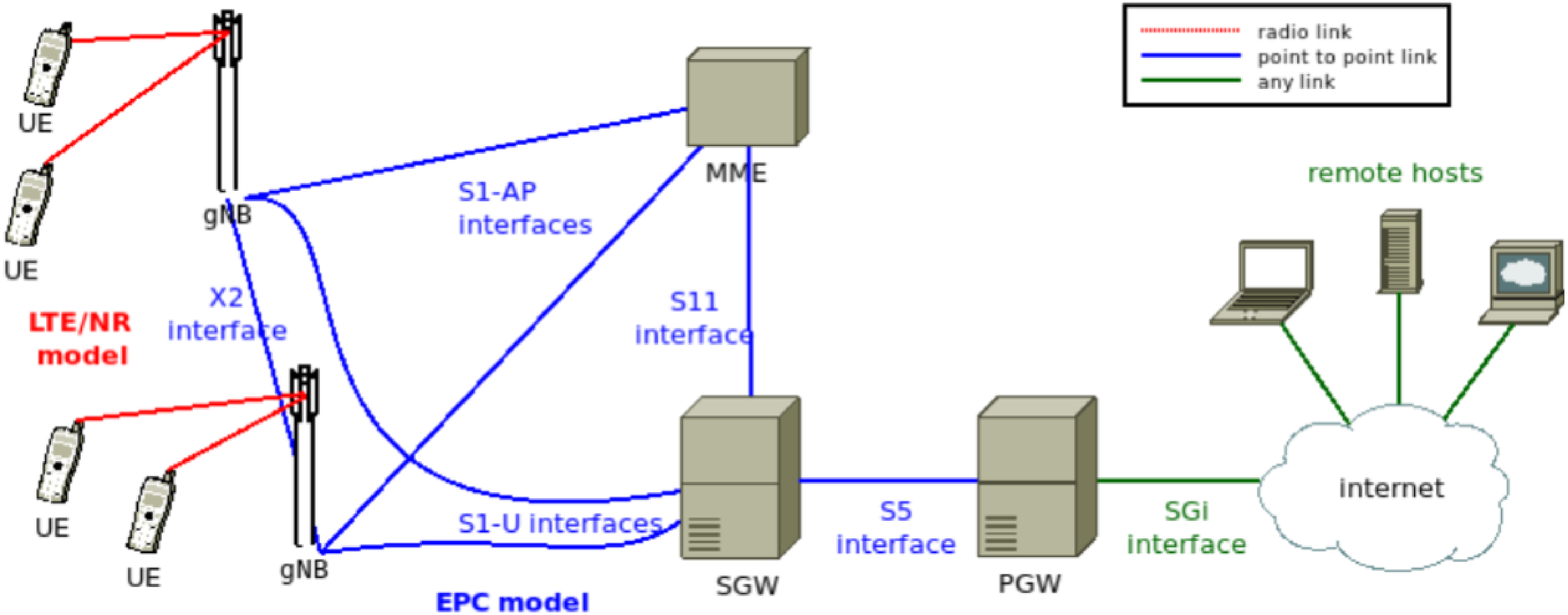


Figure: End-to-end overview

HELPERS: CcBwpHelper

- ***CcBwpHelper*** helps in the configuration of the spectrum
- There are some limitations in how the spectrum is divided, i.e., each spectrum division generates a new, independent, channel class
- Dynamic division is not supported: the configuration must be done before the simulation starts
- Attached UEs must have the same configuration of the gNB

HELPERS: BEAMFORMING HELPERS

Why are needed?

- The real beamforming procedure not supported yet in the NR module
- To configure beams properly on the antennas of the Tx and Rx devices, we need an entity that has access to these objects and controls:
  - Among which devices is performed
  - Periodicity
  - Algorithm or combination of algorithms

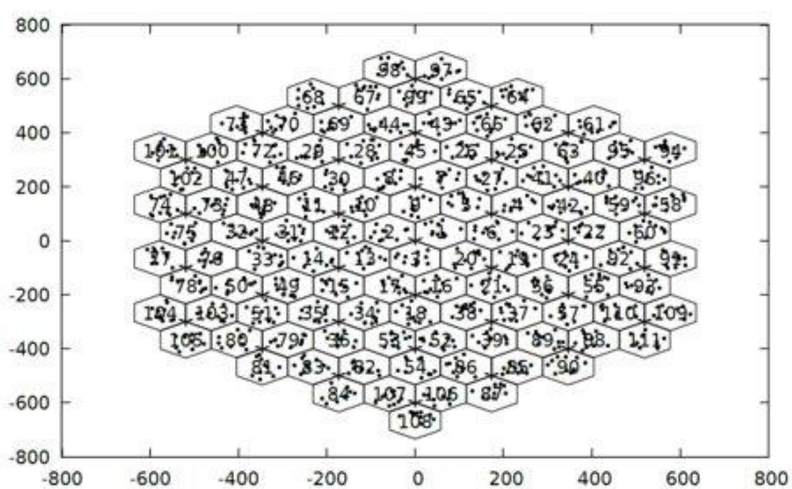
HELPERS: BEAMFORMING HELPERS

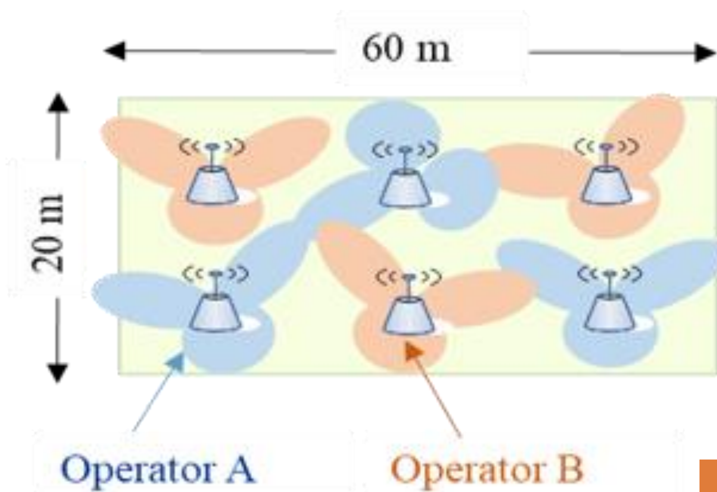
Beamforming helpers currently implemented in the NR module are:

- ***IdealBeamformingHelper***: supports ideal procedures, such as beam search and LOS
- ***RealisticBeamformingHelper***: supports the realistic procedure, such as SRS based realistic beamforming

HELPERS: TOPOLOGY HELPERS

- ***GridScenarioHelper***: can be used to create typical 3GPP indoor scenario
- ***HexagonalGridScenarioHelper*** builds the hexagonal deployment. Provides functions that prepare scripts to plot the scenario.
- ***FileScenarioHelper*** (Contribution from Peter Barnes): reads positions of the gNB devices from the file, helps you simulate the real scenarios in the simulator!





TRACES

- Many traces available in the NR module, for PHY, MAC, RLC, PDCP...
- Many examples use ***FlowMonitor*** to extract throughput, delay, jiter statistics from the simulation
- Users of the NR module do not need to work directly with trace helper, instead the NrHelper can be used to enable/disable specific traces (see NrHelper Doxygen or API)

TRACES

- Some of the trace helpers are:
  - ***NrStatsCalculator***
  - ***NrBearerStatsCalculator***
  - ***NrBearerStatsConnector***
  - ***NrBearerStatsSimple***
  - ***NrMacRxTrace***
  - ***NrPhyRxTrace***
  - ***NrMacSchedulingStats***

HELPERS: REM HELPER

- The Radio Environmental Map (REM) is a tool that helps to visualize the network coverage, including signal quality and interference
- This tool is useful to verify the deployment scenario as well as in the phases of network design and analysis

5G-LENA: REM MAP (2GHZ)

- **Scenario configuration:** UMa
- **Scenario path:** nr/examples/rem-example.cc
- **RTDs:**
  - gNB1 (0, 0, 1.5)
  - gNB2 (20, -30, 1.5)
  - gNBs antenna: 1x1
  - ISO
  - Frequency = **2e9**
  - Bandwidth = **20e6**
  - gNB txPower: 1 dBm
  - Numerology: 0
- **RRD:**
  - UE antenna: 1x1
  - ISO
  - Noise figure: 5 dBi

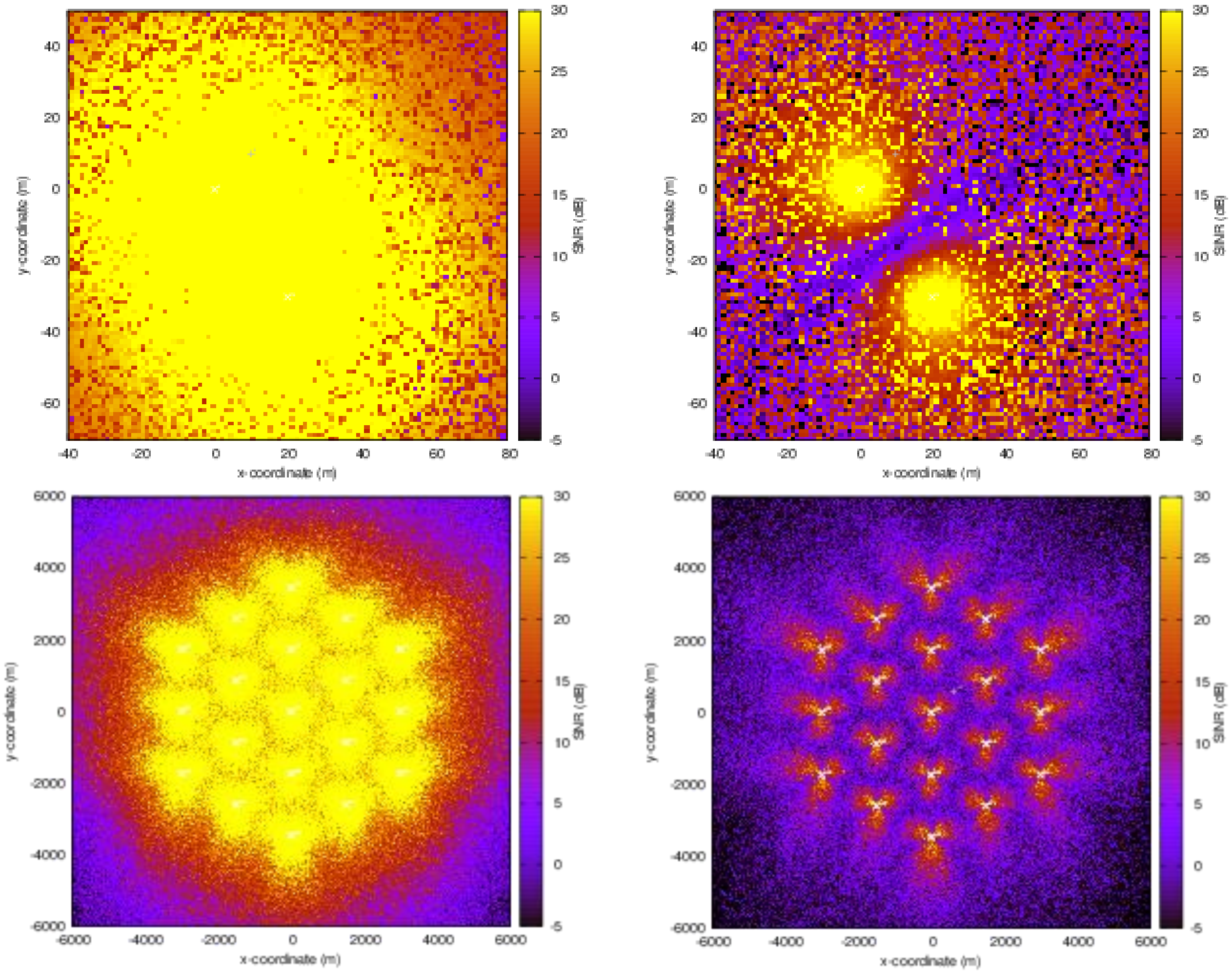
K. Koutlia, B. Bojovic, S. Lagen, L. Giupponi, ***Novel Radio Environment Map for the ns-3 NR Simulator****, in Workshop on ns-3, June 2021*

5G-LENA: REM MAP (2GHZ)

SNR | SINR

2 gNBs

21 gNBs



K. Koutlia, B. Bojovic, S. Lagen, L. Giupponi, ***Novel Radio Environment Map for the ns-3 NR Simulator***, *in Workshop on ns-3, June 2021*

5G-LENA: REM MAP (28GHZ, BEAM SHAPE)

- **Scenario configuration:** UMa
- **Scenario path:** nr/examples/rem-example.cc
- **RTDs:**
  - gNB1 (0, 0, 1.5)
  - gNB2 (20, -30 , 1.5)
  - gNBs antenna: 8x8
  - 3GPP
  - Frequency = **28e9**
  - Bandwidth = **100e6**
  - gNB txPower: 1 dBm
  - Numerology: 4
- **RRD:**
  - Ue1 with position (10, 10, 1.5)
  - Ue2 with position (25, -15, 1.5)
  - UE antenna: 1x1
  - ISO
  - Noise figure: 5 dBi

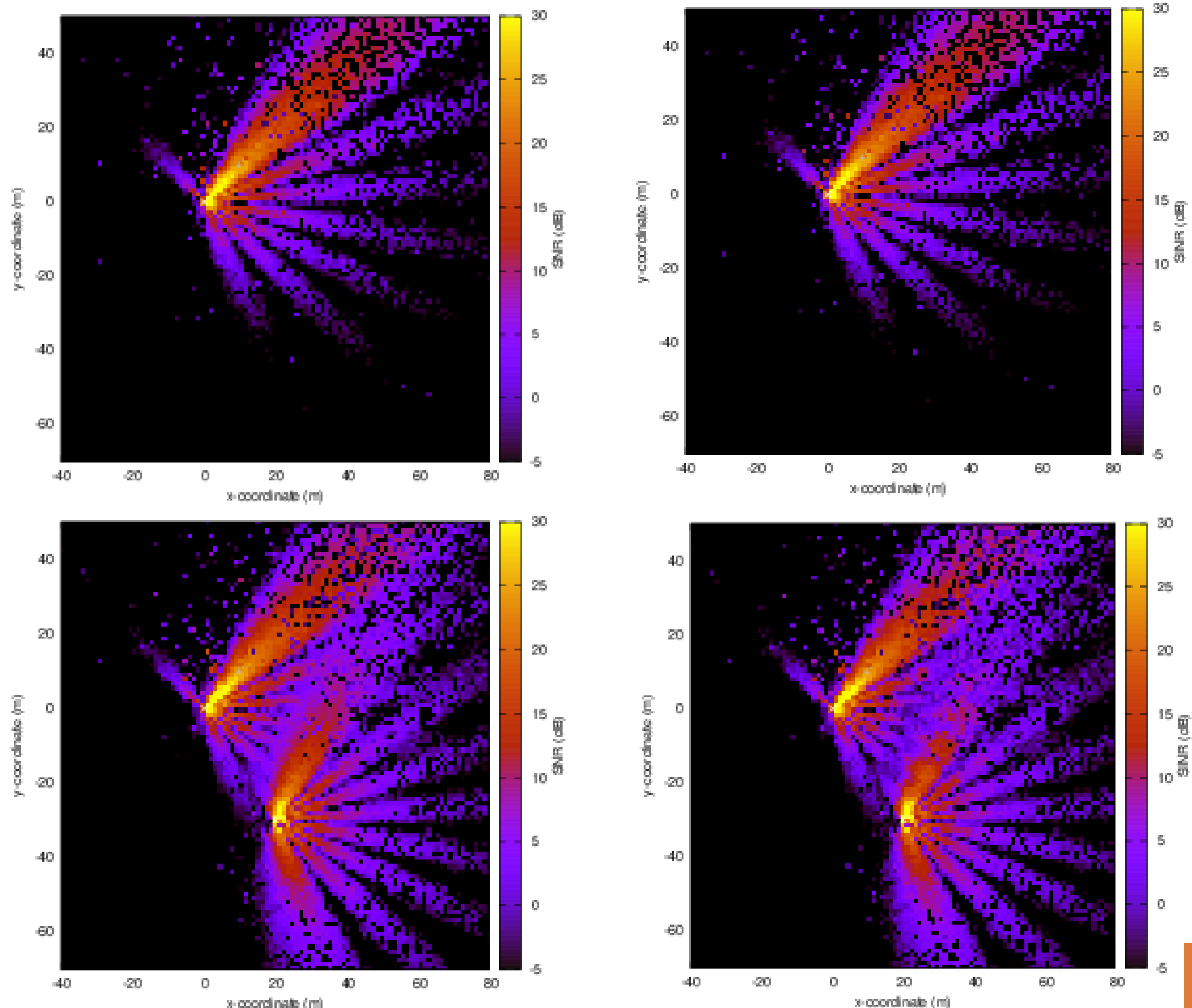
5G-LENA: REM MAP (28GHZ, BEAM SHAPE)

SNR

SINR

1 gNB

2 gNBs

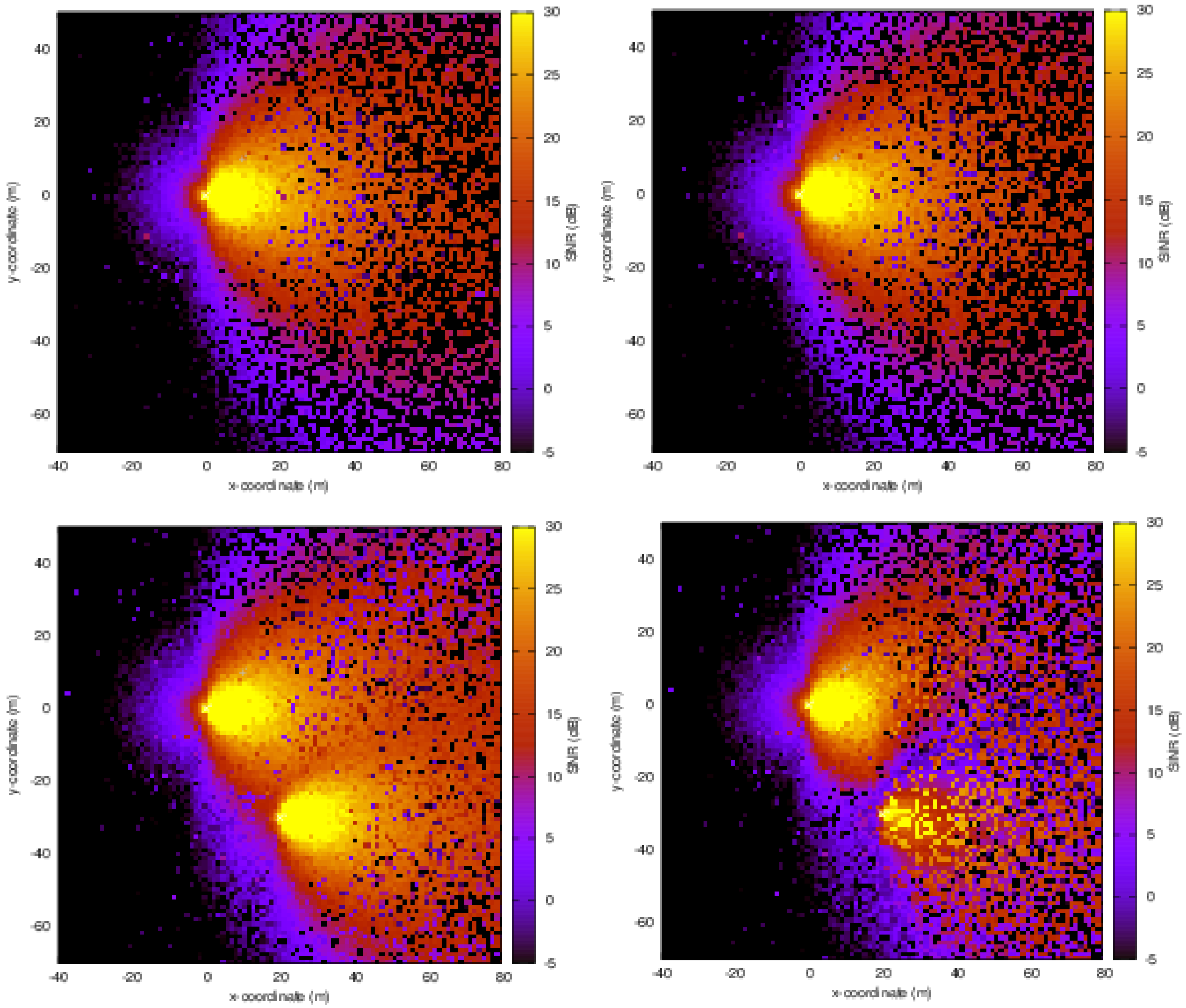


5G-LENA: REM MAP (28GHZ, COVERAGE AREA)

SNR SINR

1 gNB

2 gNBs



5G-LENA: INDOOR CALIBRATION

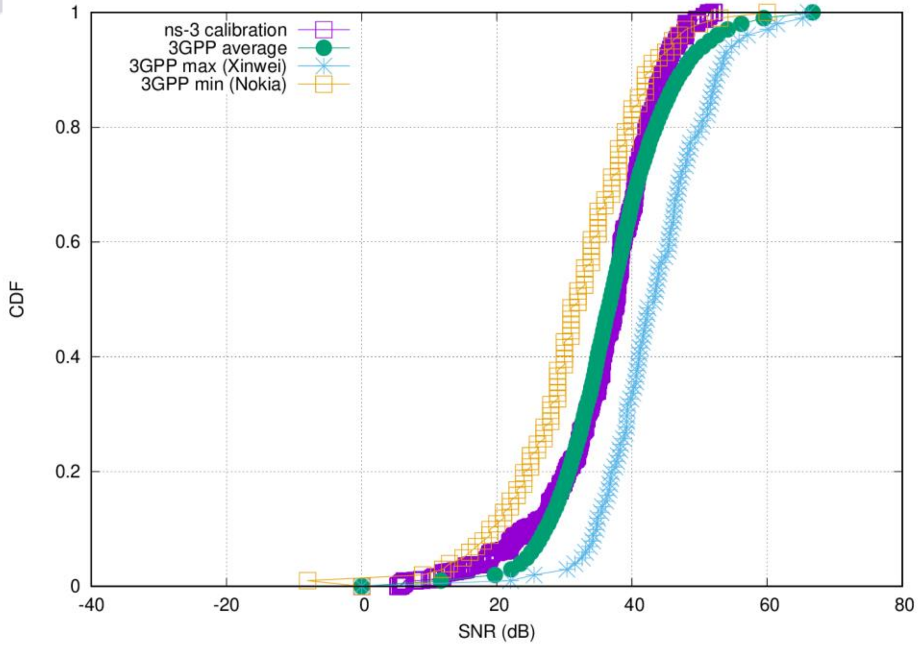
- The simulator is calibrated according to Phase 1 indoor hotspot system-level calibration for multi-antenna systems, as per Annex A.2 in [TS38802]
- Scenario is composed of:
  - 12 cells at 20 m distance, and
  - 120 UEs (100% indoor) randomly dropped in a 50 m x 120 m area [R1-1703534]
- As reference curves, we use the results provided by the companies in [R1-1709828]

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*

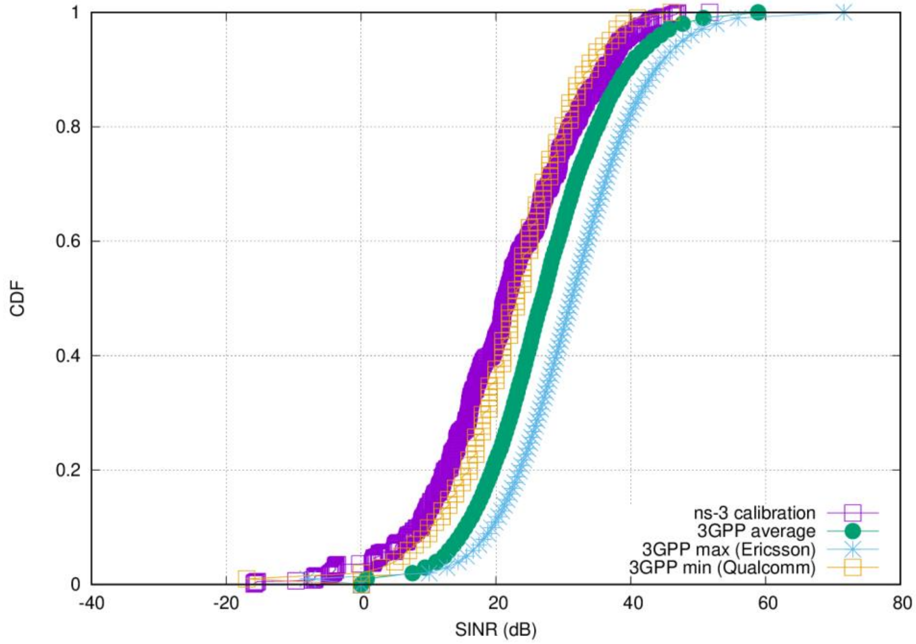
5G-LENA: INDOOR CALIBRATION

- Collaboration with

SNR



SINR



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*

5G-LENA: OUTDOOR CALIBRATION

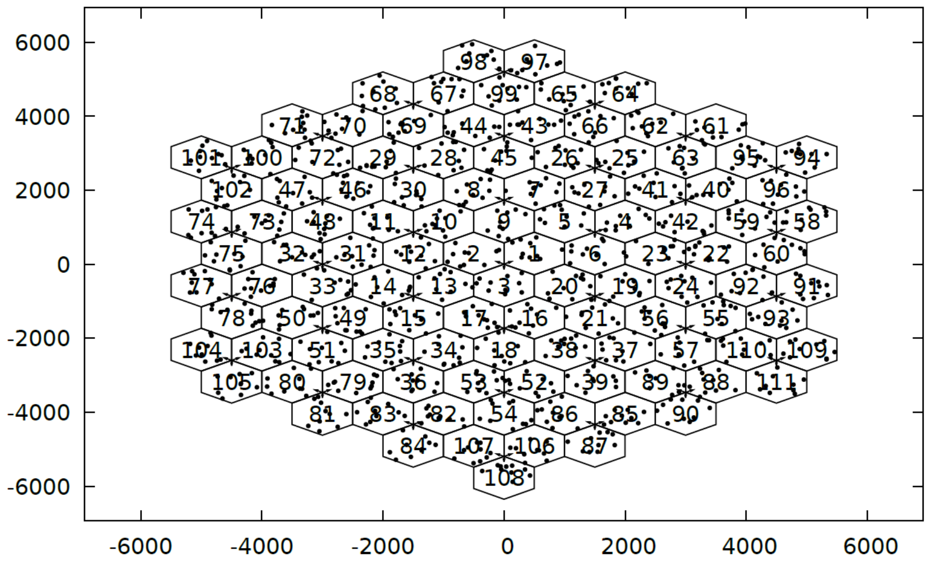
- The simulator is calibrated according to NR outdoor scenarios [RP-180524]:
  - Rural eMBB Config. A (700MHz), Config. B (4GHz)
  - Dense Urban eMBB Config. A (4GHz), Config. B (30GHz)
- 19 sites (57 cells) in hexagonal 3 rings deployment
- ISD depends on scenario
- 10 UEs/cell (570 UEs) randomly dropped in the cell area
- As reference curves, we use the results provided by the companies in [RP-180524]

K. Koutlia, B. Bojovic, Z. Ali, S. Lagen, ***Calibration of the 5G-LENA System Level Simulator in 3GPP reference scenarios****, Elsevier Simulation Modelling Practice and Theory (SIMPAT), May 2022.*

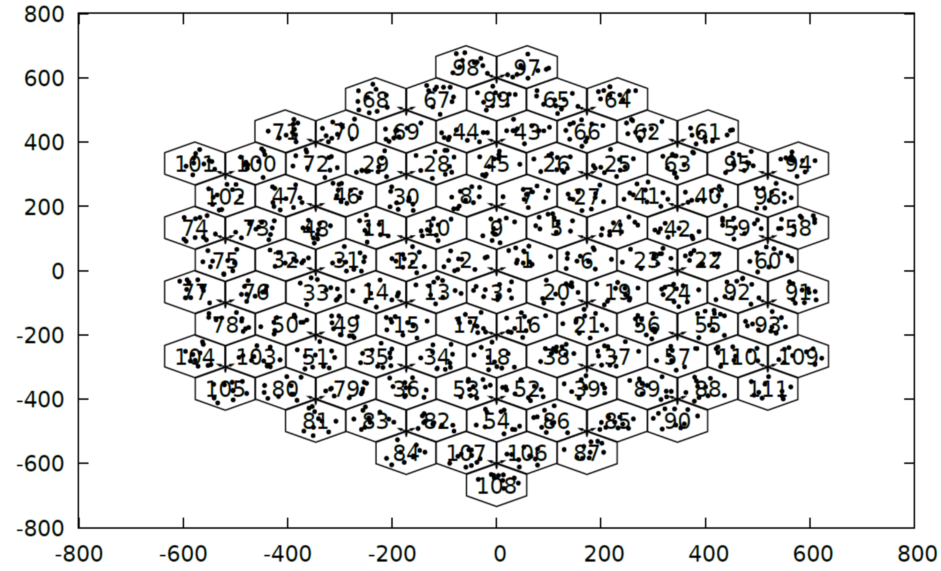
5G-LENA: OUTDOOR CALIBRATION

- Collaboration with Meta (US)

RURAL eMBB



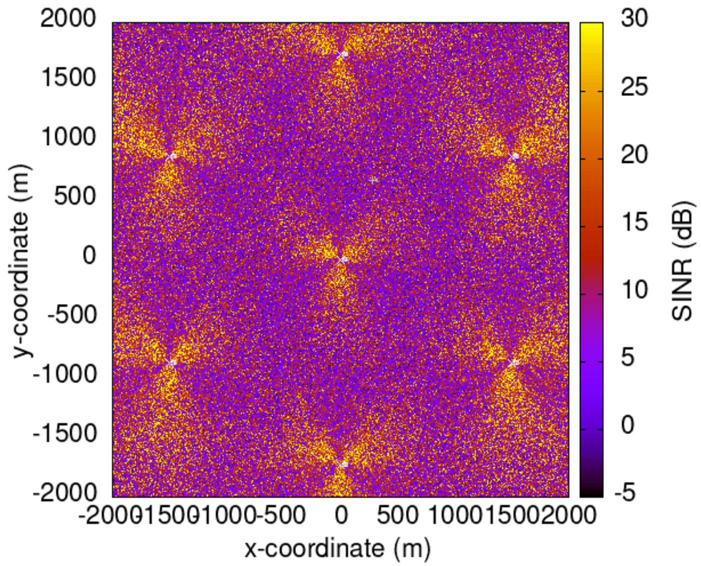
DENSE Urban eMBB

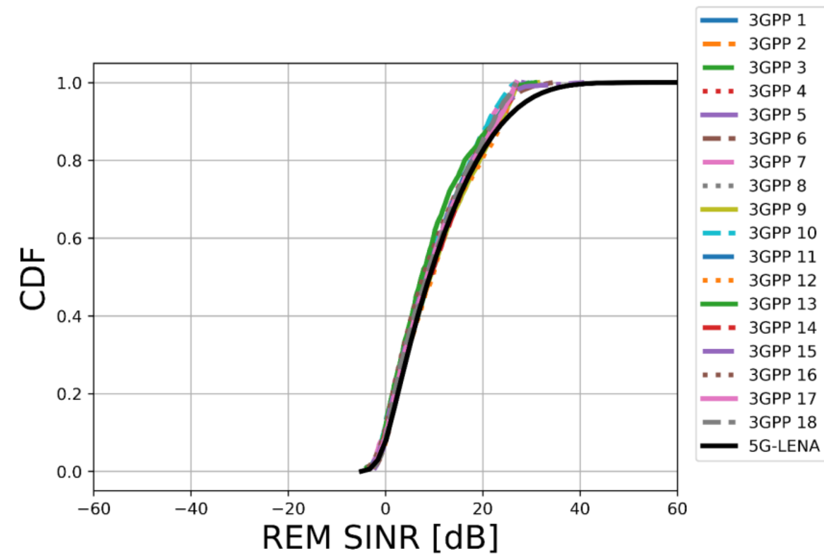


*K. Koutlia, B. Bojovic, Z. Ali, S. Lagen, **Calibration of the 5G-LENA System Level Simulator in 3GPP reference scenarios**, Elsevier Simulation Modelling Practice and Theory (SIMPAT), May 2022.*

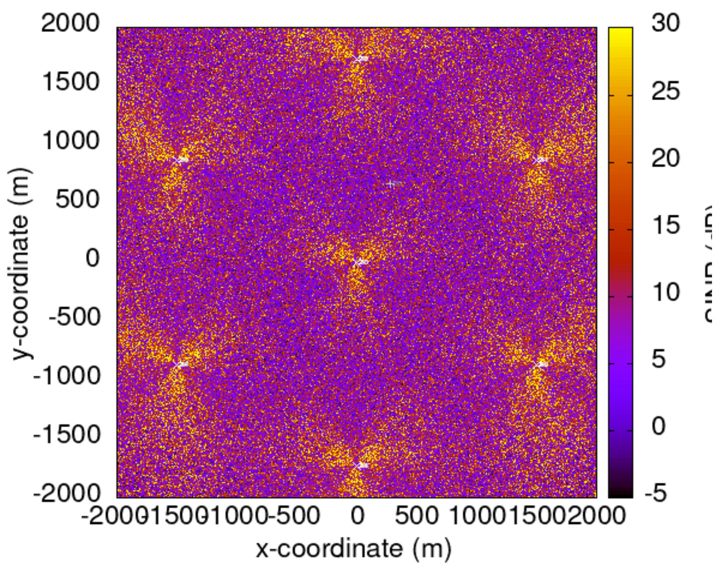
5G-LENA: OUTDOOR CALIBRATION (REM)

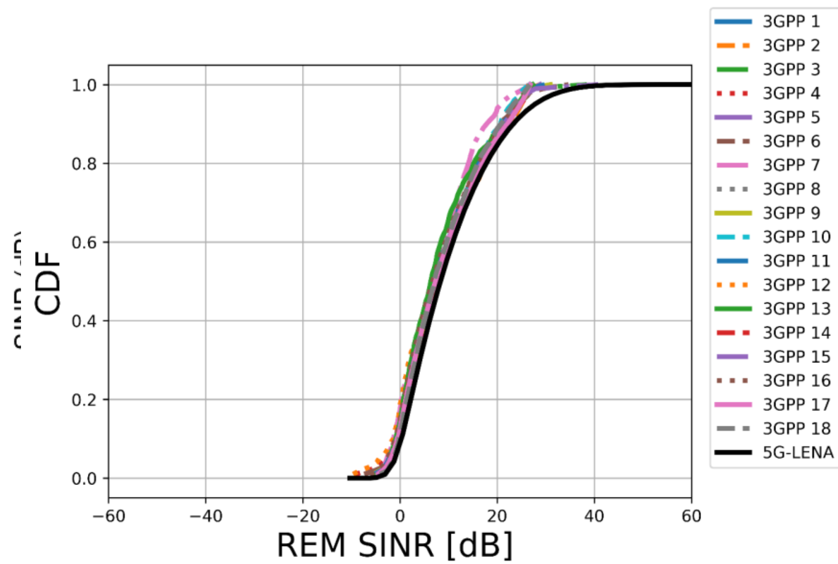
RuralA





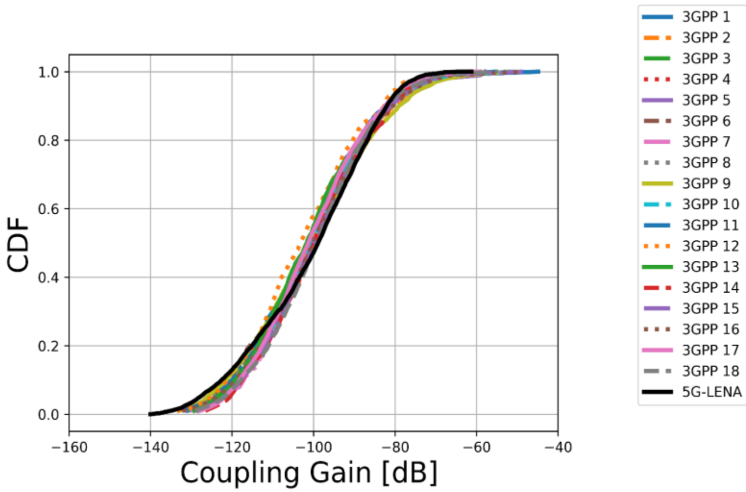
RuralB

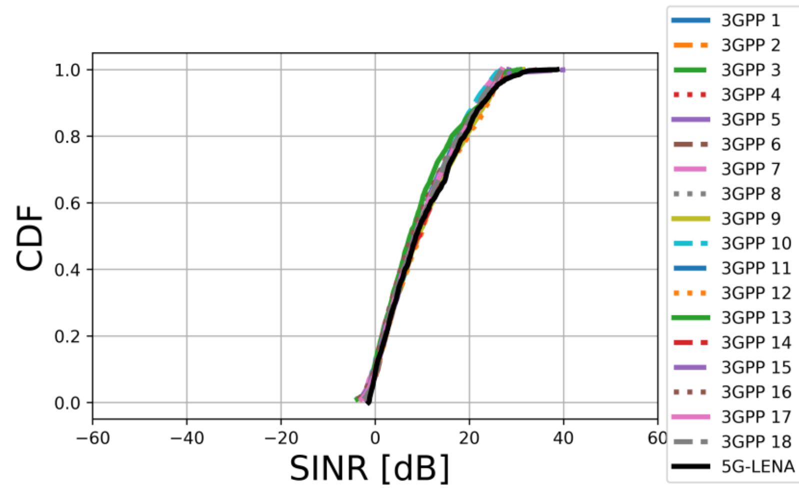




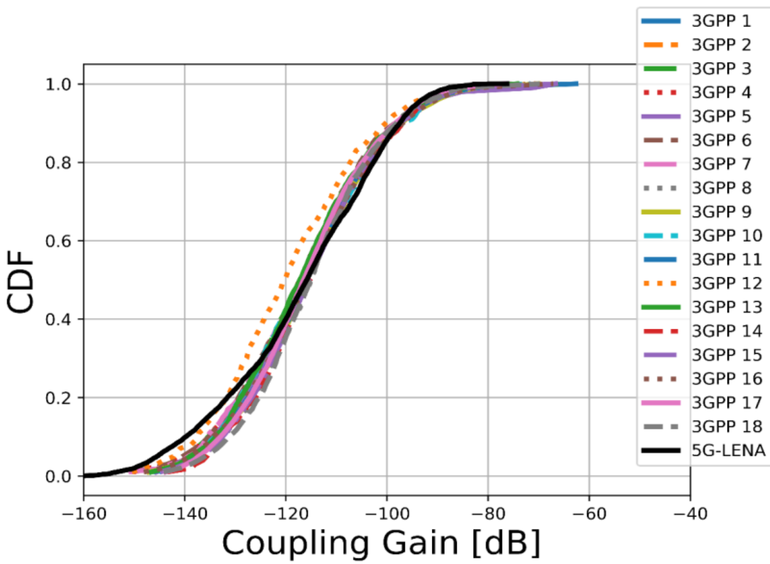
5G-LENA: OUTDOOR CALIBRATION (E2E)

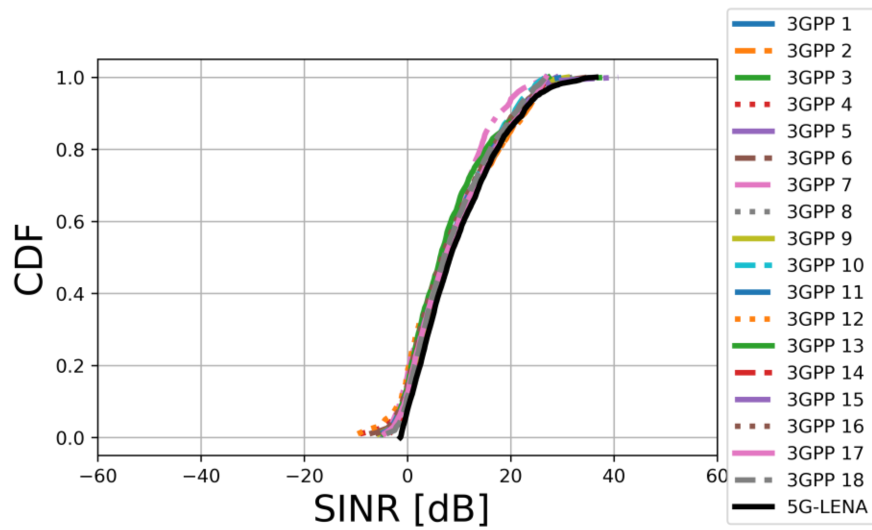
RuralA





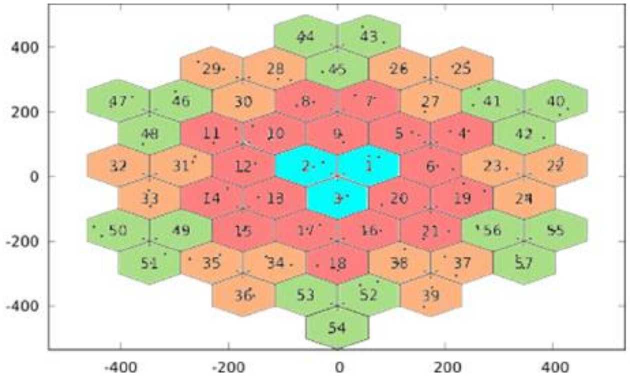
RuralB



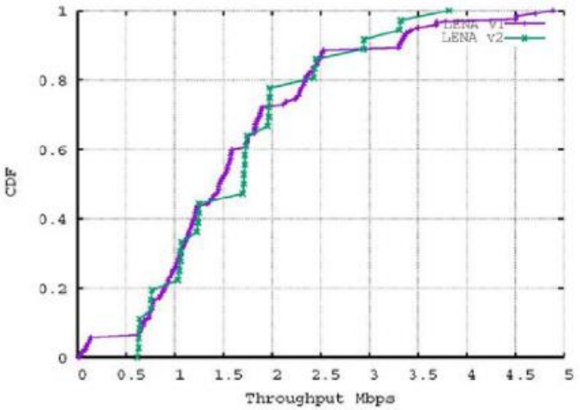


5G-LENA: COMPARISON LENA VS 5G-LENA (NS-3 LTE MODULE VS NR MODULE)

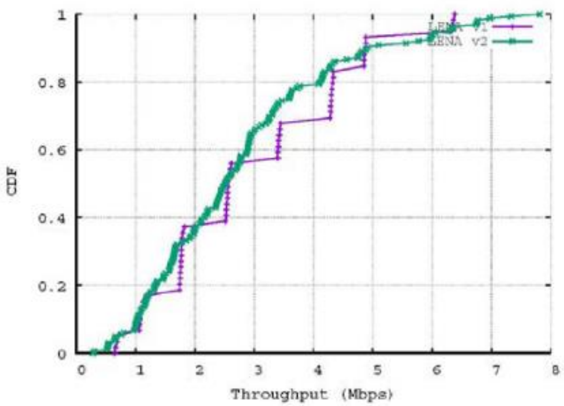
Parameters		UMi	UMa
Cell layout		Hexagonal grid, 19 macro sites, 3 sectors per site	
Inter-Site Distance (ISD)		200 m	500 m
BS antenna height		10m	25m
UE location	Outdoor/indoor	Outdoor	Outdoor
	LOS/NLOS	LOS and NLOS	LOS and NLOS
	Height in meters	$h_{UE} = 1.5$	$h_{UE} = 1.5$
UE mobility (horizontal plane only)		0km/h	0km/h
Min. BS - UE distance (2D)		10m	35m
UE distribution (horizontal)		Uniform	
Operation central frequency		2 GHz	
System Bandwidth		20 MHz (single carrier) = 100 Resource Blocks (RBs)	
BS antenna panel configuration		1x1	
UE antenna panel configuration		1x1	
Total BS transmit power		44 dBm	49 dBm
Total UE maximum transmit power (P_{max})		20 dBm	



Ring 3, 21 sites 16 UE per site, scenario UMi, RR scheduler, saturation, DL



Ring 3, 21 sites 16 UE per site, scenario UMa, RR scheduler, saturation, UL

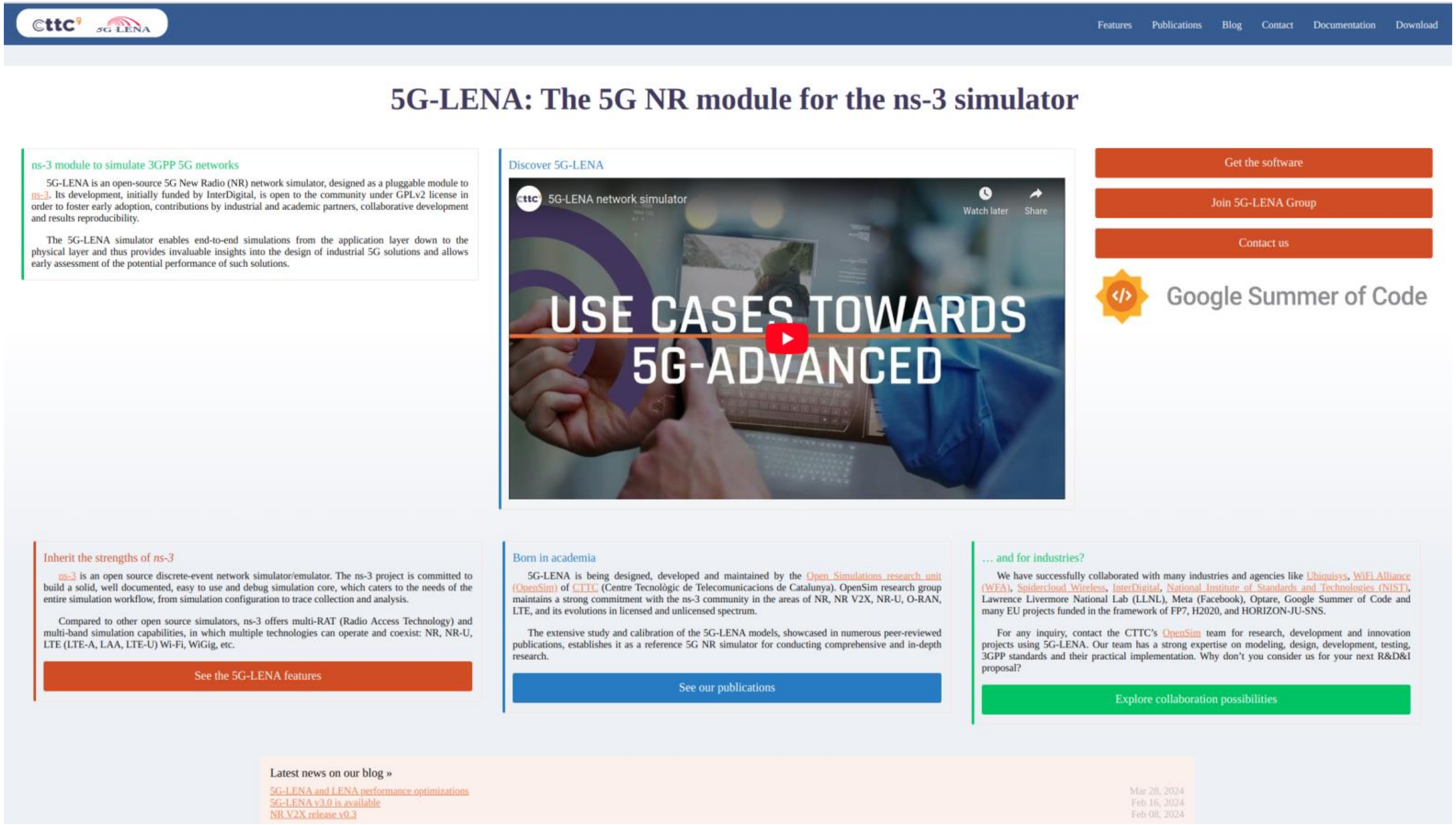


NR MODULE PART II: THE PRACTICAL PART

- NR module resources
- Instructions to download and the NR module, ns-3 and build
- The NR module folder organization
- Go through the example code
- Running the example and going through the traces
- Enabling logs of the example
- Roadmap and possible contributions
- How to contribute to the open-source NR module?

GETTING TO KNOW 5G-LENA

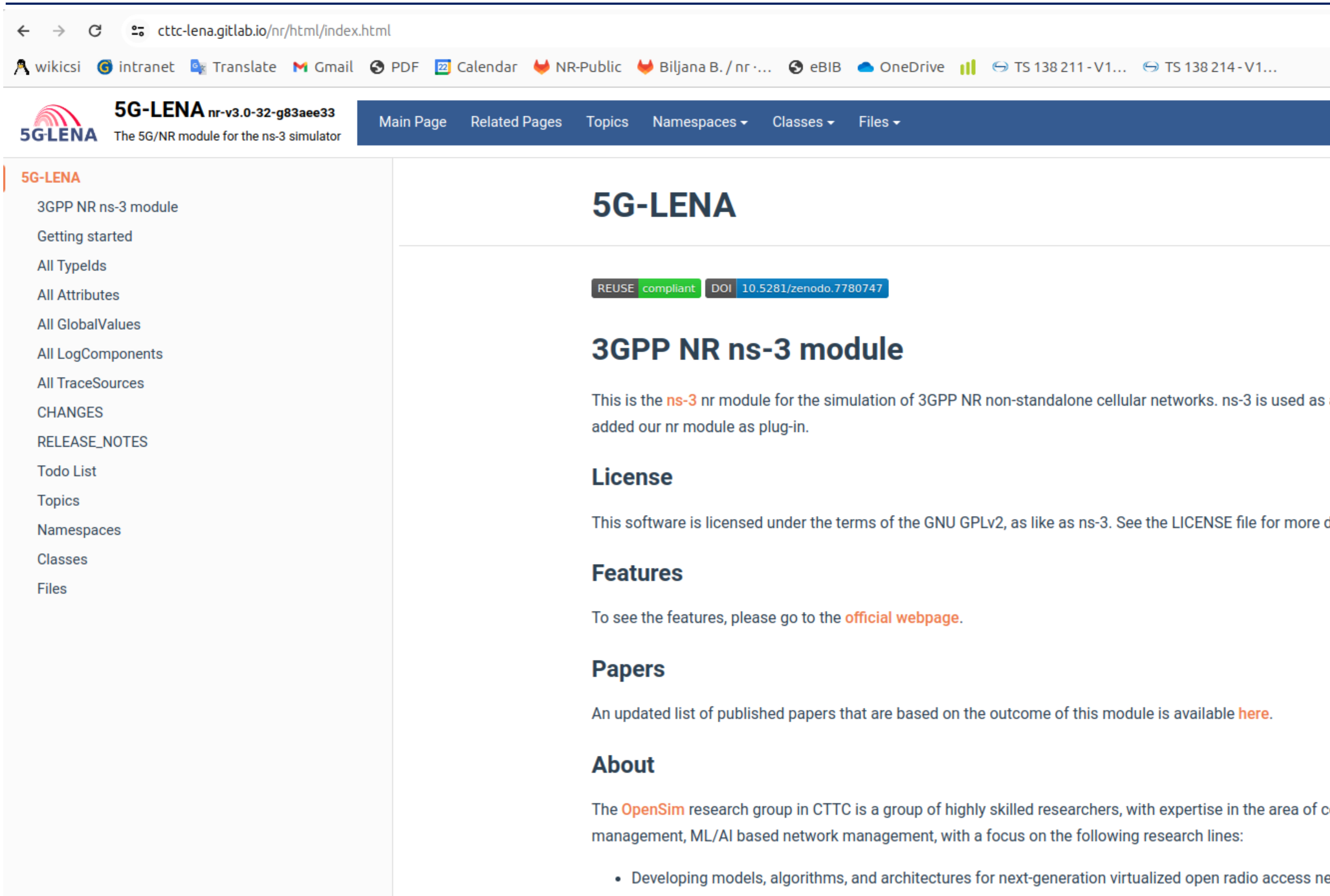
- First, good knowledge of ns-3
- Web page: https://5g-lena.cttc.es



GETTING TO KNOW 5G-LENA

- Gitlab repo:
  - NR module publicly available code: https://gitlab.com/cttc-lena/nr
  - Reporting issues
- Documentation:
  - Manual: https://cttc-lena.gitlab.io/nr/nrmodule.pdf
  - Tutorial: https://cttc-lena.gitlab.io/nr/cttc-nr-demo-tutorial.pdf
  - Doxygen: https://cttc-lena.gitlab.io/nr/html/index.html
- 5G-LENA users group:
  - https://groups.google.com/g/5g-lena-users/

5G-LENA DOXYGEN IMPROVED RECENTLY



EXAMPLE: HOW TO SETUP NS-3 WITH NR ?

- Go to the **public Gitlab NR** repo: https://gitlab.com/cttc-lena/nr and scroll down until the **README.md** and follow the instructions from there
- Or from Getting started: https://cttc-lena.gitlab.io/nr/html/index.html#getting-started

Download ns-3:

Download then checkout the compatible version of ns-3:

```
git clone https://gitlab.com/nsnam/ns-3-dev.git
cd ns-3-dev
git checkout -b ns-3.41 ns-3.41
```

To make sure everything is working properly, run the ns-3 tests:

```
$ ./ns3 configure --enable-examples --enable-tests
$ ./test.py
```

A success for both previous commands indicates an overall success, and you are ready to install the nr module.

Download the nr module:

Download then checkout the compatible version of nr:

```
cd contrib
git clone https://gitlab.com/cttc-lena/nr.git
cd nr
git checkout -b 5g-lena-v3.0.y origin/5g-lena-v3.0.y
```

Notice that since these are two independent git repositories, when you run `git status` inside of the ns-3, you will notice that the contrib/nr directory will be listed as "Untracked files". This is normal.

Test ns-3 + nr installation:

Let's configure the ns-3 + nr project:

```
./ns3 configure --enable-examples --enable-tests
```

NS-3 NR SETUP

Option A:
Full ns-3 build (builds all ns-3 modules, **2045** files):

1. git clone https://gitlab.com/nsnam/ns-3-dev.git
2. cd ns-3-dev/
3. git checkout ns-3.36.1
4. cd src/
5. git clone https://gitlab.com/cttc-lena/nr.git
6. git checkout 5g-lena-v2.2.y
7. cd ../..
8. ./ns3 configure --enable-examples --enable-tests
9. ./ns3 build

```
Modules configured to be built:
antenna                 aodv                    applications
bridge                  buildings               config-store
core                    csma                    csma-layout
dsdv                    dsr                     energy
fd-net-device           flow-monitor            internet
internet-apps           lr-wpan                 lte
mesh                    mobility                netanim
network                 nix-vector-routing      nr
olsr                    point-to-point          point-to-point-layout
propagation             sixlowpan               spectrum
stats                   tap-bridge              test
topology-read           traffic-control         uan
virtual-net-device      wave                    wifi
wimax
```

Option B:
Partial ns-3 build (builds some NR modules, **1388** files):

1. git clone https://gitlab.com/nsnam/ns-3-dev.git
2. cd ns-3-dev/
3. git checkout ns-3.36.1
4. cd src/
5. git clone https://gitlab.com/cttc-lena/nr.git
6. git checkout 5g-lena-v2.2.y
7. cd ../..
8. ./ns3 configure --enable-examples --enable-tests **--enable-modules=flow-monitor,stats,nr**
9. ./ns3 build

```
Modules configured to be built:
antenna                 applications            bridge
buildings               config-store            core
csma                    fd-net-device           flow-monitor
internet                internet-apps           lte
mobility                network                 nr
point-to-point          propagation             spectrum
stats                   test                    traffic-control
virtual-net-device
```

NS-3 NR SETUP

- Once the compilation has finished following the instructions for Option B from the previous slide, if all went fine, you should see the following lines:

```
[1388/1388] Linking CXX executable ../build/utils/ns3.36.1-print-introspected-doxygen-default
Finished executing the following commands:
cd cmake-cache; cmake --build . -j 7 ; cd ..
```

EXAMPLE: THE NR MODULE REPO ORGANIZATION

- network
- nix-vector-routing
- nr [5g-lena-v2.2.y] nr: RELEASE_NOTES and CHANGES updated for release v2.2
  - doc
  - examples
  - helper
  - model
  - test
  - utils
  - CHANGES.md
  - CMakeLists.txt
  - LICENSE
  - Makefile
  - README.md
  - RELEASE_NOTES.md
- olsr
- openflow

EXAMPLE: THE NR MODULE REPO ORGANIZATION

- examples
  - lena-lte-comparison
  - cttc-3gpp-channel-example.cc
  - cttc-3gpp-channel-nums.cc
  - cttc-3gpp-channel-nums-fdm.cc
  - cttc-3gpp-channel-simple-fdm.cc
  - cttc-3gpp-channel-simple-ran.cc
  - cttc-3gpp-indoor-calibration.cc
  - cttc-channel-randomness.cc
  - cttc-error-model.cc
  - cttc-error-model-amc.cc
  - cttc-error-model-comparison.cc
  - cttc-fh-compression.cc
  - cttc-lte-ca-demo.cc
  - cttc-nr-cc-bwp-demo.cc
  - cttc-nr-demo.cc
  - cttc-nr-mimo-demo.cc
  - cttc-nr-notching.cc
  - cttc-realistic-beamforming.cc
  - rem-beam-example.cc
  - rem-example.cc
  - CMakeLists.txt

- lena-lte-comparison
  - flow-monitor-output-stats.cc
  - flow-monitor-output-stats.h
  - lena-lte-comparison.cc
  - lena-lte-comparison.h
  - lena-lte-comparison-campaign.cc
  - lena-lte-comparison-user.cc
  - lena-v1-utils.cc
  - lena-v1-utils.h
  - lena-v2-utils.cc
  - lena-v2-utils.h
  - power-output-stats.cc
  - power-output-stats.h
  - rb-output-stats.cc
  - rb-output-stats.h
  - sinr-output-stats.cc
  - sinr-output-stats.h
  - slot-output-stats.cc
  - slot-output-stats.h
  - example-sites.104.csv
  - example-sites.1062.csv
  - example-sites.2.csv
  - example-sites.22.csv

RUN CTTC-NR-DEMO EXAMPLE

- We will work with **cttc-nr-demo.cc** example
- To run the example type in the command line:
  ./ns3 run cttc-nr-demo
- The command line output of the example shows flow monitor statistics of 2 flows:

```
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 6000
  Tx Bytes:   768000
  TxOffered:  10.240000 Mbps
  Rx Bytes:   767744
  Throughput: 10.236587 Mbps
  Mean delay:  0.276044 ms
  Mean jitter:  0.030032 ms
  Rx Packets: 5998
Flow 2 (1.0.0.2:49154 -> 7.0.0.3:1235) proto UDP
  Tx Packets: 6000
  Tx Bytes:   7680000
  TxOffered:  102.400000 Mbps
  Rx Bytes:   7667200
  Throughput: 102.229333 Mbps
  Mean delay:  0.900970 ms
  Mean jitter:  0.119907 ms
  Rx Packets: 5990


  Mean flow throughput: 56.232960
  Mean flow delay: 0.588507
```

CTTC-NR-DEMO EXAMPLE PARAMETERS

- What parameters provides this example?
- To find out type in the command line:

  ./ns3 run cttc-nr-demo -- --PrintHelp

- The cmd line output of this command should be something like:

```
biljkus@biljkus-Latitude-5400:~/Desktop/workspace-wns3-2022/ns-3-dev$ ./ns3 run "cttc-nr-demo --PrintHelp"
[0/2] Re-checking globbed directories...
ninja: no work to do.
 [Program Options] [General Arguments]

Program Options:
    --gNbNum:                 The number of gNbs in multiple-ue topology [1]
    --ueNumPergNb:            The number of UE per gNb in multiple-ue topology [2]
    --logging:                Enable logging [false]
    --doubleOperationalBand:  If true, simulate two operational bands with one CC for each band,and each CC
rue]
    --packetSizeUll:          packet size in bytes to be used by ultra low latency traffic [100]
    --packetSizeBe:           packet size in bytes to be used by best effort traffic [1252]
    --lambdaUll:              Number of UDP packets in one second for ultra low latency traffic [10000]
    --lambdaBe:               Number of UDP packets in one second for best effor traffic [10000]
    --simTime:                Simulation time [+1s]
    --numerologyBwp1:         The numerology to be used in bandwidth part 1 [4]
    --centralFrequencyBand1:  The system frequency to be used in band 1 [2.8e+10]
    --bandwidthBand1:         The system bandwidth to be used in band 1 [1e+08]
    --numerologyBwp2:         The numerology to be used in bandwidth part 2 [2]
    --centralFrequencyBand2:  The system frequency to be used in band 2 [2.82e+10]
    --bandwidthBand2:         The system bandwidth to be used in band 2 [1e+08]
    --totalTxPower:           total tx power that will be proportionally assigned to bands, CCs and bandwidt
    --simTag:                 tag to be appended to output filenames to distinguish simulation campaigns [de
    --outputDir:              directory where to store simulation results [./]

General Arguments:
    --PrintGlobals:              Print the list of globals.
    --PrintGroups:               Print the list of groups.
    --PrintGroup=[group]:        Print all TypeIds of group.
    --PrintTypeIds:              Print all TypeIds.
    --PrintAttributes=[typeid]:  Print all attributes of typeid.
    --PrintVersion:              Print the ns-3 version.
    --PrintHelp:                 Print this help message.
```

EXAMPLE: TRY OUT SOME OF THE PARAMETERS

- By default, as we could see when printing options, there is 1 gNB and 2 UEs per gNB)

- Task: Create 4 flows.
- One possible solution:

./ns3 run cttc-nr-demo -- --gNbNum=2

```
Program Options:
    --gNbNum:                  The number of gNbs in multiple-ue topology [1]
    --ueNumPergNb:             The number of UE per gNb in multiple-ue topology [2]
```

```
biljkus@biljkus-Latitude-5400:~/Desktop/workspace-w
[0/2] Re-checking globbed directories...
ninja: no work to do.
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 6000
  Tx Bytes:   768000
  TxOffered:  10.240000 Mbps
  Rx Bytes:   767744
  Throughput: 10.236587 Mbps
  Mean delay:  0.290423 ms
  Mean jitter:  0.043759 ms
  Rx Packets: 5998
Flow 2 (1.0.0.2:49154 -> 7.0.0.3:1234) proto UDP
  Tx Packets: 6000
  Tx Bytes:   768000
  TxOffered:  10.240000 Mbps
  Rx Bytes:   767744
  Throughput: 10.236587 Mbps
  Mean delay:  0.277839 ms
  Mean jitter:  0.032824 ms
  Rx Packets: 5998
Flow 3 (1.0.0.2:49155 -> 7.0.0.4:1235) proto UDP
  Tx Packets: 6000
  Tx Bytes:   7680000
  TxOffered:  102.400000 Mbps
  Rx Bytes:   7641600
  Throughput: 101.888000 Mbps
  Mean delay:  3.070216 ms
  Mean jitter:  0.179758 ms
  Rx Packets: 5970
Flow 4 (1.0.0.2:49156 -> 7.0.0.5:1235) proto UDP
  Tx Packets: 6000
  Tx Bytes:   7680000
  TxOffered:  102.400000 Mbps
  Rx Bytes:   7641600
  Throughput: 101.888000 Mbps
  Mean delay:  3.358872 ms
  Mean jitter:  0.179734 ms
  Rx Packets: 5970
```

EXAMPLE: CONFIGURE THE SAME DATA RATE AND IN BOTH BWPS

- How to configure to achieve the same throughput/delay on both BWPs?
- First spot the differences in the default parameter configuration of the BWPs and of the flows.
- Solution:

  ./ns3 run "cttc-nr-demo --numerologyBwp1=2 --packetSizeUll=1252"

```
biljkus@biljkus-Latitude-5400:~/Desktop/workspace-wns3-2022/ns-3-dev$ ./ns3 run "cttc-nr-demo --PrintHelp"
[0/2] Re-checking globbed directories...
ninja: no work to do.
 [Program Options] [General Arguments]

Program Options:
    --gNbNum:                  The number of gNbs in multiple-ue topology [1]
    --ueNumPergNb:             The number of UE per gNb in multiple-ue topology [2]
    --logging:                 Enable logging [false]
    --doubleOperationalBand:   If true, simulate two operational bands with one CC for each band,and each CC
rue]
    --packetSizeUll:           packet size in bytes to be used by ultra low latency traffic [100]
    --packetSizeBe:            packet size in bytes to be used by best effort traffic [1252]
    --lambdaUll:               Number of UDP packets in one second for ultra low latency traffic [10000]
    --lambdaBe:                Number of UDP packets in one second for best effor traffic [10000]
    --simTime:                 Simulation time [+1s]
    --numerologyBwp1:          The numerology to be used in bandwidth part 1 [4]
    --centralFrequencyBand1:   The system frequency to be used in band 1 [2.8e+10]
    --bandwidthBand1:          The system bandwidth to be used in band 1 [1e+08]
    --numerologyBwp2:          The numerology to be used in bandwidth part 2 [2]
    --centralFrequencyBand2:   The system frequency to be used in band 2 [2.82e+10]
    --bandwidthBand2:          The system bandwidth to be used in band 2 [1e+08]
    --totalTxPower:            total tx power that will be proportionally assigned to bands, CCs and bandwidt
    --simTag:                  tag to be appended to output filenames to distinguish simulation campaigns [de
    --outputDir:               directory where to store simulation results [./]

General Arguments:
    --PrintGlobals:               Print the list of globals.
    --PrintGroups:                Print the list of groups.
    --PrintGroup=[group]:         Print all TypeIds of group.
    --PrintTypeIds:               Print all TypeIds.
    --PrintAttributes=[typeid]:   Print all attributes of typeid.
    --PrintVersion:               Print the ns-3 version.
    --PrintHelp:                  Print this help message.
```

```
[0/2] Re-checking globbed directories...
ninja: no work to do.
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 6000
  Tx Bytes:   7680000
  TxOffered:  102.400000 Mbps
  Rx Bytes:   7671040
  Throughput: 102.280533 Mbps
  Mean delay:  0.835065 ms
  Mean jitter:  0.119991 ms
  Rx Packets: 5993
Flow 2 (1.0.0.2:49154 -> 7.0.0.3:1235) proto UDP
  Tx Packets: 6000
  Tx Bytes:   7680000
  TxOffered:  102.400000 Mbps
  Rx Bytes:   7671040
  Throughput: 102.280533 Mbps
  Mean delay:  0.835065 ms
  Mean jitter:  0.119991 ms
  Rx Packets: 5993
```

EXAMPLE: ENABLE SOME OF NR/LTE LOGS

- **Enable different types of logs:**

NS_LOG=NrHelper ./ns3 run cttc-nr-demo

NS_LOG=GridScenarioHelper ./ns3 run cttc-nr-demo

NS_LOG=LtePdcp ./ns3 run cttc-nr-demo

NS_LOG=LteRlcUm ./ns3 run cttc-nr-demo

NS_LOG=NrGnbMac ./ns3 run cttc-nr-demo

NS_LOG=NrMacSchedulerNs3 ./ns3 run cttc-nr-demo

NS_LOG=NrGnbPhy ./ns3 run cttc-nr-demo

NS_LOG=NrAmc ./ns3 run cttc-nr-demo

NS_LOG=IdealBeamformingHelper ./ns3 run cttc-nr-demo

EXAMPLE: NR TRACES

- In cttc-nr-demo.cc enable traces: **nrHelper->EnableTraces();**
- Rerun, in the root project folder there will be 23 trace files generated:

1. UlPathlossTrace.txt
2. TxedUePhyCtrlMsgsTrace.txt
3. TxedGnbPhyCtrlMsgsTrace.txt
4. RxedUePhyCtrlMsgsTrace.txt
5. RxedGnbPhyCtrlMsgsTrace.txt
6. NrUlRlcStatsE2E.txt
7. NrUlPdcpStatsE2E.txt
8. NrDlRlcStatsE2E.txt
9. NrDlPdcpStatsE2E.txt
10. DlPathlossTrace.txt
11. DlCtrlSinr.txt
12. TxedUeMacCtrlMsgsTrace.txt
13. TxedGnbMacCtrlMsgsTrace.txt
14. RxPacketTrace.txt
15. RxedUePhyDlDciTrace.txt
16. RxedUeMacCtrlMsgsTrace.txt
17. RxedGnbMacCtrlMsgsTrace.txt
18. NrDlTxRlcStats.txt
19. NrDlRxRlcStats.txt
20. NrDlPdcpTxStats.txt
21. NrDlPdcpRxStats.txt
22. NrDlMacStats.txt
23. DlDataSinr.txt

5G-LENA MODULES ROADMAP & POTENTIAL CONTRIBUTIONS

- Ideally, in future, the NR module will have its own 3GPP NR standard compliant:
  - RLC (TBD, contributions welcome!)
  - PDCP (TBD, contributions welcome!)
  - RRC (some work has been done by OpenSim CTTC, but not clear yet the release date, if you also work on this contact us to sync!)
  - Core Network (TBD, contributions welcome!)
- NR-U module needs to be upgraded to the latest NR release

5G-LENA MODULES ROADMAP & POTENTIAL CONTRIBUTIONS

- Once the NR module will have its own upper layers, the development done in its custom ns-3-dev should be moved to the corresponding layers in the NR module
- currently these changes are in the LTE module, because the NR module does not have its own implementation of these layers

TOWARDS EVOLVED 5G-LENA

5G NR Network Simulator

- 5G:
  - NR RLC, PDCP, SDAP, RRC layers
  - 5G core network
  - Full MIMO model (PHY, MAC)
  - Simplified channel model (alternative to 3GPP SCM)

- 5G-Advanced:
  - XR enhancements, QoS management
  - AIML for the air interface
  - sidelink evolution
  - MIMO evolution for DL/UL
  - Enhanced dynamic spectrum access
  - UAVs support and NTN improvements
  - Full duplex

- 6G: Once defined by the standard…
  - Channel modeling for above 100GHz frequency bands
  - 6G RAN modeling: PHY, MAC, RLC, etc.
  - 6G-compliant PHY abstraction model, considering PHY split
  - Decentralized RAN architecture

5G-LENA DEVELOPMENT STRATEGY

- Many new features to be developed towards 5G-Advanced and 6G and many researchers and companies are already using 5G-LENA to implement them, but they are rarely contributing back to 5G-LENA public repository
- Collaborative development by researchers and telecom companies from all around the globe can accelerate 5G-LENA development towards 6G
- More users/companies -> more testing, validations, calibrations
- **Objective:** encourage contributions to 5G-LENA by researchers/companies
- **How?**
  - Since 2022, 5G-LENA has fully **open-access**, so that: 1) anyone can access (no need for permission), 2) anyone can create merge requests towards NR public repo
  - **More often** 5G-LENA **releases**, so all companies/researchers using 5G-LENA can easily upgrade their code and stay up-to date to the latest 5G-LENA easier contributions
  - New **release strategy**: each 5G-LENA release is linked to a specific ns-3-dev release (previously, we were aligned with ns-3-dev master, and this was creating problems to some researchers/companies)
  - More **tutorials** to help start with 5G-LENA
  - GSoC, collaborations with universities

HOW TO CONTRIBUTE?

- Merge requests are allowed since June 2022
- When to contribute? If you do some of the following with 5G-LENA:
  - find and solve some bug
  - add some new parameter
  - create a completely and different example or test
  - parametrize existing piece of code
  - develop a completely new feature
  - extend the tracing system through files or the databases
  - improve visualization of the scenario through the python scripts
  - or whatever else that you think would be useful to other NR users

HOW TO CONTRIBUTE?

- Contributing process is basically the same as for the ns-3 simulator
- Basic steps:
  - create your own fork from the public nr,
  - create a feature branch on your forked NR repo, and
  - once the pipelines pass, and you consider clean and ready for review create a MR towards official NR master branch: https://gitlab.com/cttc-lena/nr

NR MODULE PUBLICATION LIST

Journal publications (1):

- *L. Vignati, G. Nardini, M. Centenaro, P. Casari, S. Lagen, B. Bojovic, S. Zambon, L. Turchet, Is Music in the Air? Evaluating 4G and 5G Support for the Internet of Musical Things, IEEE Access, 2024.*
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- *B. Bojovic, S. Lagen, K. Koutlia, X. Zhang, P. Wang, L. Yu, Enhancing 5G QoS Management for XR Traffic Through XR Loopback Mechanism, IEEE Journal on Selected Areas in Communications, vol. 41, no. 6, pp. 1772-1786, June 2023.*
- *K. Koutlia, B. Bojovic, S. Lagen, X. Zhang, P. Wang, J. Liu, System Analysis of QoS Schedulers for XR Traffic in 5G NR, Elsevier Simulation Modelling Practice and Theory 125 (2023), 102745*
- *S. Lagen, B. Bojovic, K. Koutlia, X. Zhang, P. Wang, Q. Qu, QoS Management for XR Traffic in 5G NR: A Multi-Layer System View & End-to-End Evaluation, IEEE Communications Magazine, May 2023.*
- *S. Lagen, X. Gelabert, L. Giupponi, A. Hansson, Fronthaul-aware Scheduling Strategies for Dynamic Modulation Compression in Next Generation RANs, IEEE Transactions on Mobile Computing, vol. 22, no. 5, pp. 2725-2740, May 2023, DOI.*
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- *S. Lagen, X. Gelabert, A. Hansson, M. Requena, L. Giupponi, Fronthaul Compression Control for shared Fronthaul Access Networks, IEEE Communications Magazine, May 2022. Available here.*

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Journal publications (2):

- *K. Koutlia, B. Bojovic, Z. Ali, S. Lagen, Calibration of the 5G-LENA System Level Simulator in 3GPP reference scenarios, Elsevier Simulation Modelling Practice and Theory (SIMPAT), May 2022. Available here.*
- *S. Lagen, X. Gelabert, A. Hansson, M. Requena, L. Giupponi, Fronthaul Compression Control for shared Fronthaul Access Networks, in IEEE Communications Magazine, May 2022. Available here.*
- *S. Lagen, X. Gelabert, L. Giupponi, A. Hansson, Fronthaul-aware Scheduling Strategies for Dynamic Modulation Compression in Next Generation RANs, in IEEE Transactions on Mobile Computing, Nov. 2021, DOI.*
- *Z. Ali, S. Lagen, L. Giupponi, R. Rouil, 3GPP NR V2X Mode 2: Overview, Models and System-level Evaluation, IEEE Access, vol. 9, pp. 89554-89579, June 2021, DOI.*
- *S. Lagen, L. Giupponi, A. Hansson, X. Gelabert, Modulation Compression in Next Generation RAN: Air Interface and Fronthaul trade-offs, IEEE Communications Magazine, Vol. 59, No. 1, pp. 89-95, January 2021, DOI.*
- *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.*
- *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.*
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- *G. Frangulea, B. Bojovic, S. Lagen, NR-U and WiFi Coexistence in sub-7 GHz bands: Implementation and Evaluation of NR-U Type 1 Channel Access in NS3, in Workshop on ns-3, June 2024.*
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- *B. Bojovic, S. Lagen, Enabling NGMN mixed traffic models for ns-3, in Workshop on ns-3, June 2022.*
- *B. Bojovic, Z. Ali, S. Lagen, ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO, in Workshop on ns-3, June 2022.*
- *S. Lagen, X. Gelabert, L. Giupponi, A. Hansson, Fronthaul-Aware Scheduling Strategies for Next Generation RANs, in Proceedings of Global Communications Conference (GLOBECOM), 7-11 December 2021, Madrid (Spain).*
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- *T. Zugno, M. Drago, S. Lagen, Z. Ali, M. Zorzi, Extending the ns-3 Spatial Channel Model for Vehicular Scenarios, in Workshop on ns-3, June 2021. Available* *here*.
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- *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*.

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