

5G-LENA NR MODULE OVERVIEW: MODELS, IMPLEMENTATION, NR-U EXTENSION AND EXAMPLES

21/06/2022, WNS3 TUTORIAL

BILJANA BOJOVIĆ

SENIOR RESEARCHER

OpenSim Research Unit at CTTC, Spain



Centre Tecnològic de
Telecomunicacions de Catalunya

ORGANIZATION

- **13:30 – 14:30 UTC**
 - **Part I: The theoretical part**
 - The introduction to the NR module,
 - The NR module architecture and design, the NR protocol stack,
 - The main PHY/MAC features in the NR module,
 - NR module calibration,
 - NR-U extension, and
 - NR module helpers.
- **14:30 – 14:45 UTC**
 - **15 min break**
- **14:45 – 15:15 UTC**
 - **Part II: The practical part**
 - A hands-on session using a typical NR module example, with a goal to explain how to build the desired topology, configure the NR parameters, go through the NR module traces and logs.
 - NR module learning resources, team members, contributing to NR module and publications.



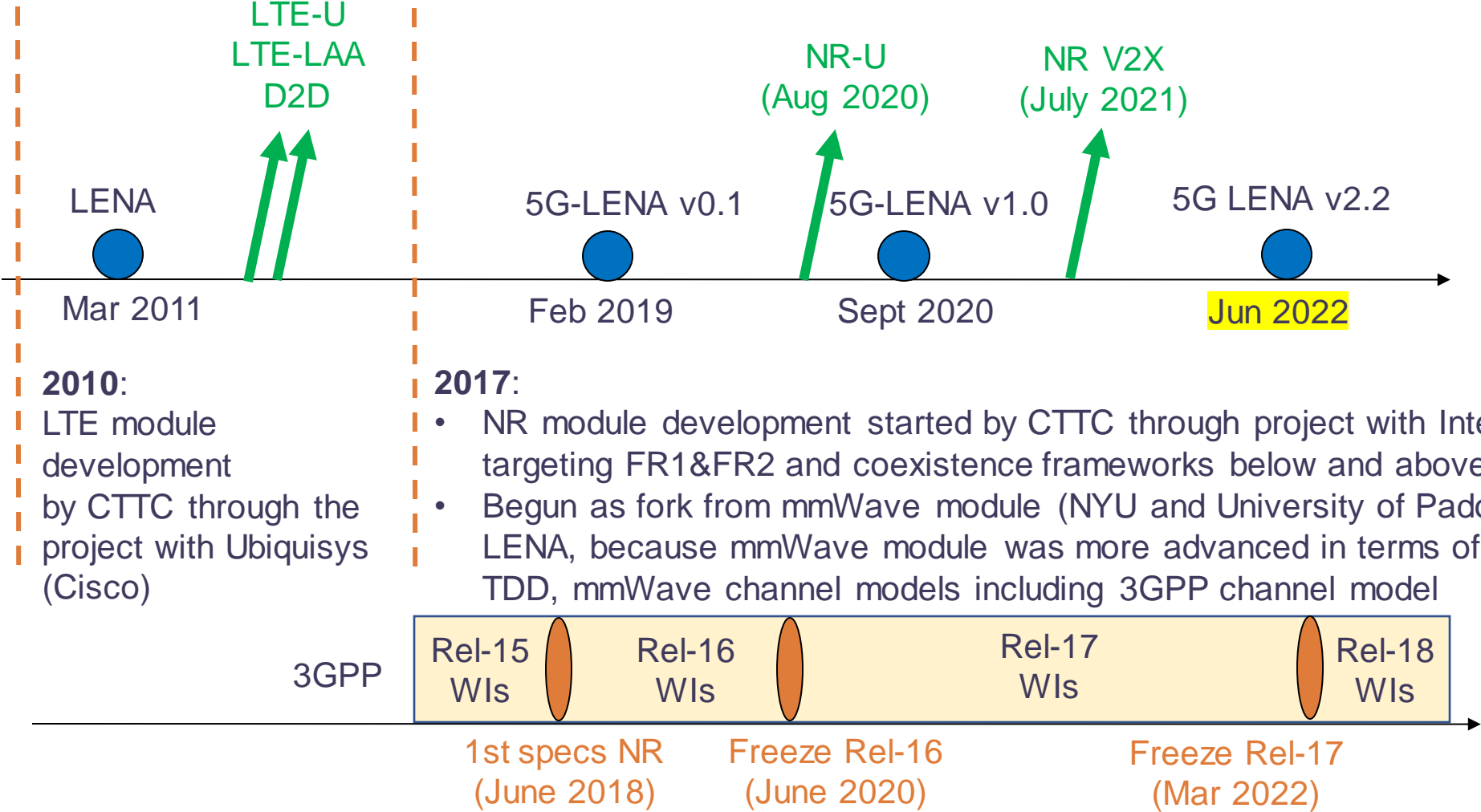
NR MODULE PART I: THEORETICAL PART

- 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 HISTORY: RELEASES AND EXTENSIONS

4G LTE: ns-3 LENA module and its extensions (LTE-U, LAA, D2D)

5G NR: ns-3 NR module and extensions (NR-U, V2X)



NR MODULE MODELING FEATURES AND ASSUMPTIONS (1/2)

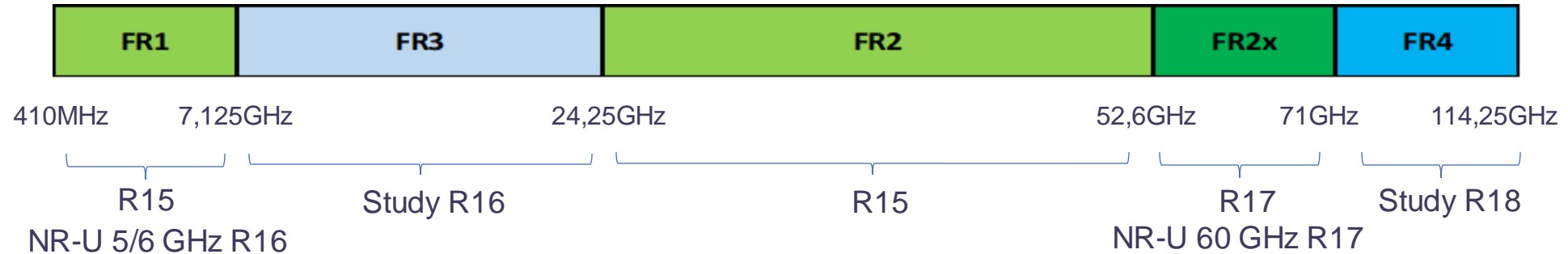
- NSA architecture: 5G RAN and 4G EPC
- Flexible and automatic configuration of the NR frame structure through multiple numerologies
- OFDMA and TDMA-based access modes with variable TTIs
 - Radio signal model granularity in time domain: OFDM symbol.
 - Radio signal model granularity in frequency domain: Resource Block.
- Schedulers: PF, RR and MR
- PHY layer abstraction:
 - Considering LDPC codes for data channels
 - PHY abstraction for DL and UL control channels: No error model.
- Duplexing schemes: TDD/FDD
- 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 : Realistic S1-AP, X2-C, S5 and S11 models.
- Simplified EPC: One MME and one SGW and PGW.

NR MODULE MODELING FEATURES AND ASSUMPTIONS (2/2)

- Support for FDM of numerologies through different bandwidth parts (BWPs)
- UL grant-based access scheme with scheduling request and 3GPP-compliant buffer status reporting
- NR-compliant processing timings (K1, K2)
- BWP/CC managers and architecture to support operation through multiple BWPs/CCs
- Beamforming
 - 2 ideal beamforming methods: no physical resource is employed, ideal channel state acquisition is assumed, computed offline (no real training, no 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: Dual-Polarized MIMO model, exploiting dual-polarized antennas, up to 2 streams per user, rank indicator reporting support and rank adaptation algorithms based on SINR thresholds

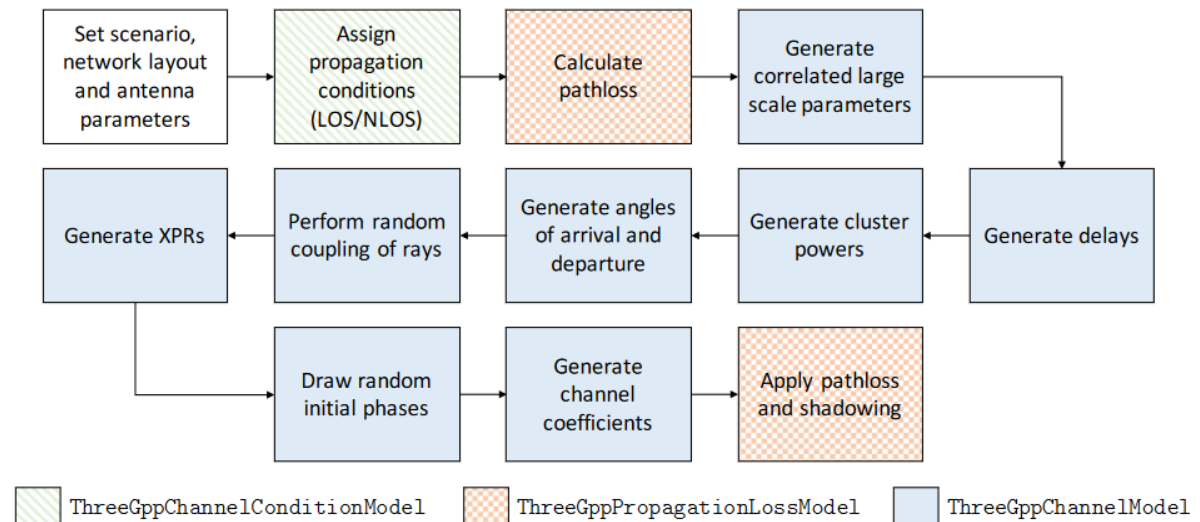
5G-LENA FREQUENCY BANDS

- 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



5G-LENA: CHANNEL MODEL

- Spatial channel model 3GPP TR 38.901 (0.5-100 GHz freq. range)
- **Pathloss and shadowing:**
 - Available models: InH Office-Open, InH Office-Mixed, Rural Macro, Urban Macro, Urban Micro Street-Canyon, V2V-Highway, V2V-Urban
 - LOS and NLOS conditions can also be enforced
- **Fast fading:** follows step-by-step the 3GPP channel model in TR 38.901 to generate channel matrices; N clusters, M rays, AoD/AoA, Doppler, polarization
- **Channel generation procedure:**



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*.

NR END-TO-END ARCHITECTURE OVERVIEW

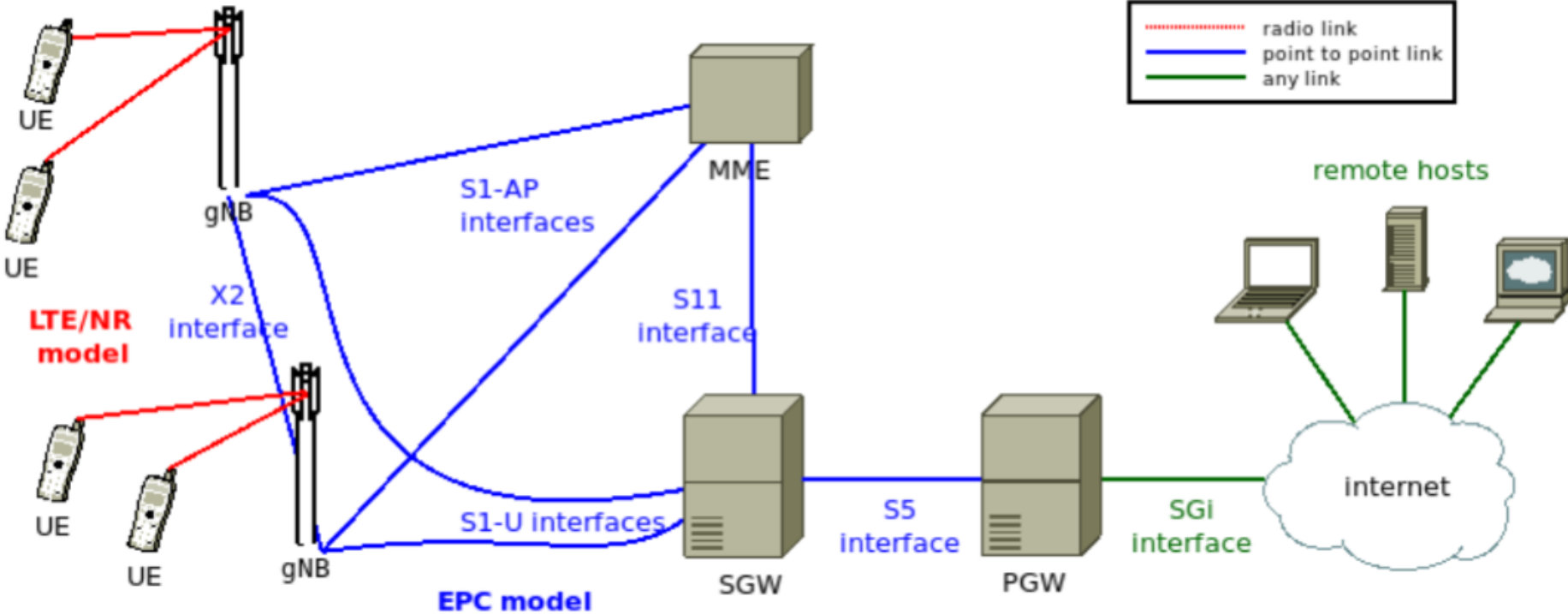
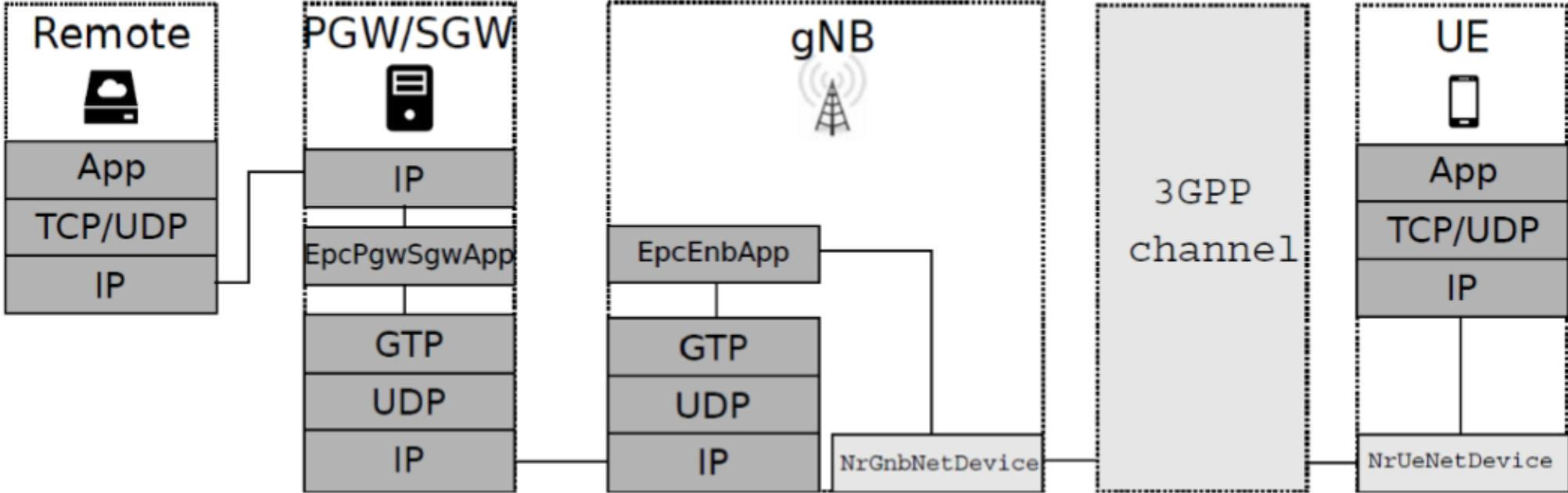


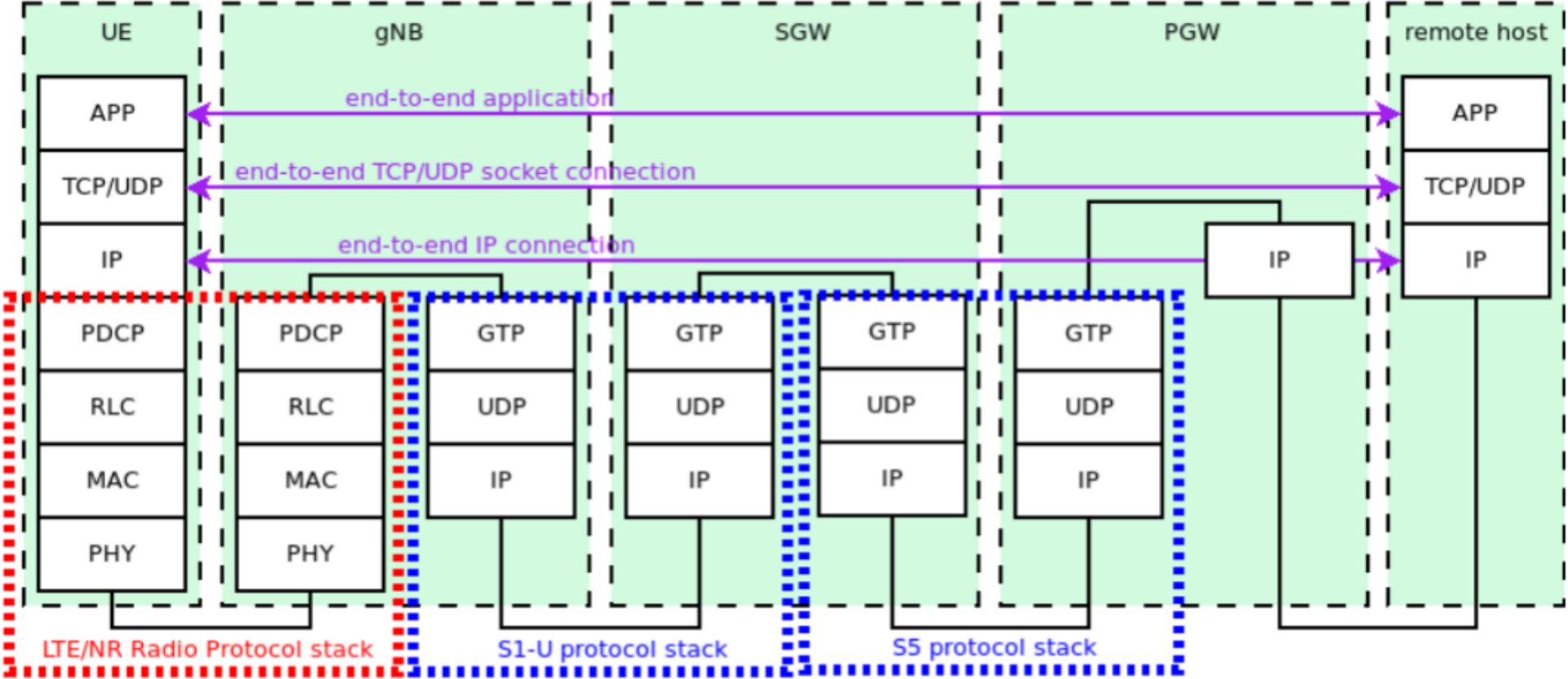
Figure: End-to-end overview

NR END-TO-END ARCHITECTURE OVERVIEW

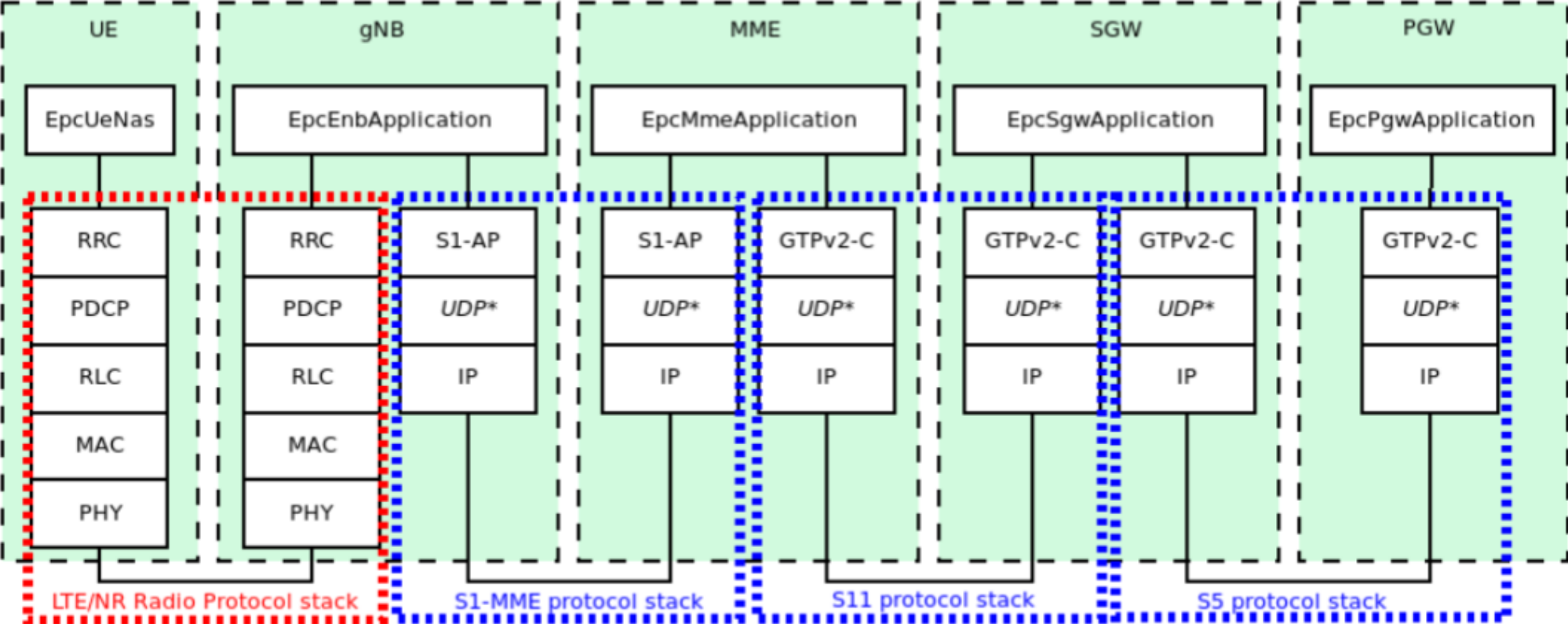


LTE/NR DATA PLANE PROTOCOL STACK

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



LTE/NR CTRL PLANE PROTOCOL STACK



NR PROTOCOL STACK AND ARCHITECTURE

- NR module dependencies
 - NR module has completely new MAC and PHY
 - NR module relies on the upper layers from the LTE module: RLC, PDCP, NAS, RRC, and, also, the EPC
- In this tutorial we focus on the NR module models, thus we focus on PHY and MAC, and in general on NR module models and helpers
- Later in the slides we will explain the ROADMAP

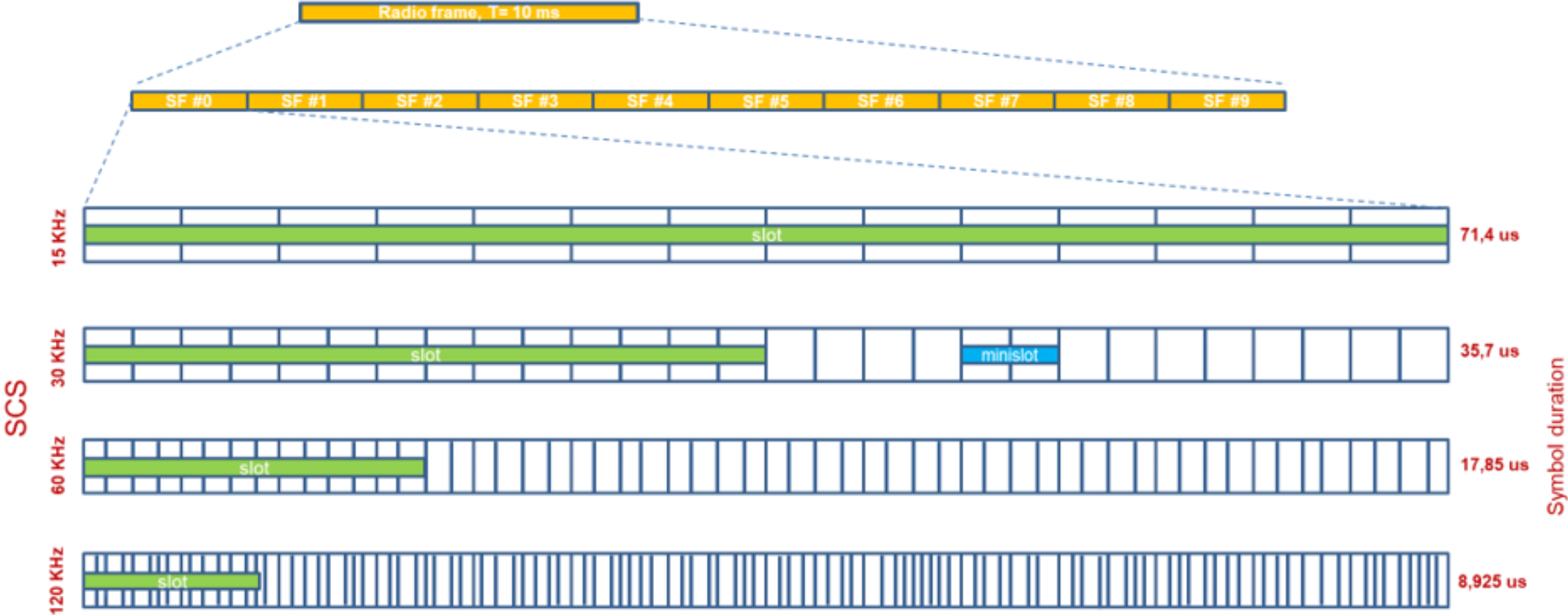


NR PHY LAYER

- Frame structure model and numerologies
- BWPs and FDM of numerologies
- Duplexing schemes
- 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

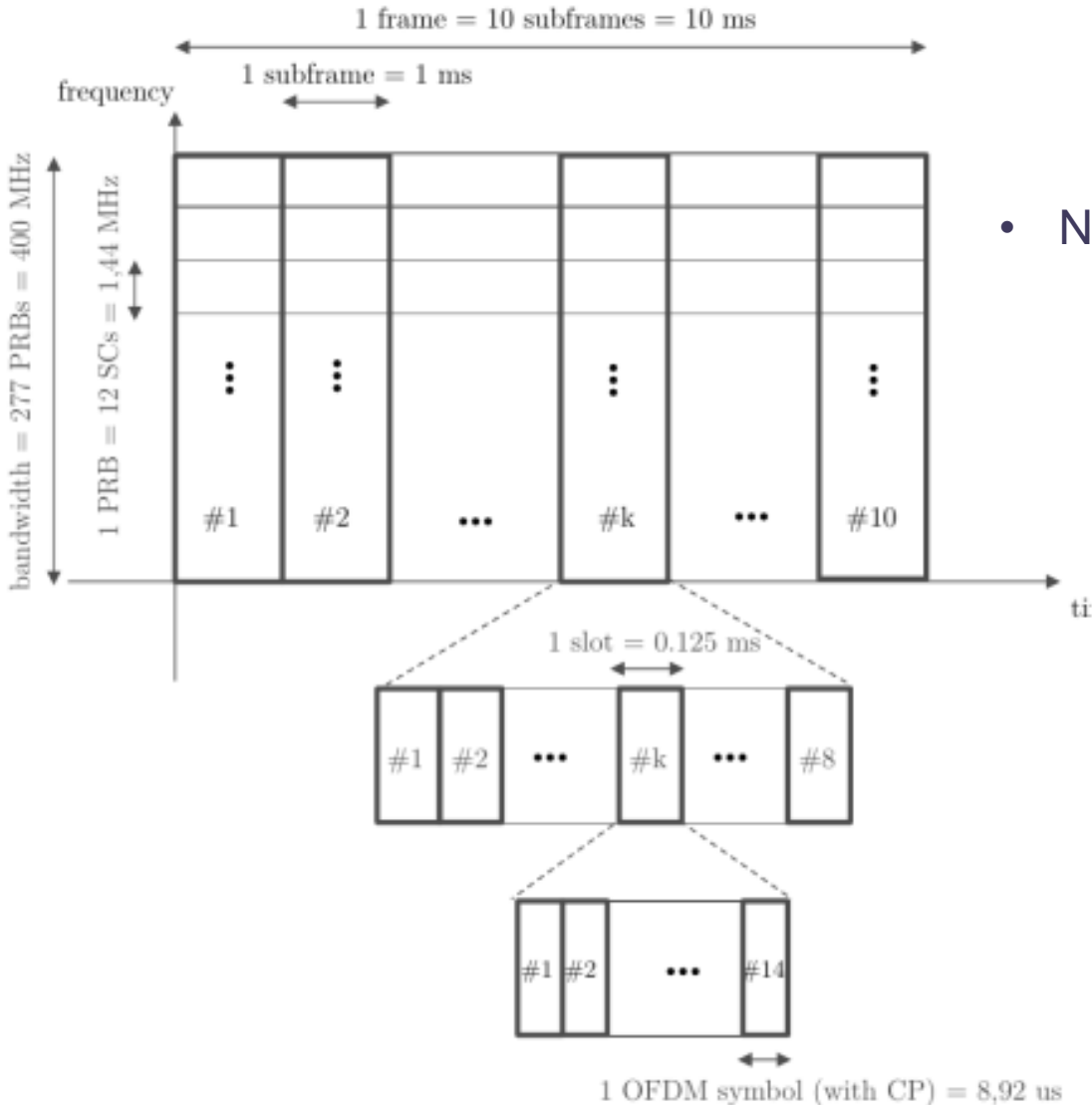
- In 5G NR, the subcarrier spacing (SCS) can range from 15 kHz to 480 kHz
- Flexible numerology results in flexible time/freq-slot structure
- 6 frame structures are currently included in the NR module



NR PHY: FRAME STRUCTURE MODEL AND NUMEROLOGIES

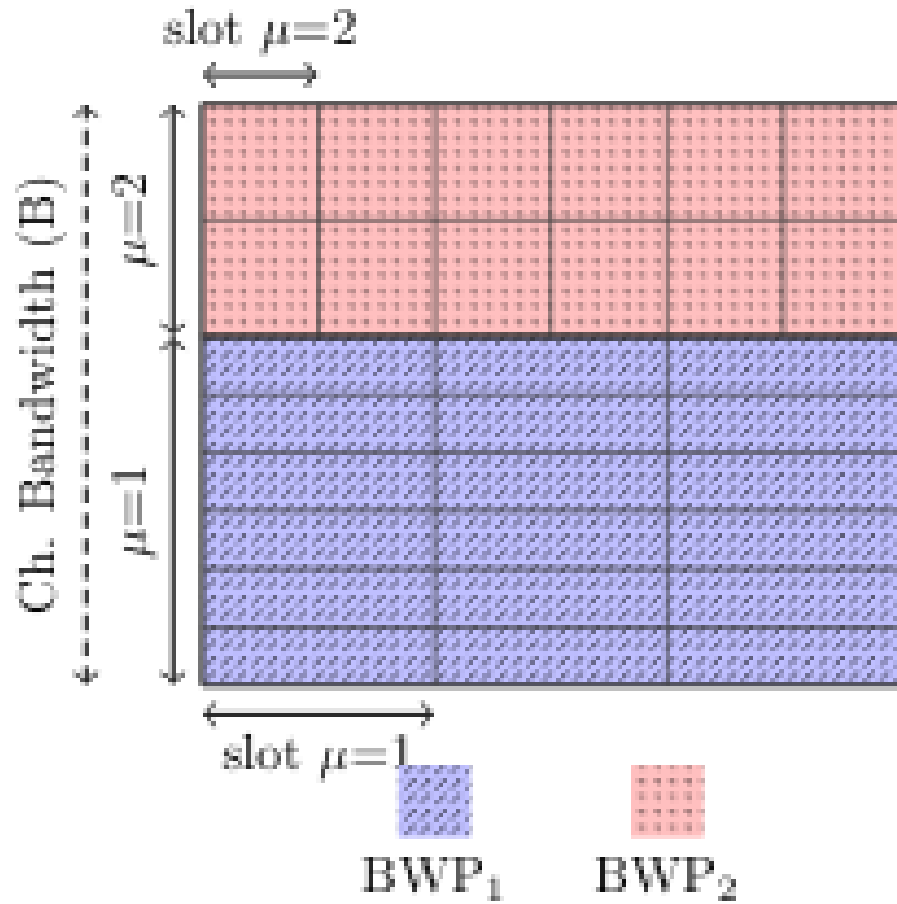
Numerology	0	1	2	3	4	5
Frame length	10ms	10ms	10ms	10ms	10ms	10ms
Number of subframes per frame	10	10	10	10	10	10
Subframe length	1ms	1ms	1ms	1ms	1ms	1ms
Number of slots per subframe	1	2	4	8	16	32
Slot length	1ms	500us	250us	125us	62.5us	31.25us
Number of OFDM symbols per slot	14	14	14	14	14	14
OFDM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

NR PHY: FRAME STRUCTURE MODEL AND NUMEROLOGIES



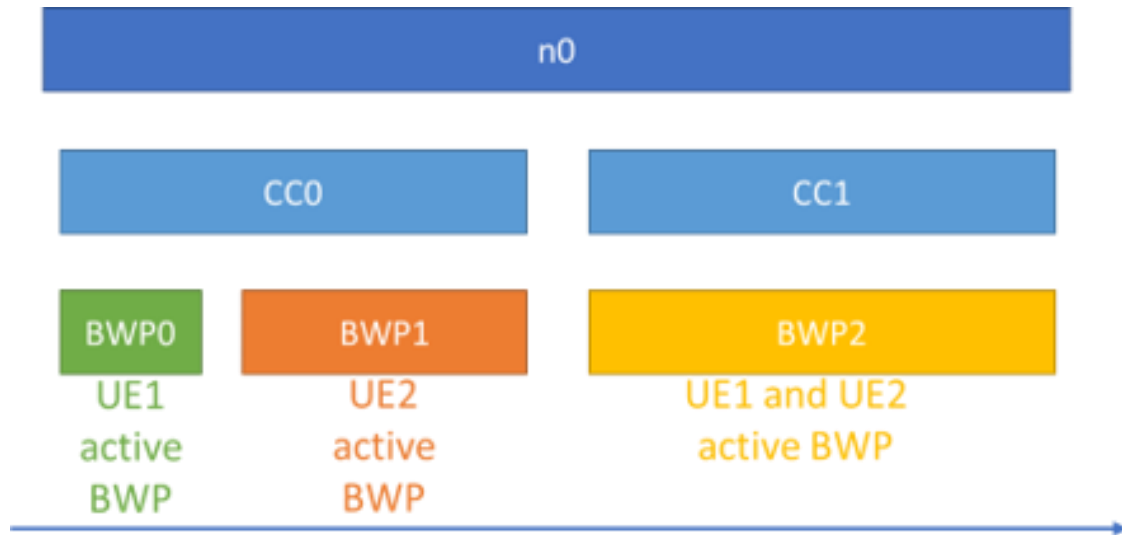
- NR frame structure example for:
 - numerology 3
 - normal CP, and
 - 400 MHz bandwidth
 - $400 \text{ MHz} / 1.44 \text{ MHz} = 277 \text{ PRB}$

NR PHY: FDM OF NUMEROLOGIES



- FDM of numerologies through different BWPs, to address the trade-off between latency and throughput for different types of traffic by physically dividing the bandwidth in two or more BWPs.
- The user can configure FDM bands statically before the simulation starts, i.e., the channel model does not support run time configurations.
- Run time reconfigurations would require RRC improvements.

NR PHY: DUPLEXING SCHEMES



- Both FDD and TDD duplexing modes are supported:
 - Frequency domain granularity: Resource Block (RB)
 - Time domain granularity: Symbol.
- A gNB can be configured with multiple carriers, some being FDD and other TDD.
- Each carrier can be further split into various BWPs, under the assumption that all the BWPs are orthogonal in frequency.
- The gNB can simultaneously transmit and receive through different BWPs.
- The UE is active in a single BWP at a time (using the current default BWP manager, however, another BWP manager algorithm can be added to the NR module to support different behaviour).

NR PHY: TDD

- With TDD, both UL and DL are implemented in one BWP, with a configured pattern.
- NR module supports configurable TDD patterns.
- The TDD pattern is represented by a vector of slot types, e.g. [D D D F U], and it is repeated with a pre-configured periodicity.
- NR supports different slot types:
 - DL-only (“D”)
 - UL-only (“U”)
 - Flexible (“F”)
 - Special (“S”)

NR PHY: FDD

- FDD duplexing is modeled through the usage of two paired bandwidth parts, where one is dedicated to transmitting DL data and CTRL, and the other for the transmission of the associated UL data and CTRL.
- The user should configure each bandwidth part with a DL-only (or UL-only) pattern, and then configure a link between the two bandwidth parts 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: the configuration is needed for correctly routing that message from one bandwidth part to the other
- DL-only and UL-only patterns:
 - DDDDDD...
 - UUUUUU...
- Paired BWPs have to be configured with the same numerology.

NR PHY: CQI FEEDBACK

- NR defines a Channel Quality Indicator (CQI), which is reported by the UE and can be used for MCS index selection at the gNB for DL data transmissions
- NR defines three tables of 4-bit CQIs (see Tables 5.2.2.1-1 to 5.2.2.1-3 in [TS 38.214])
- 5G-LTE supports CQI Table1 and CQI Table2 (i.e., Table 5.2.2.1-1 and Table 5.2.2.1-2)
- 5G-LTE supports the generation of wideband CQI that is computed based on the data channel (PDSCH). Such value is a single integer that represents the entire channel state or better said, the (average) state of the resource blocks that have been used (neglecting RBs with 0 transmitted power).
- The AMC module maps the SINR measurement to a CQI index.
- Such value 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** – the power is uniformly distributed over the whole set of RBs, i.e., power per RB is fixed. However, if an RB is not allocated to any data transmission, the transmitted power over that RB is null (no interference is generated in that RB).
 - uniform power allocation over **the active RBs**, i.e., over the set of RBs used by the transmitter (e.g., gNB in DL or UE in UL). In this case, power per RB depends on the number of the active RBs for the specific slots, depends on the scheduling, thus varies per slot.
- Regardless the power allocation scheme, 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* and configurable through the attribute *PowerAllocationType* of *NrGnbPhy* and *NrUePhy* classes.

NR PHY: INTERFERENCE MODEL

- The interference model is based on the well-known Gaussian interference models, according to which the powers of interfering signals (in linear units) are summed up together to determine the overall interference power.
- The useful and interfering signals, as well as the noise power spectral density, are processed to calculate the SNR, the SINR, and the RSSI (in dBm).
- SINR computation: 5G-LENA considers a data-based method, where both the useful and interference signals derive from the PDSCH.
- Implemented in: ***nr-interference.h/cc***

NR PHY: SPECTRUM MODEL

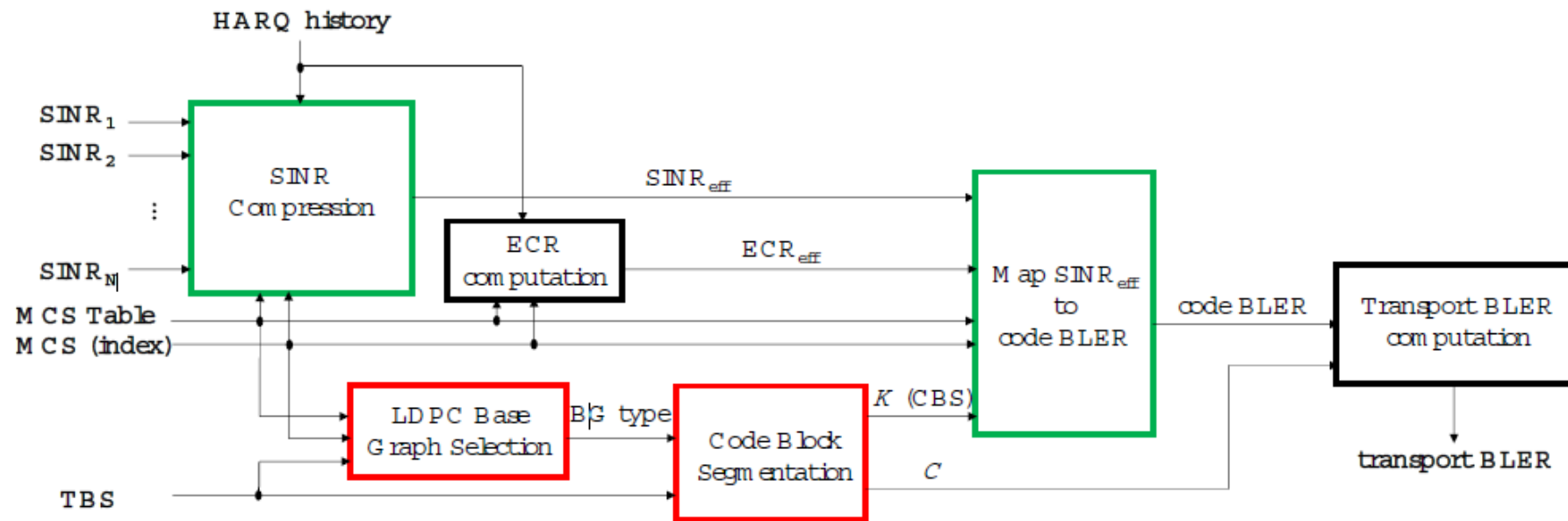
- Radio spectrum usage follows the usual way to represent radio transmission in the ns-3 simulator, i.e., the spectrum module handles the signal propagation through the wireless channel.
- Since BWPs are orthogonal, each BWP is modeled through a separate instance of the of the spectrum channel.
- Each NR device will have as many PHY instances as it supports BWPs.
- We have recently extended the spectrum model to pass as argument the antenna arrays of the transmitter and the receiver.
- The combination of the tx and rx antenna gain (given by the configured beam and the antenna element radiation pattern), the propagation loss, and the channel characteristics, provide the value of the received power spectral density for each transmitted signal.
- NR module support for the ns-3 spectru is implemented in: ***nr-spectrum-phy.h/cc:***
 - In FDD system like ns-3 LTE implementation, it is enough to attach the PHY instance only to the channel instance on which the device is listening (i.e., ***LteSpectrumPhy***)
 - However, for TDD systems the same device can transmit and receive through the same spectrum channel instance, hence the PHY layer of the devices in the NR module is more complex at the spectrum part than that of the ns-3 LTE module, i.e., ***NrSpectrumPhy*** is attached to listen on the same channel on which is also transmitting.

NR PHY: ANTENNA MODEL

- Antenna arrays: Uniform planar arrays (UPA) specified by the number of antennas in each dimension (M×N)
- Two models supported:
 - BF:
 - 1 UPA (sector) per gNB
 - 1 UPA (panel) per UE
 - SU-MIMO:
 - 1 UPA (sector) per gNB composed of 2 sub-partitions of antenna, which are cross polarized
 - 1 UPA (panel) per UE composed of 2 sub-partitions of antenna, which are cross 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

- The NR module supports an L2SM abstraction based on the Exponential Effective SNR Metric (EESM) method. This model is used for the PHY abstraction for the DL and UL DATA channels and can be used (if configured) for the AMC.
- BLER-SINR curves provided by InterDigital, for block size, base graph and MCS:
 - MCS/CQI table 1 (up to 64QAM) and MCS/CQI table 2 (up to 256QAM), as per TS 38.214
 - LDPC BG1 and BG2, and LDPC base graph 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

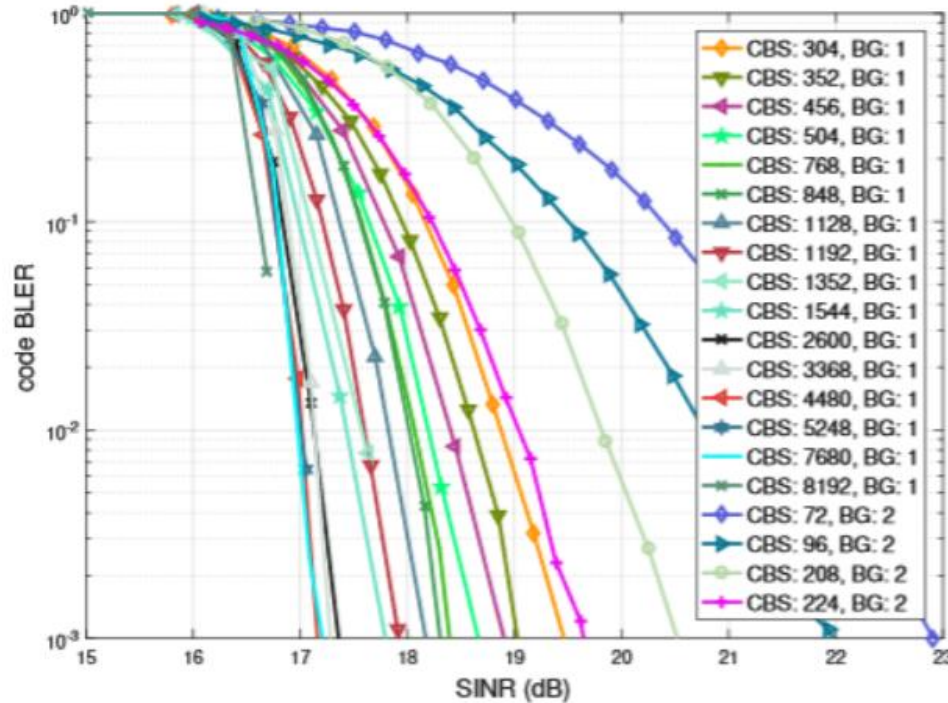


Figure: MCS23 of MCS Table1

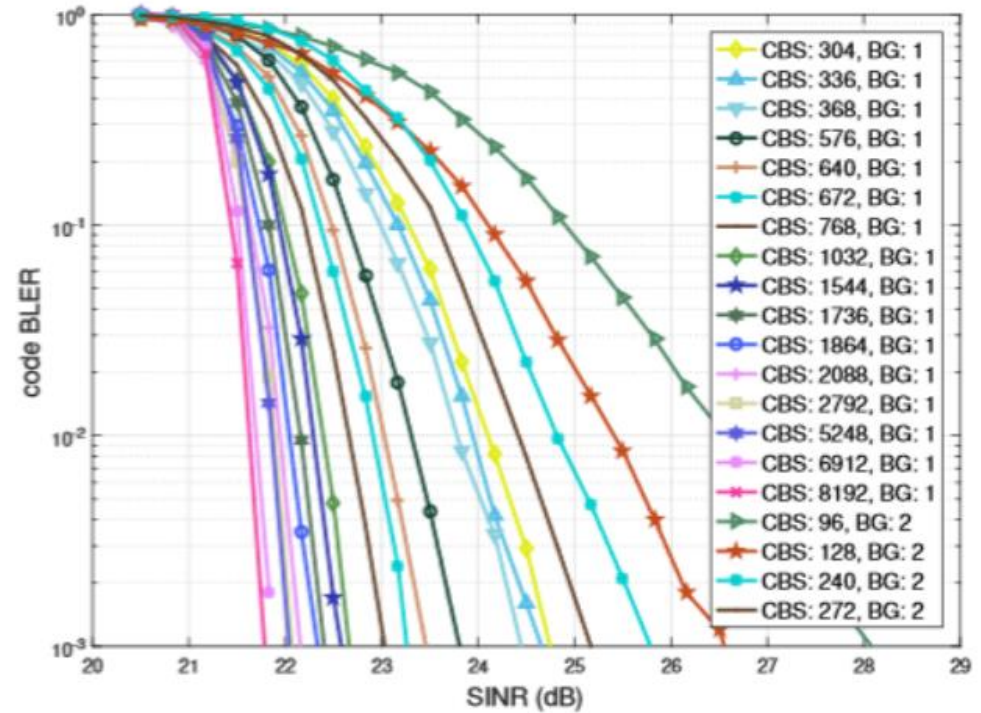


Figure: MCS21 of MCS Table2

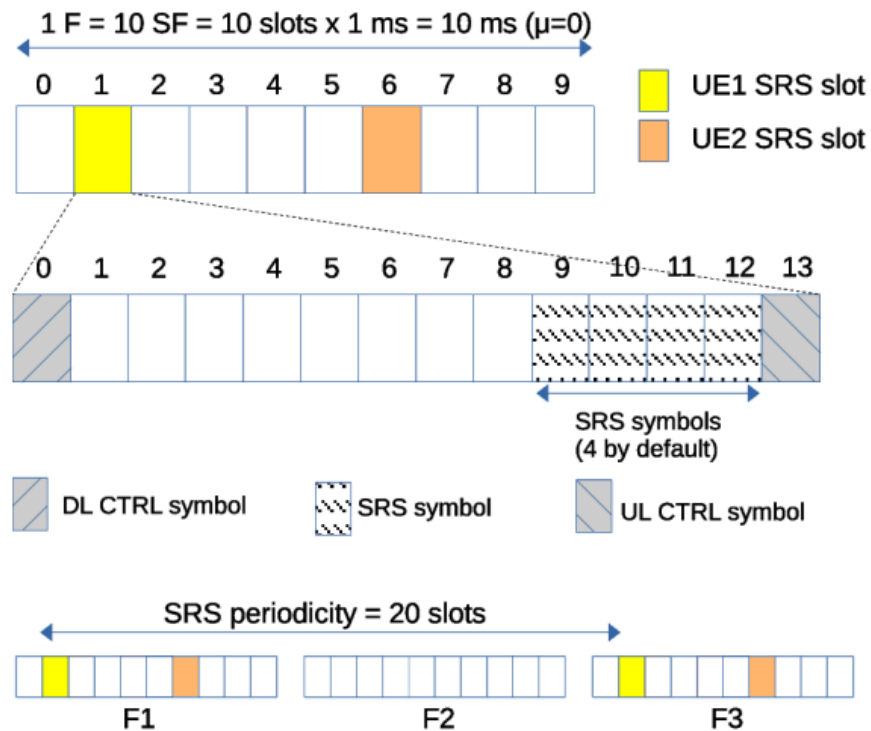
- Look up tables available in: [ns-3-dev/src/nr/model/nr-eesm-t1.cc](#) and [nr-eesm-t2.cc](#)
- MCS/CQI table 1 (up to 64QAM) and MCS/CQI table 2 (up to 256QAM)

NR PHY: BEAMFORMING MODEL

- Beamforming of the UPA is specified by means of the beamforming (BF) vector (weights of antenna elements).
- If SISO is configured, a single spatial stream is sent per receiver's UPA and the multiple antennas are used to concentrate the radiated power towards the receiver's location. If DP-MIMO then there are two streams.
- NR module supports ideal and realistic BF methods.
 1. **Ideal BF methods**, assume no physical resource is employed, ideal channel state acquisition is assumed, they are computed offline, i.e., no real training, no BF overhead. Ideal BF methods supported by the NR module are:
 - **Beam-search method** (it is assumed that there is a discrete number of beams from a pre-designed codebook; sweeps TX/RX BF vectors based on num. horizontal antennas and elevation angle steps, and chooses the best pair)
 - **LOS-path method** (assumes perfect knowledge of the pointing angle between devices (DoA); it is used to steer the BF vectors towards the LOS path)
 2. **Realistic BF**: For TDD systems, based on SRS reception, an abstraction model estimates the channel matrix. The abstraction model is used, as in typical network-level simulations, to avoid the related signal processing operations and reduce its computational complexity.
- All these methods are **analog BF methods** (only the phases of the BF weights are being changed). However, the ns-3 BF vectors are general enough to support changing also the amplitudes of the different BF weights, and so, could support hybrid and digital BF.

NR PHY: SRS TRANSMISSION AND RECEPTION

- SRS transmission typically spans over 1, 2 or 4 consecutive OFDM symbols at the end of the NR slot.
- In the frequency domain, since the minimum transmission granularity in 5G-LENA module is an RB in frequency domain, all subcarriers are used for SRS transmission.
- Implemented scheduling-based SRS (it is not configured through RRC)



- Example of SRS transmissions of 2 UEs.
 - Maximum 1 UE SRS transmission per slot in 5G-LENA due to granularity in freq.
 - Considering SRS periodicity equal to 20 slots.
 - Numerology considered is $\mu = 0$.
 - F stands for frame and SF for subframe.
- SRS scheduling is implemented in: ***nr-mac-scheduler-srs-default.h/cc***

NR PHY: UPLINK POWER CONTROL

- Uplink Power Control (ULPC) allows to adjust the transmission power of a UE, and as such it plays a critical role in reducing inter-cell Interference.
- Open and closed loop modes:
 - In the open loop the UE transmission power depends on the estimation of the downlink path loss and channel configuration.
 - In closed loop, additionally allows the gNB to control the UE transmission power by means of explicit TPC included in the DCI. In closed Loop, two modes are available:
 - the absolute mode, according to which the txPower is computed with absolute TPC values, and
 - the accumulation mode, which instead computes the txPower using accumulated TPC values
- 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***

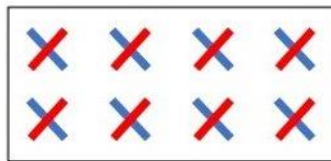
NR PHY: HARQ

- 5G-LENA HARQ features:
 - 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.
- PHY abstraction for HARQ:
 - Two methods: Chase Combining (CC) and Incremental Redundancy (IR)
 - HARQ-IR changes the effective SINR and the ECR (Effective Code Rate),
 - HARQ-CC changes the effective SINR.
 - In both cases 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*

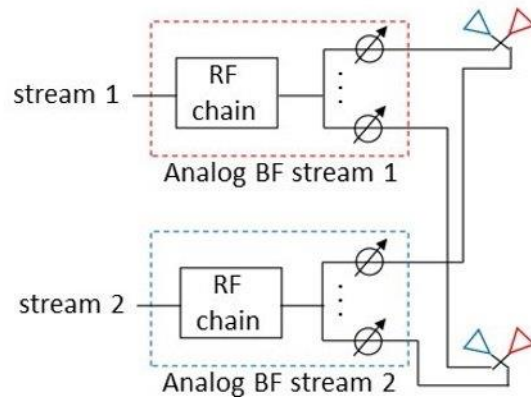
NR PHY: SU-MIMO

- 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

(a) Cross-polarized panel array antenna model in 3GPP, with $M=2$, $N=4$, $P=2$



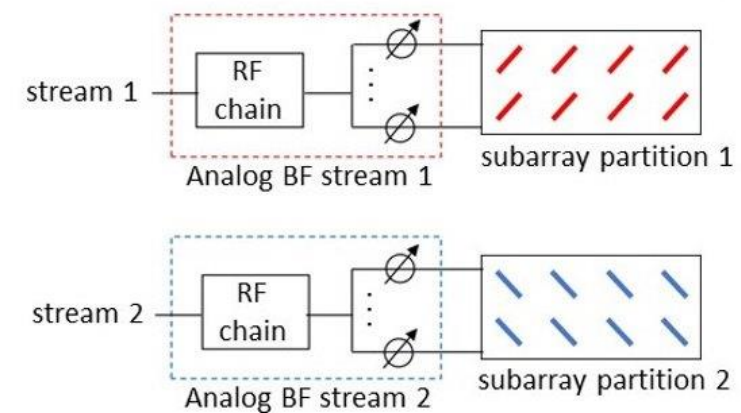
(b) MIMO model for mmWave with cross-polarized antennas



(a) Subarray partition concept for the 3GPP panel antenna array
subarray partition 1 subarray partition 2



(b) MIMO model for mmWave with subarray partition concept





NR MAC LAYER

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

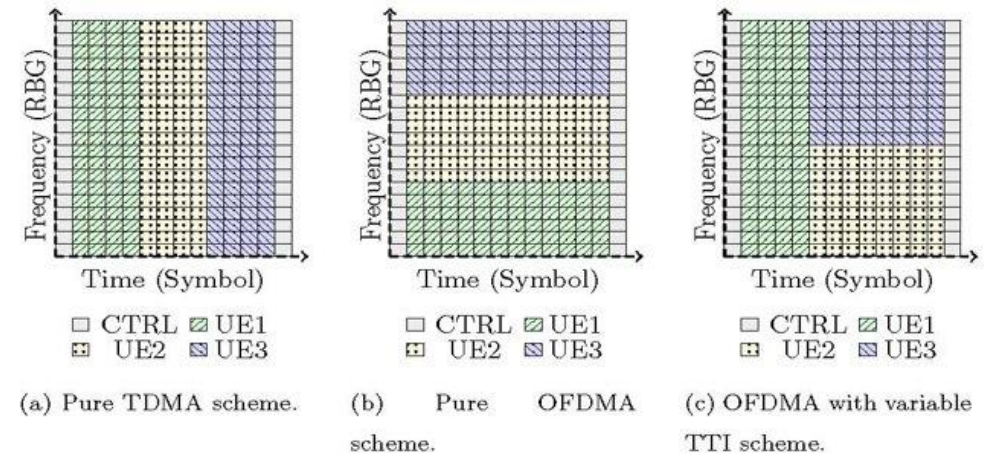
NR MAC: OFDMA AND TDMA

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.
- Depending on the SCS and the operational band, RBs are grouped into RBGs (Resource Block Group): 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 (with 1's) 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

- OFDMA and TDMA with single-beam capability and variable TTI
- TDMA: a single UE is scheduled per TTI
- Pure OFDMA: multiple UEs associated to the same beam can be scheduled per TTI, using all available symbols, but over different PRB.
- OFDMA with variable TTI: it can allocate different RBGs and a variable number of OFDM symbols.
- Dynamic scheduled based access for DL and UL (UL-grant based)

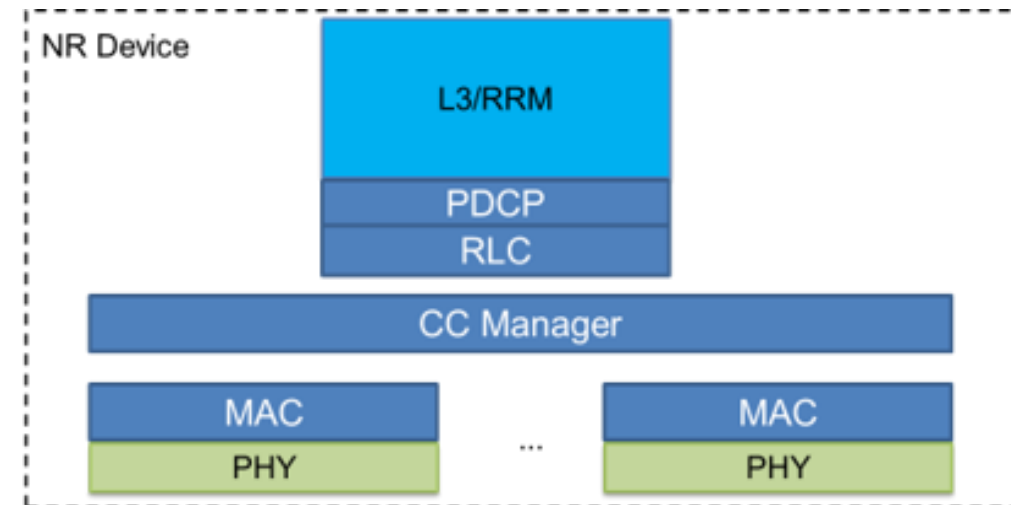


NR MAC: ADAPTIVE MODULATION AND CODING (AMC) MODEL

- 5G-LENA MAC layer supports:
 - To fix the MCS to a predefined value, both for DL and UL transmissions, separately.
 - Two AMC models for link adaptation:
 - Error model-based:
 - The MCS index is selected to meet a target transport BLER (e.g., 0.1). In this case, the PHY abstraction model is used for link adaptation.
 - Shannon-based:
 - Chooses the highest MCS that gives a spectral efficiency lower than the one provided by the Shannon rate.

NR MAC: BWP MANAGER

- NR devices have an architecture that 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
- BWP (also CC) manager:
 - Allocates flows to BWP based on their QCI (FDM of numerologies strategy for multiple BWPs)
 - Other rules/algorithms for CC manager can be implemented.



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 LCID (Logical Channel ID) subheader contains information on of the following data.
 - The Buffer Status Report is modeled as a MAC CE.

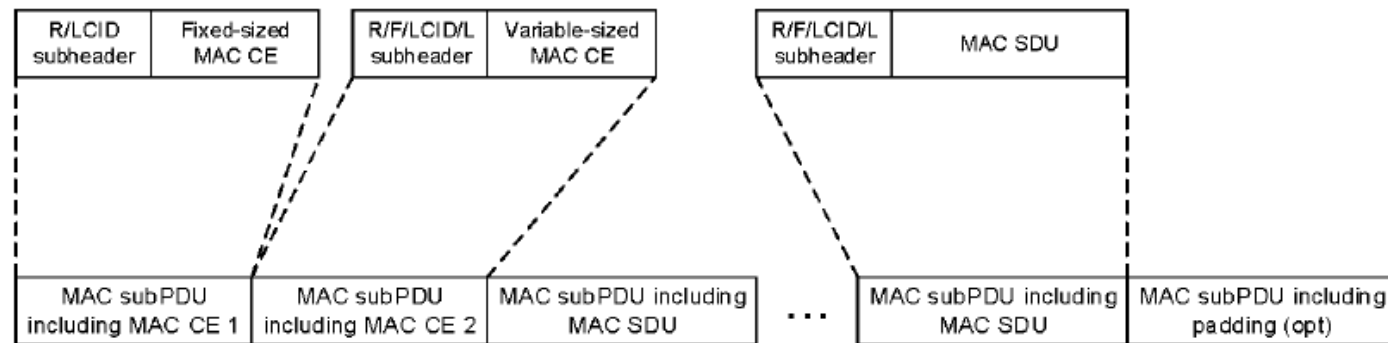


Figure: MAC PDU extracted from TS 38.321

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).
 - Quantization and limits are not included, to allow the simulator to operate in larger bandwidths than specified NR's.
 - It depends on MCS table, MCS index and resource allocation (in terms of OFDM symbols and RBs).
- TBS is computed as follows:

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

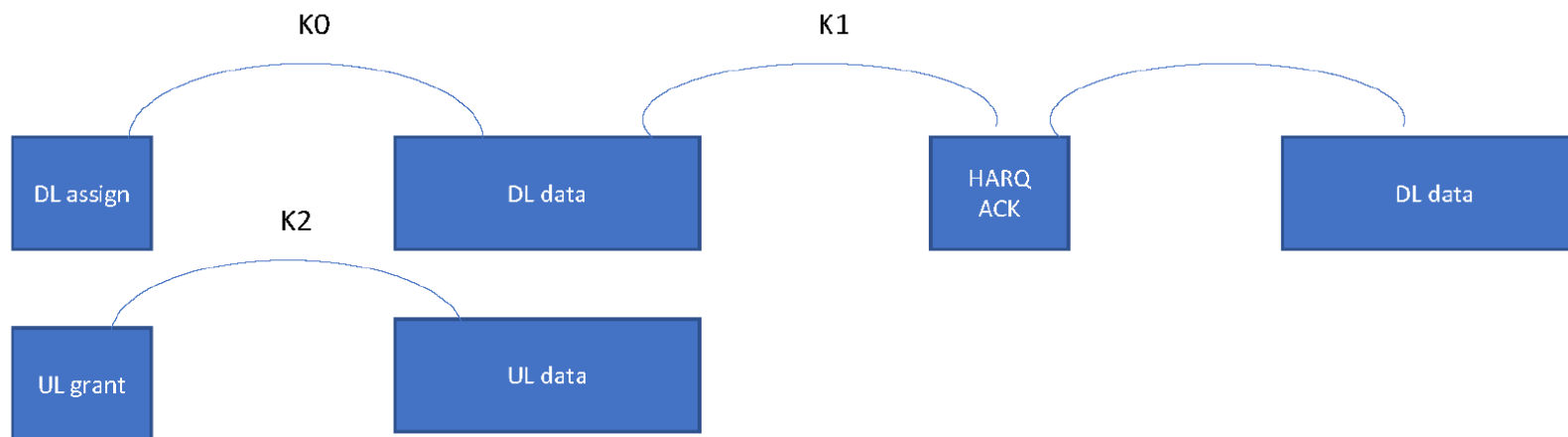
- where :
 - R is the Effective Code Rate (ECR) of selected MCS;
 - Q is the modulation order;
 - n_s is the number of allocated OFDM symbols;
 - n_{rb} is the number of allocated RBs;
 - n_{refSc} is the number of reference subcarriers carrying DMRS (Demodulation reference signal) per RB
- Finally, the CRC attachment to the TB is subtracted (24 bits).

NR MAC: SCHEDULING

- Schedulers API follows the FemtoForum specification for LTE MAC Scheduler Interface
- The core class of the NR module schedulers design is ***NrMacSchedulerNs3***.
- NR MAC scheduler model supports:
 - Dynamic scheduled based access for DL (as LTE)
 - UL grant-based (as LTE)
 - OFDMA with variable TTI: it can allocate different RBGs and a variable number of OFDM symbols.
 - For TDMA, symbols are divided among active UEs.
 - For OFDMA, symbols are divided among beams (load-based rule), and then within the symbols allocated to a beam, UEs are scheduled in different PRBs.
 - HARQ has priority over new data transmissions, UL has priority over DL.
 - Scheduling algorithms supported: PF/RR/MR, and **new QoS schedulers to be included soon!**
- 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.

NR MAC: TIMING RELATIONS

- At slot x scheduler takes decisions for :
 - DL slot $x + L1L2CtrlLatency$, and
 - UL slot $x + L1L2CtrlLatency + K2$
- NR MAC supports flexible scheduling and DL HARQ feedback timings in the communication between the eNB/gNB and the UE as specified in [TS 38.213], [TS 38.214]:
 - $K0$: 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 (since the timings are in number of slots).
 - 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 (time domain resource assignment field).

	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)

- NR MAC supports the UL scheduling request.
- The procedure can be summarized as follows:
 - In slot n , data to be transmitted arrives to the UE RLC queue. UE prepares a SR to be sent to the gNB (MAC), informing of data to transmit, and it takes 2 slots to prepare/encode the SR, 1 more slot for SR to reach the UE PHY (the air), and 1 more slot for gNB to receive the slot containing the SR. Hence, the gNB MAC receives the SR in $n + 4$.
 - The MAC scheduler schedules resources in UL in $n + 4$ for 12 bytes, to include the BSR and some data, to be sent in $n + 4 + L1L2 + K2$.
 - **The UE receives the UL DCI at $n + 4 + L1L2$** and uses additional $K2$ slots to prepare the data plus the BSR.
 - At slot $n + 4 + L1L2 + K2 + 1$ the gNB MAC scheduler has received the data and BSR and knows that there is more data in UE's queue, and prepares the allocation for the UE to transmit such data at:
 $(n + 4 + L1L2 + K2 + 1) + L1L2 + K2$

NR MAC: NOTCHING

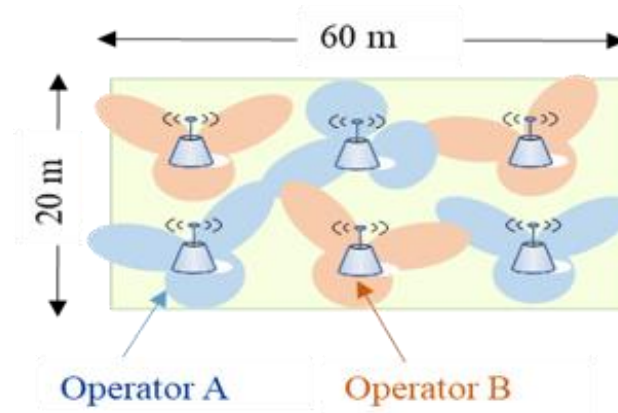
- The NR module supports UL Frequency Avoidance (UFA), aka as spectrum notching.
- Notching is a technique that restricts the usage of certain Resource Block Groups (RBGs) for UL transmissions referred to as “notched” RBGs.
- The UFA feature is implemented on top of the TDMA/OFDMA scheduler classes (*NrMacSchedulerTdma* and *NrMacSchedulerOfdma*).
- 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 lengths depends on the BW
 - An example: 1 1 1 1 1 0 1 1 1 1 0 0 0 0 1 1 1 1 0 1 1 1 1
- Based on the notching mask, the scheduler performs scheduling, e.g., calculates the number of the available RBGs, skips during the scheduling process the notched RBGs.

NR MAC: DP-MIMO

- To support MAC operation for MIMO some of the main MAC functionalities got extended:
 - CQI management
 - DCI creation
 - HARQ feedback processing
- The main classes/structures that have been extended to support multiple streams are:
 - ***NrMacSchedulerCQIManagement***, ***DCqiInfo***
 - ***DciInfoElementTdma*** (modified the TB-related structure, i.e., instead of MCS, NDI, RV, and the TB size for a single stream, now there is a C++ vector for holding TB-related information for each stream)
 - ***DIHarqiInfo*** (extended to support HARQ feedback per stream)
- Whether the scheduler at the gNB should schedule two streams or one depends on the RI value reported by a UE in a DL CQI report
- The scheduler embeds a unique HARQ process id in every DCI it creates, and this functionality remains the same, i.e., scheduler schedules multiple streams using a single DCI, thus, the same HARQ process id is used for all of them (aligned with 3GPP standard).
- In the case of NACK, scheduler keeps scheduling only one stream (for which it received NACK) until the TB is successfully decoded or the maximum number of retransmissions is reached.

NR-U EXTENSION

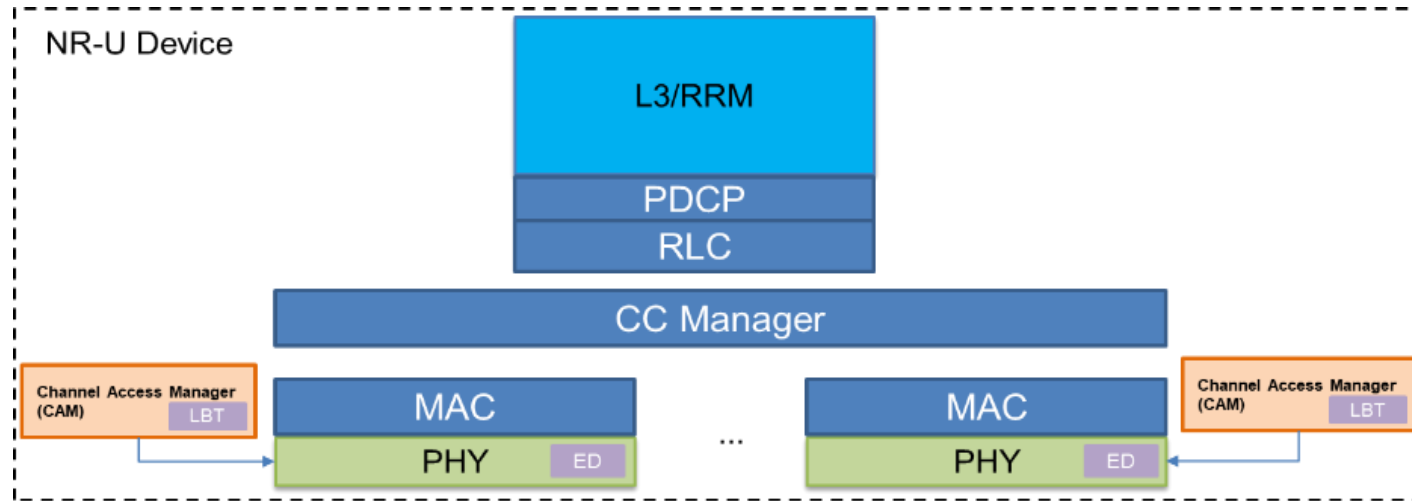
- Result from collaboration with Interdigital which started due to our previous experience with studies on coexistence at 5GHz, which we carried out with WFA and Spidercloud Wireless.
- More than 2 years of collaboration between spring 2017 and fall 2019.
- Objectives:
 - Design operation of NR-U at 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, **NR-U and IEEE 802.11 Technologies Coexistence in Unlicensed mmWave Spectrum: Models and Evaluation**, in *IEEE Access*, vol. 8, pp. 71254-71271.

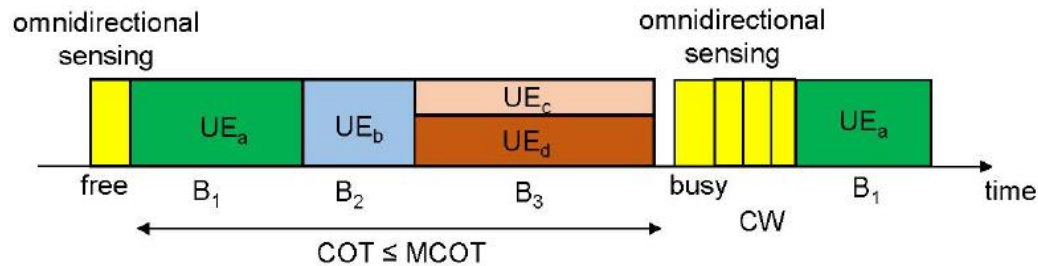
S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojovic, A. Demir, M. Beluri, **New Radio Beam-based Access to Unlicensed Spectrum: Design Challenges and Solutions**, *IEEE Commun. Surveys & Tutorials*, Oct. 2019

NR-U EXTENSION: ARCHITECTURE



Features:

- LBT after MAC
- CAM: AlwaysOn, OnOff, LBT (Cat2, Cat3, Cat4)
- 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: LBT AND ED

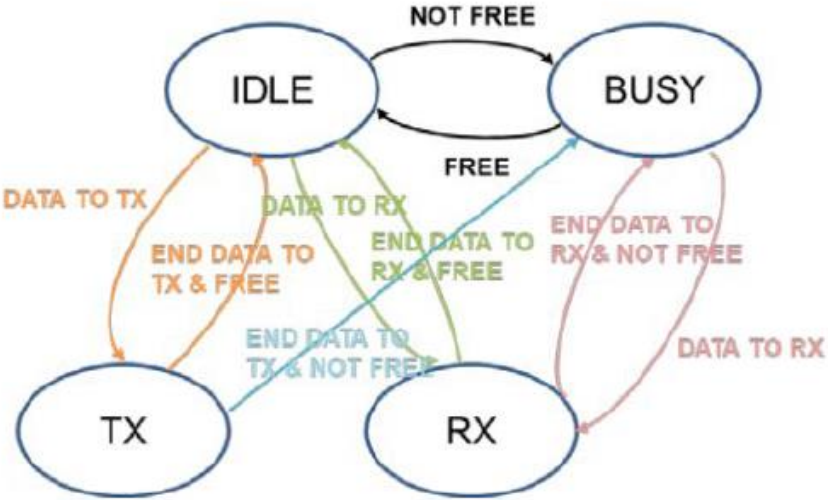
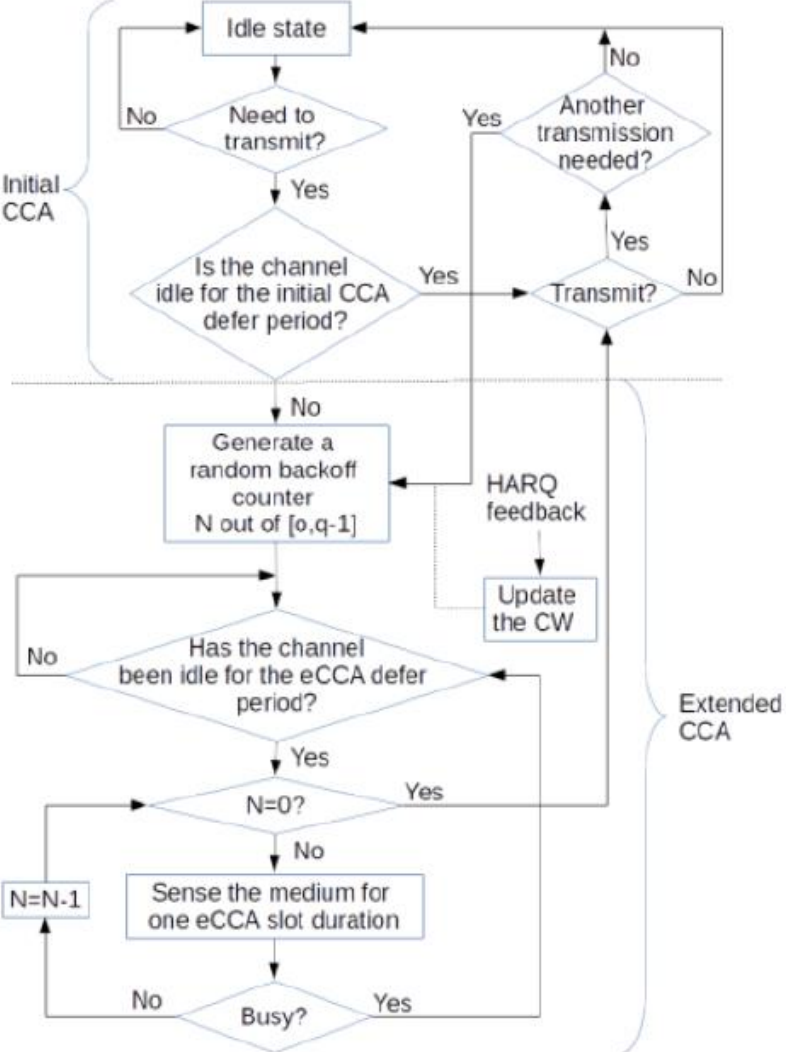
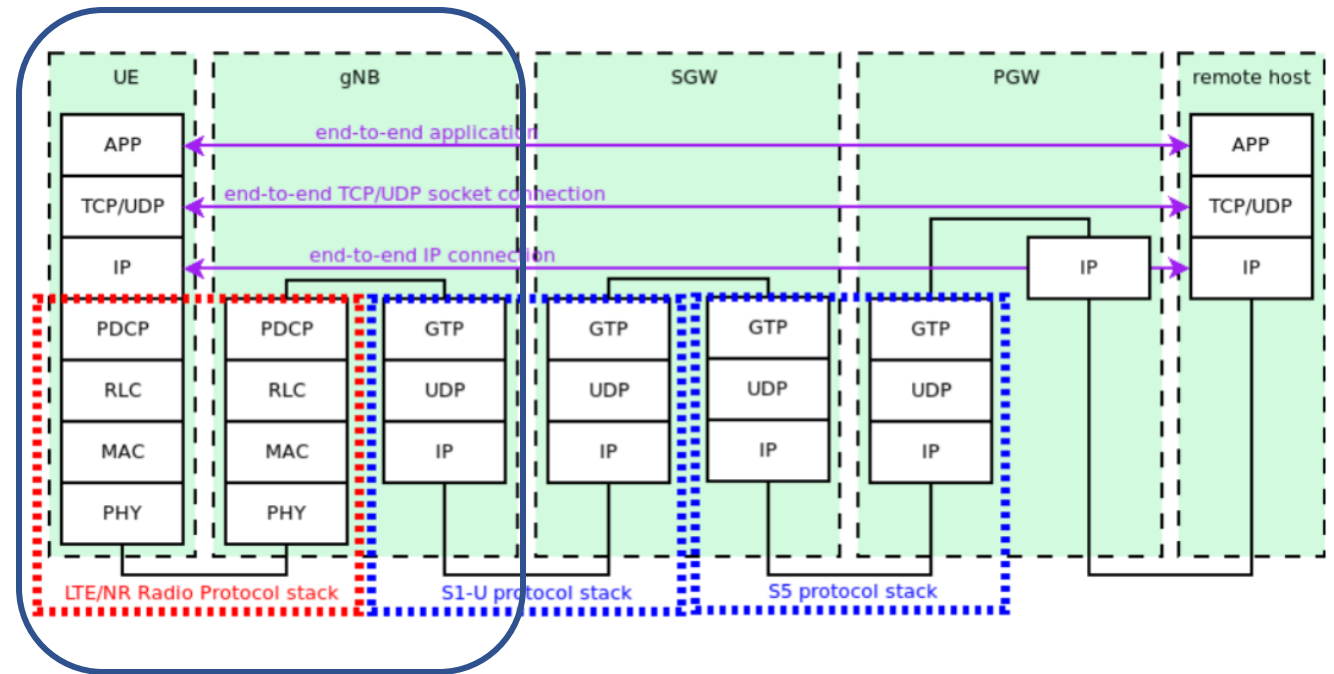


Figure: Listen Before Talk

HELPERS: NrHelper

- The main and central helper in the NR module. Why is needed?
 - Manually 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 APIs, would be nearly impossible for the users of the NR module
- **NrHelper** is there to help you with tasks such as:
 - create NR UE and gNB devices
 - attach them
 - creates 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

- For the core network is used 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.
- In this regards, we only offer the option to connect them through Point-To-Point links.

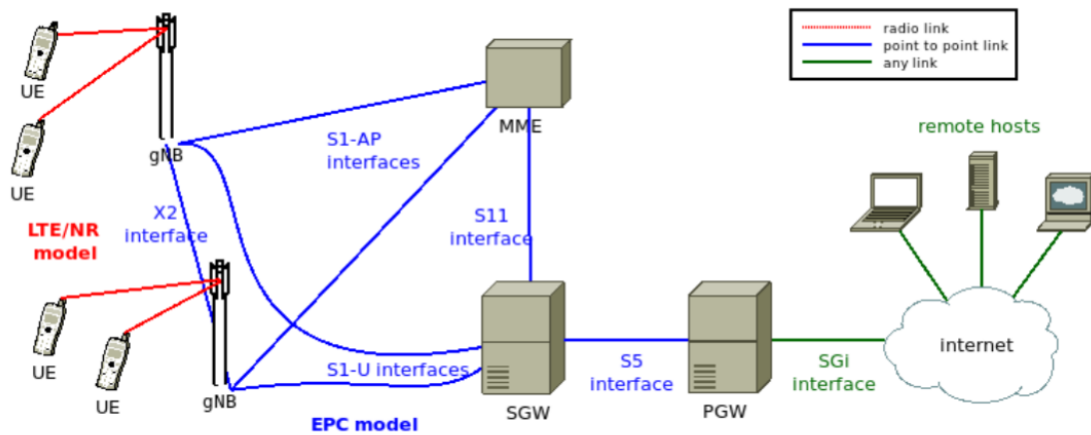
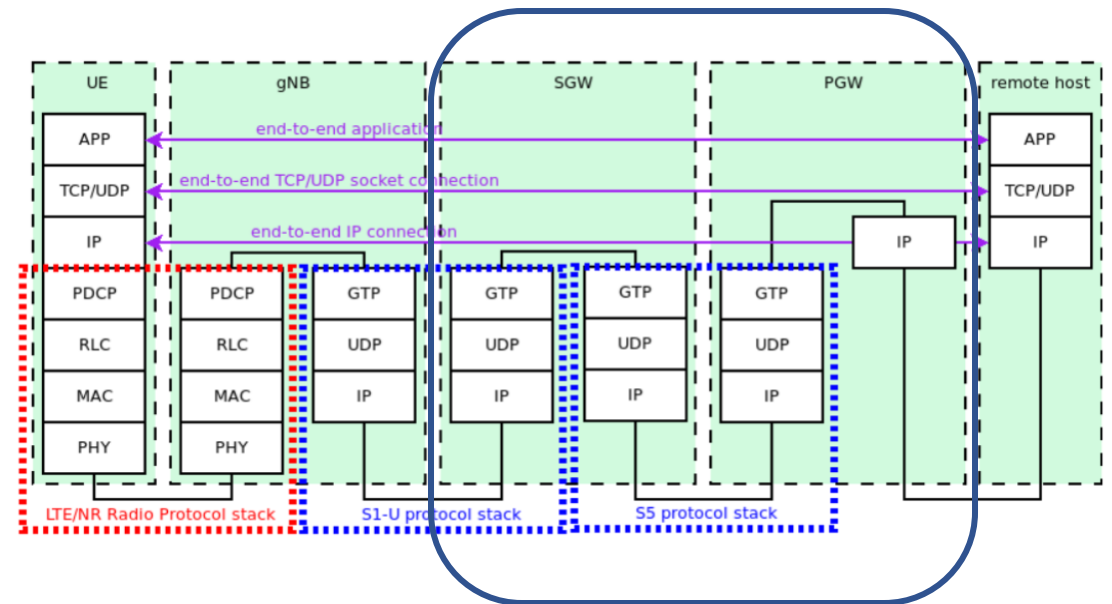


Figure: End-to-end overview



HELPERS: CcBwpHelper

- *CcBwpHelper* helps in the configuration of the spectrum division.
- 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.

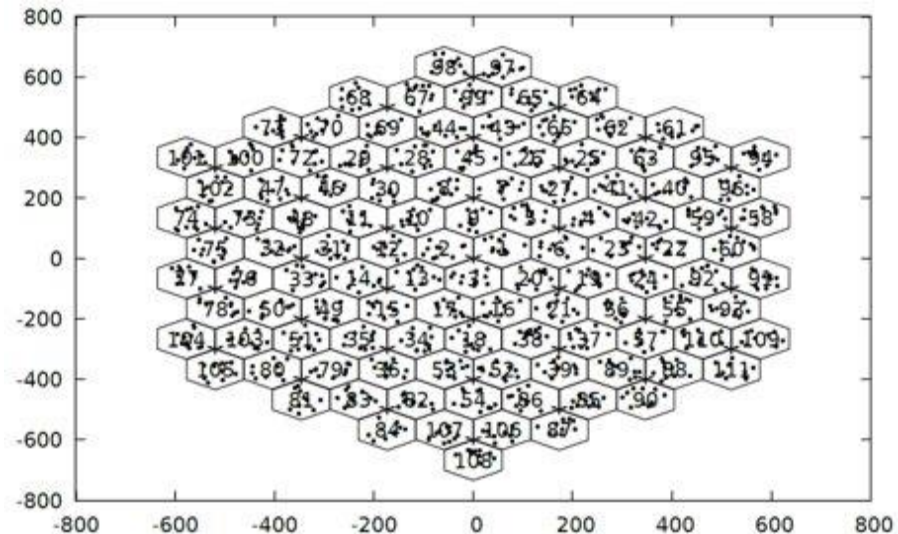
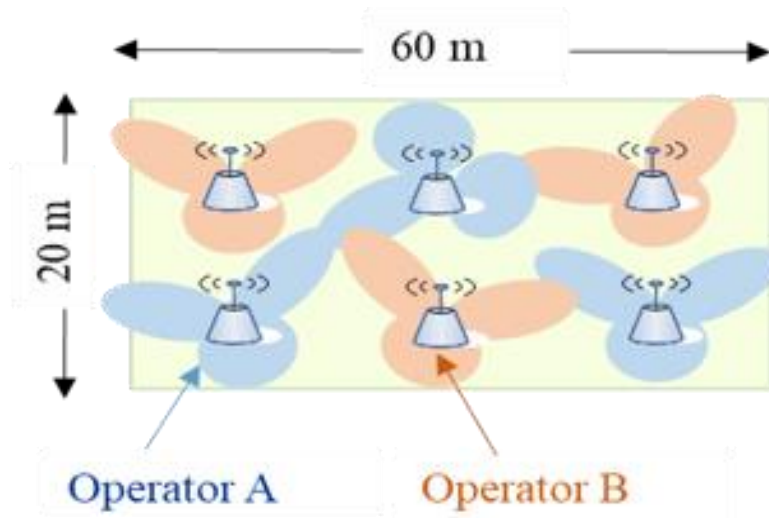
HELPERS: BEAMFORMING HELPERS

Why are needed?

- The real procedure for the beamforming is not supported yet in the NR module. Hence, in order to be able to configure properly beams on the antennas of the transmitting and receiving devices, we need an entity that has access to these objects, and which can based on the users configuration determine:
 - among which devices the beamforming method should be performed
 - how often (periodicity)
 - which algorithm or combination of algorithms to use to determine the beamforming vectors for the communicating devices
- 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: SCENARIO OR TOPOLOGY HELPERS

- Scenario helpers serve to build topologies
- Various scenario helpers are available in the NR module:
 - **GridScenarioHelper**: can be used to create typical 3GPP indoor scenario
 - **HexagonalGridScenarioHelper** (recently extended to support up to 5 rings!): as its name says it helps you build the hexagonal deployment. Provides functions that prepare you 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

- There are many traces available in the NR module, for PHY, MAC, RLC, PDCP...
- Additionally, in many examples you can see how to configure ***FlowMonitor*** to extract throughput/delay/jitter statistics from the simulation.
- Users of the NR module usually do not need to work directly with trace helper, can just instead use the NrHelper to enable/disable specific traces (see NrHelper Doxygen or API)
- Some of the trace helpers are:
 - ***NrStatsCalculator***
 - ***NrBearerStatsCalculator***
 - ***NrBearerStatsConnector***
 - ***NrBearerStatsSimple***
 - ***NrMacRxTrace***
 - ***NrPhyRxTrace***
 - ***NrMacSchedulingStats***



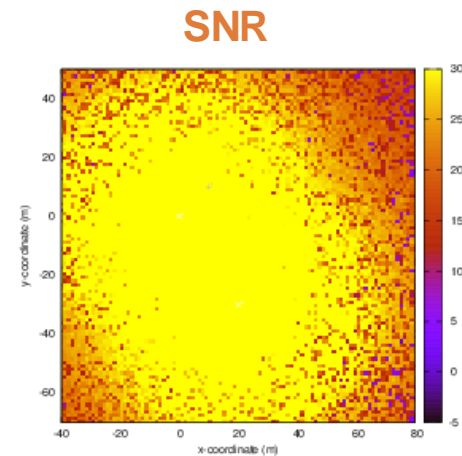
HELPERS: REM HELPER

- 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.

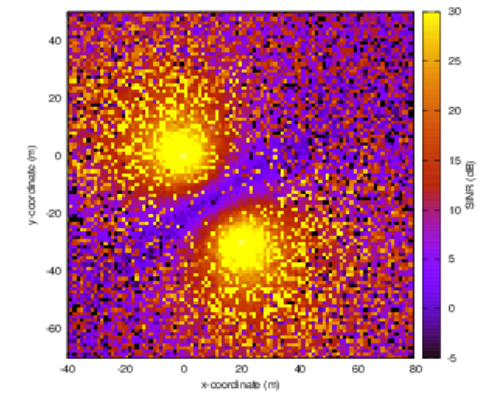
5G-LENA: REM MAP (2GHZ)

- 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

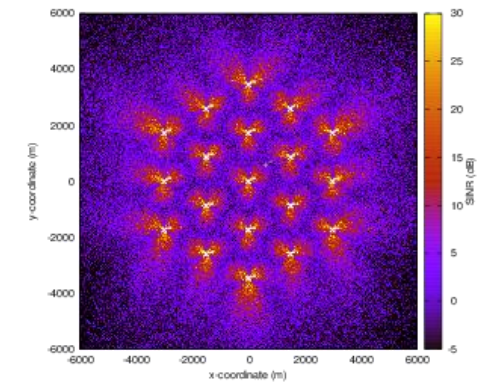
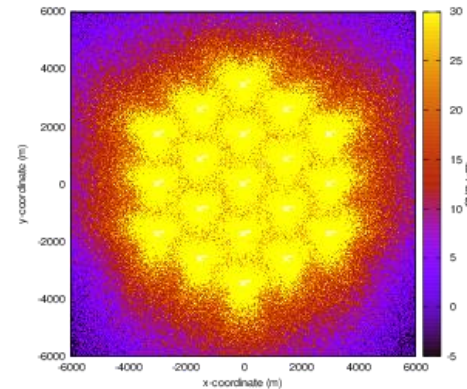
2 gNBs



SINR



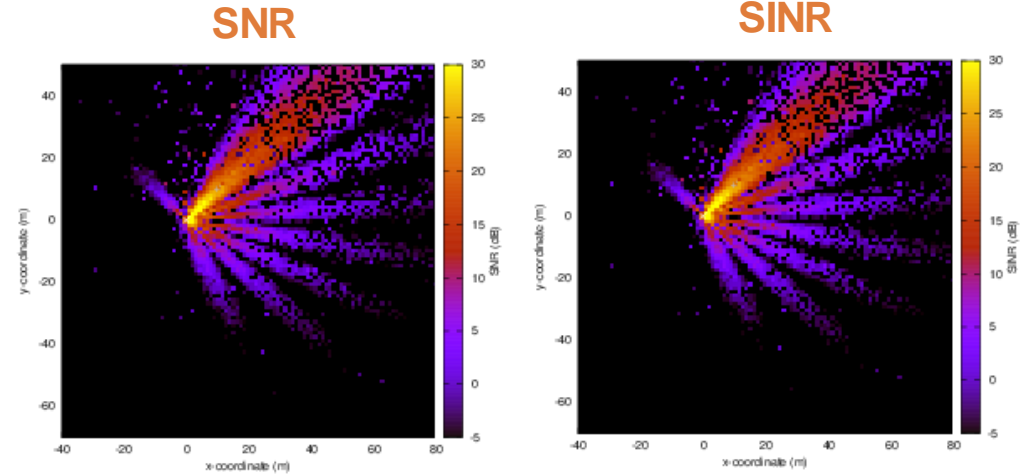
21 gNBs



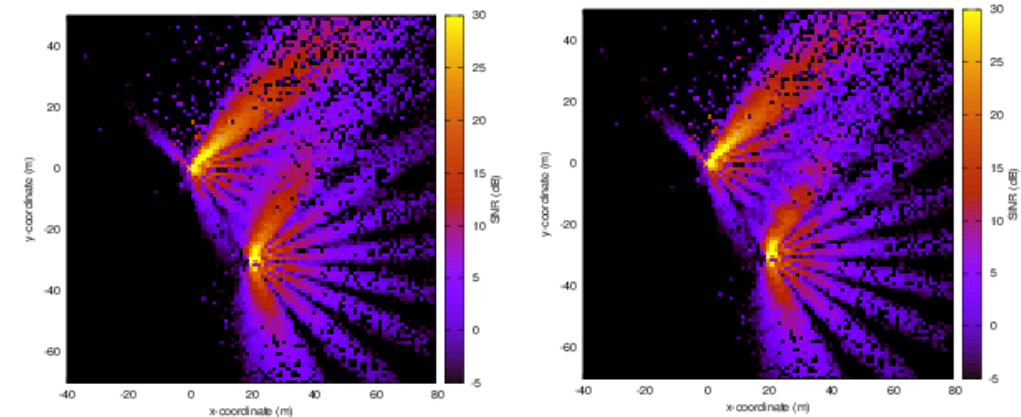
5G-LENA: REM MAP (28GHZ, BEAM SHAPE)

- 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

1 gNB



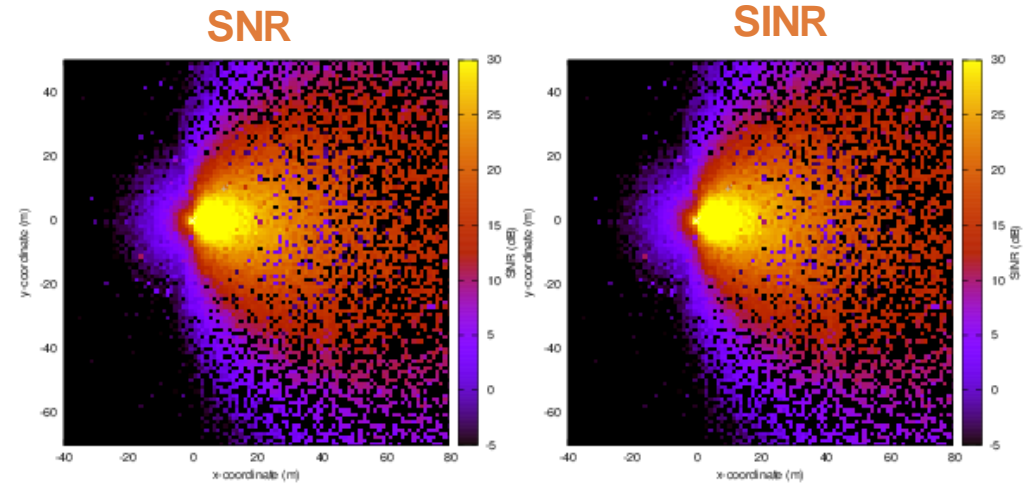
2 gNBs



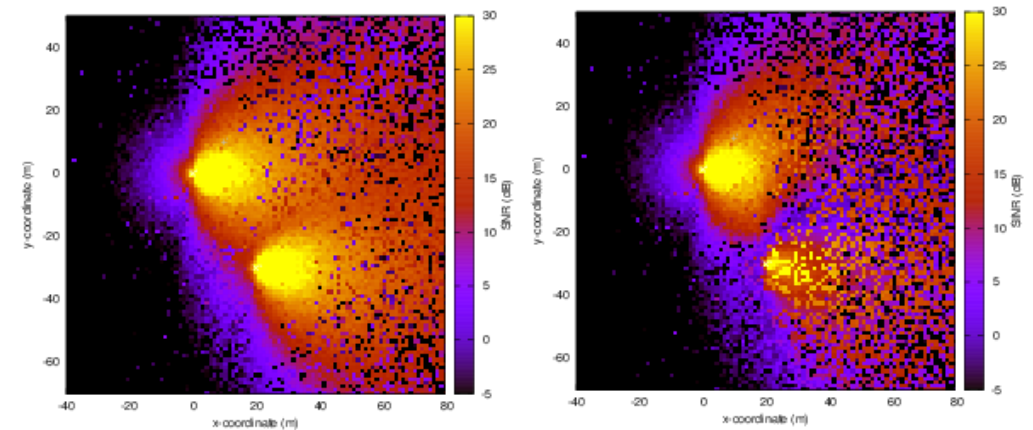
5G-LENA: REM MAP (28GHZ, COVERAGE AREA)

- 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 dB

1 gNB

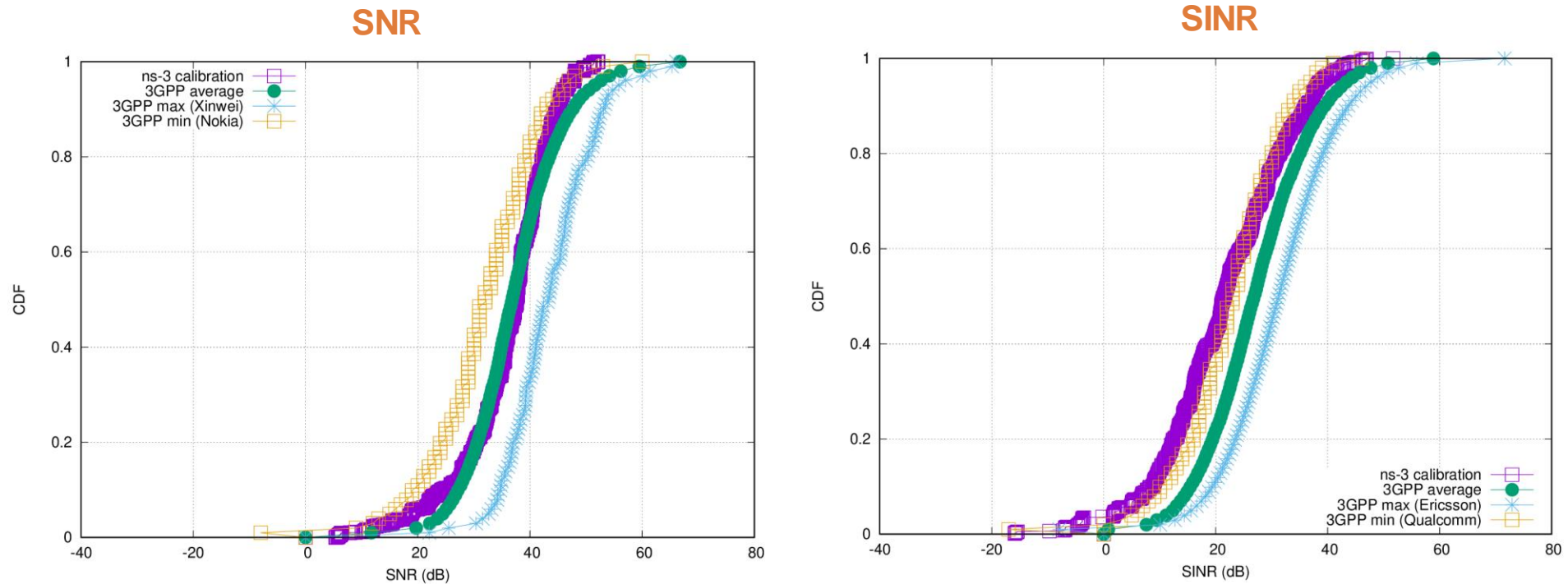


2 gNBs



5G-LENA: INDOOR CALIBRATION

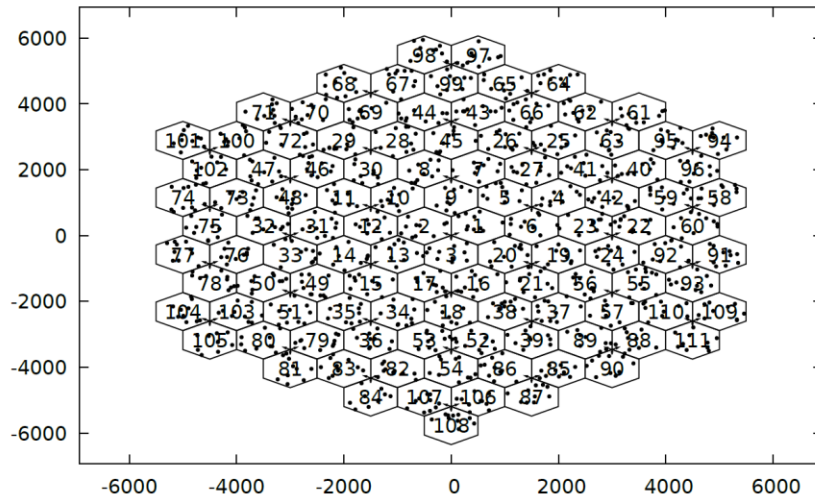
- The simulator is calibrated according to Phase 1 indoor hotspot system-level calibration for multi-antenna systems, as per Annex A.2 in [TS38802].
- The deployment scenario is composed of 12 cells at 20 m distance, and 120 UEs (100% indoor) randomly dropped in a 50 m x 120 m area [R1-1703534].
- As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



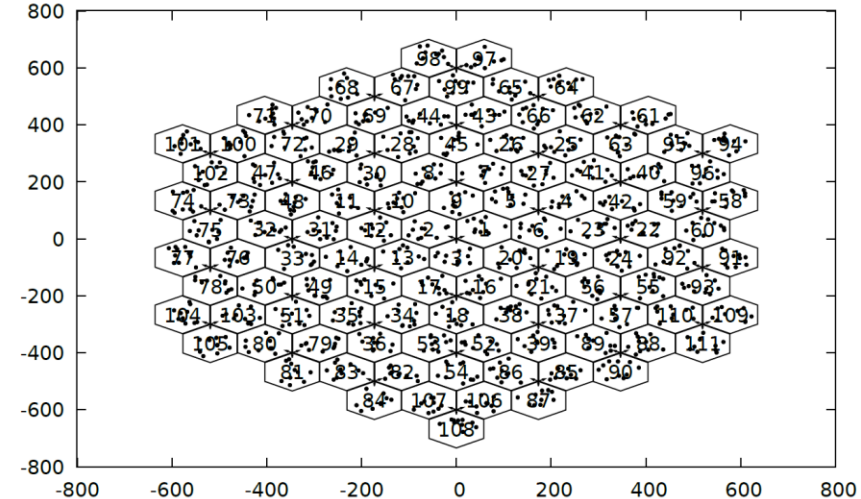
5G-LENA: OUTDOOR CALIBRATION

- The simulator is calibrated according to NR outdoor scenarios [RP-180524]:
 - RuralA, RuralB: Rural eMBB Config. A (700MHz), Config. B (4GHz)
 - DenseA, DenseB: Dense Urban eMBB Config. A (4GHz), Config. B (30GHz)
- The deployment scenario is composed of 19 sites (57 cells) in hexagonal 3 rings deployment, at different ISD distances (depending on scenario), and 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].

RURAL eMBB

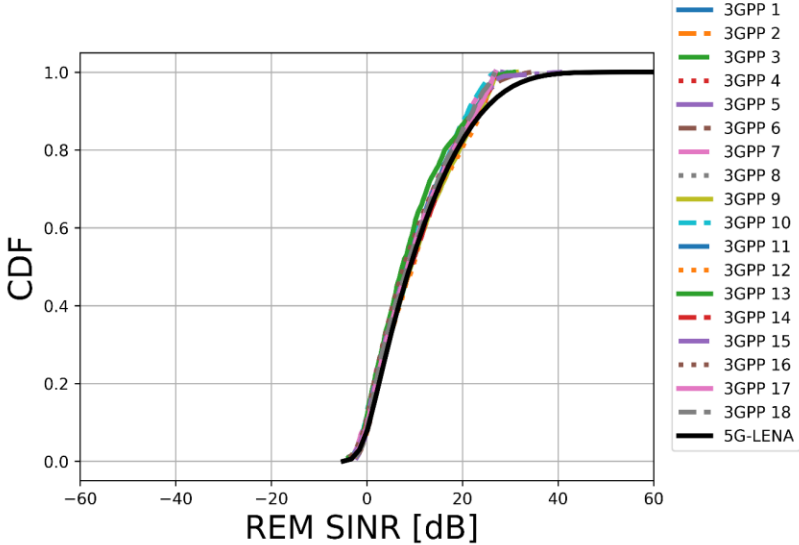
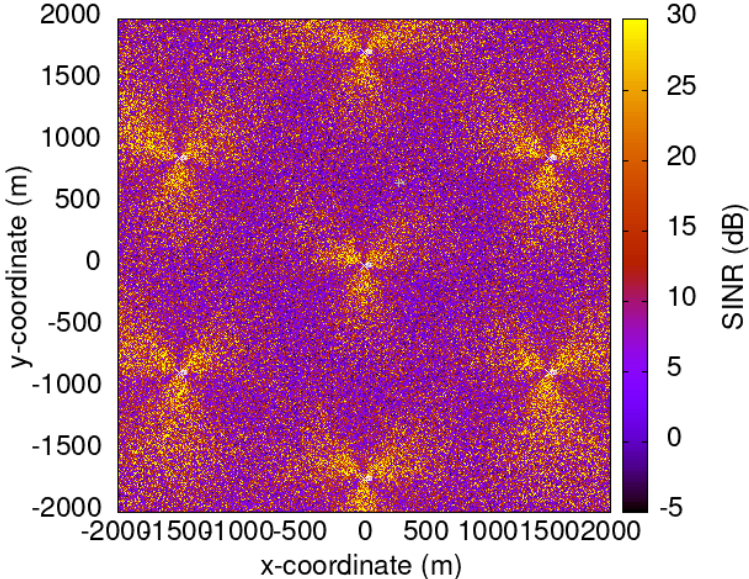


DENSE Urban eMBB

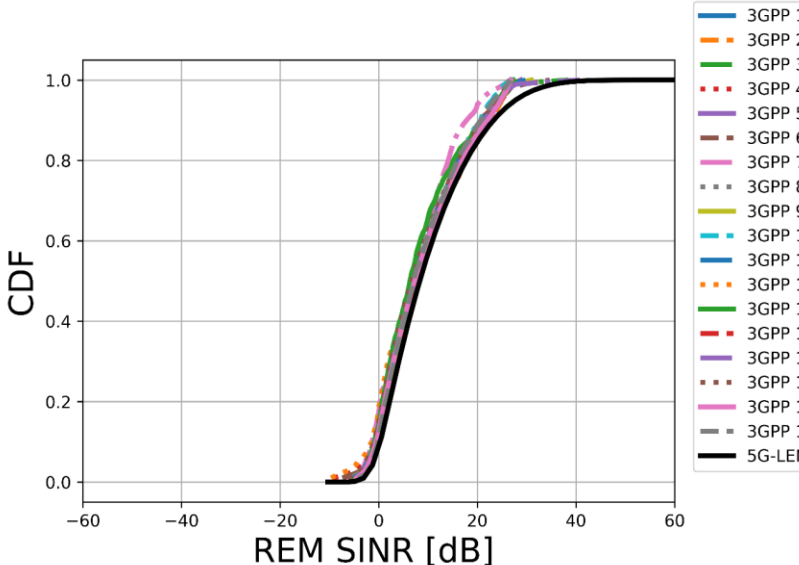
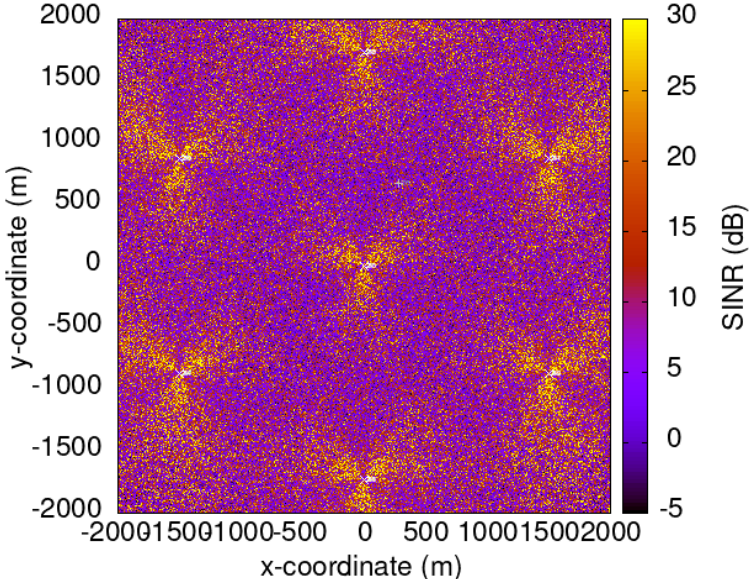


5G-LENA: OUTDOOR CALIBRATION (REM)

RuralA

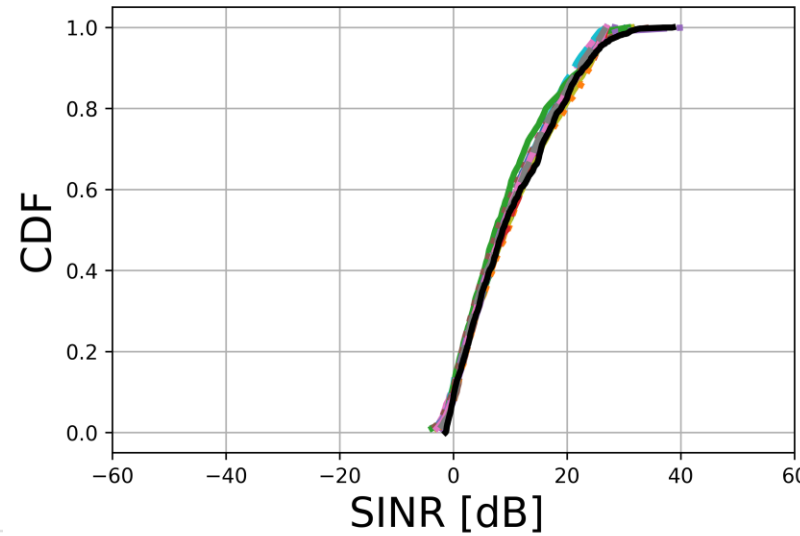
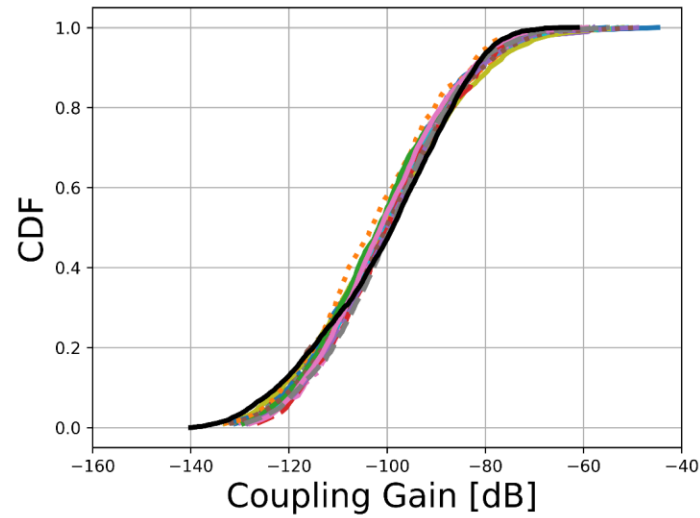


RuralB

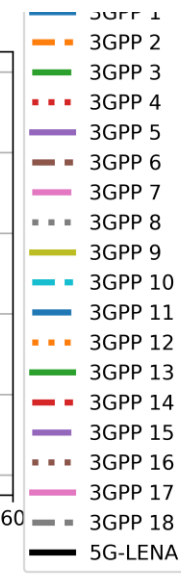
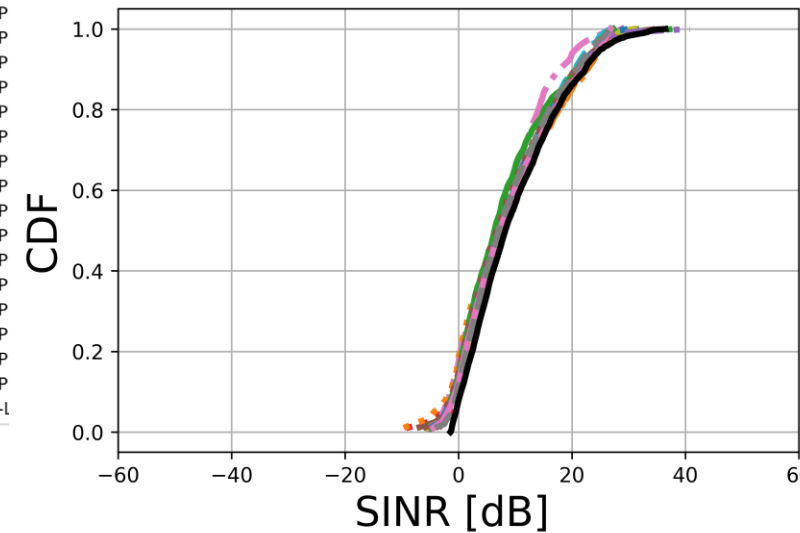
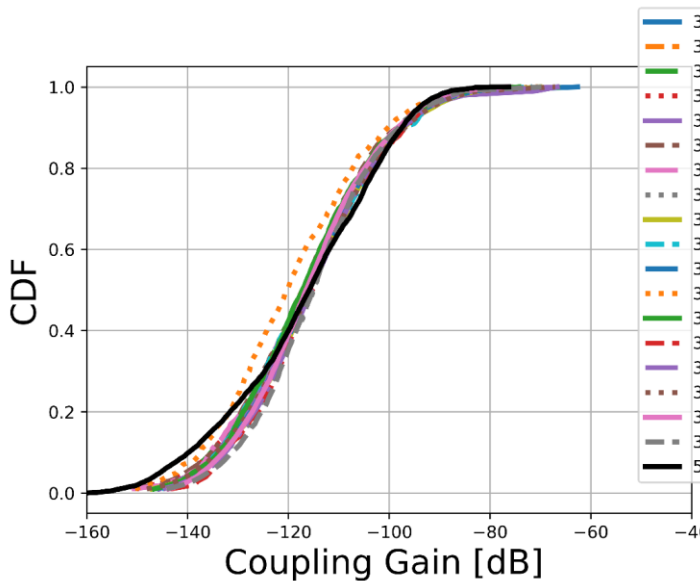


5G-LENA: OUTDOOR CALIBRATION (E2E)

RuralA



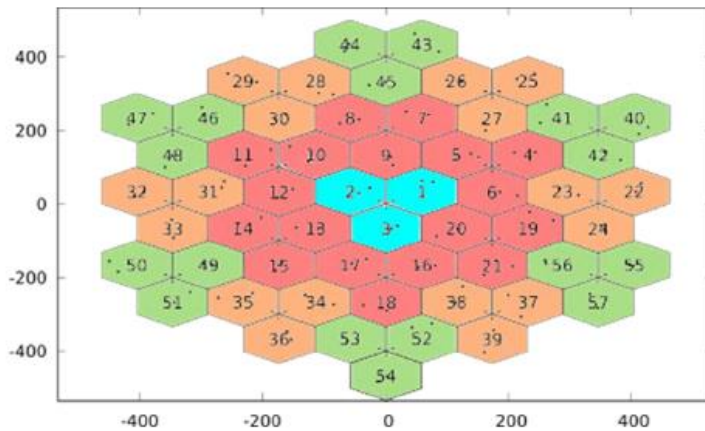
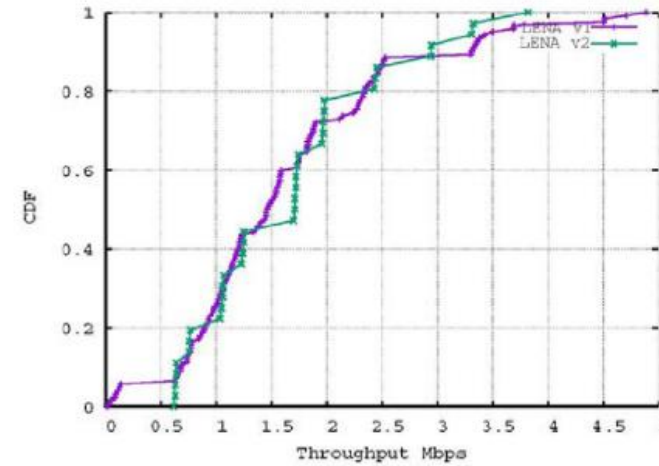
RuralB



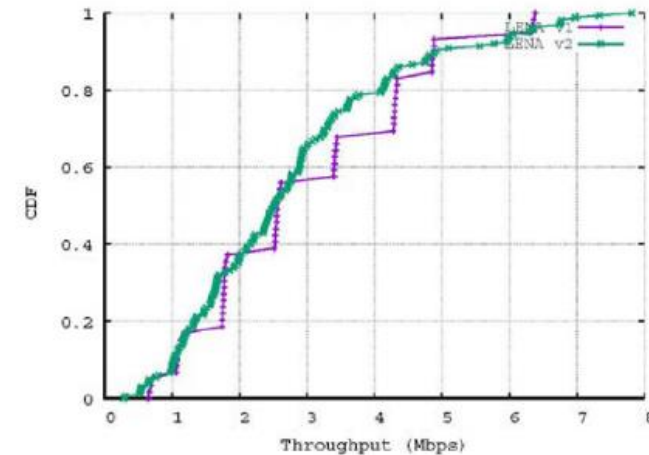
5G-LENA: COMPARISON LENA VS 5G-LENA (NS-3 LTE MODULE VS NR MODULE)

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: WEB PAGE, DOCUMENTATION & PAPERS, GITLAB REPO, AND USERS GROUP

- Good knowledge of ns-3 simulator is required!
- Web page: <https://5g-lena.cttc.es>
- More than 1000 5G-LENA users/gitlab members, including many leading telecom companies
- 5G-LENA web page:
 - Full NR module documentation in PDF
 - Source code Doxygen documentation
 - Links with the CTTC publications related to the 5G-LENA modules
 - Getting started section -> for quick installation guide
 - Publications section with links to the paper with open access (arXiv or Zenodo)
- Gitlab repo:
 - NR module publicly available code: <https://gitlab.com/cttc-lena/nr>
 - Reporting issues
- 5G-LENA users group:
 - <https://groups.google.com/g/5g-lena-users/>

The screenshot shows the homepage of the 5G-LENA simulator. At the top, there is a navigation bar with links for Features, Publications, Manual (PDF), Docs (Doxygen), Getting Started, Services, Download, Blog, and Contact. The main heading is "5G-LENA simulator". Below this, there are several sections:

- ns-3 module to simulate 3GPP 5G networks:** A text box explaining that 5G-LENA is a GPLv2 New Radio (NR) network simulator, designed as a pluggable module to ns-3. It mentions its development was initially funded by InterDigital and is open to the community for early adoption and reproducibility.
- Get the software:** A button labeled "Get the software" with the subtext "along with complete source code".
- Join 5G-LENA Group:** A button labeled "Join 5G-LENA Group" with the subtext "to discuss, collaborate and share results".
- Inherit the strengths of ns-3:** A text box describing ns-3 as an open source discrete-event network simulator/emulator, highlighting its solid, well-documented, and easy-to-use nature.
- Born in academia:** A text box explaining that 5G-LENA was born within the Mobile Networks group at CTTC (Centre Tecnològic de Telecomunicacions de Catalunya).
- ... and for industries?:** A text box listing various industry and academic partners, including Ubiquity, WiFi Alliance, Spidercloud Wireless, InterDigital, National Institute of Standards and Technology (NIST), Lawrence Livermore National Lab (LLNL), Google Summer of Code, and many EU projects.

At the bottom, there is a "Latest news on our blog" section with a link to "5G-LENA v2.0 and v2.1 are available" and a date of "May 09, 2022".

EXAMPLE: HOW TO SETUP NS-3 WITH NR ?

OPTION 1:

- 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

README.md

3GPP NR ns-3 module

This is an [ns-3](#) 3GPP NR module for the simulation of NR non-standalone cellular networks. Ns-3 is used as a base, on top of which we will add our module as plug-in (with limitations that will be discussed below).

Installation for an authorized developer

We try to keep in sync with the latest advancements in ns-3-dev. By the version 1.0, we have upstreamed all our patches to ns-3-dev, making our module independent from the ns-3 version used. Since the version 1.3, for each NR release we will recommend which ns-3 release to use.

Brand new installation of ns-3-dev repository

To download a working copy of the ns-3-dev repository with the latest changes, you can do the following:

```
$ git clone https://gitlab.com/nsnam/ns-3-dev.git
$ cd ns-3-dev
```

At this step, you should check in RELEASE_NOTES.md which is the recommended ns-3 release to use for the specific NR release, and then you can switch to the corresponding ns-3 release branch, e.g., in the following way:

```
$ git checkout ns-3.36
```

You can replace "36" with the specific release that you want to use.

If the recommended ns-3 release is not available yet (such in the case that NR is released before the recommended ns-3 release), then you can use ns-3 master until ns-3 recommended release is ready.

Provide your username and password when asked.

EXAMPLE: HOW TO SETUP NS-3 WITH NR ?

OPTION 2:

- Or follow the **Getting started** instructions from <https://5g-lena.cttc.es/>

Getting started

Get started with 5G-LENA in matter of minutes.

Contents

- [Download the ns-3 part of the 5G-LENA project](#)
 - [Download a brand new ns-3-dev repository](#)
 - [Test the installation](#)
- [Download the 5G-LENA core project](#)
- [Contributing to 5G-LENA](#)
- [Get familiar with ns-3 and the NR module](#)
 - [ns-3 tutorials](#)
 - [NR documentation](#)
- [Upgrading 5G-LENA](#)

In order to start with the NR module you should have some confidence with the ns-3 environment. You can find on the ns-3 web site all the necessary information.

In the following instructions, we will download and build the 5G-LENA project, and we will point out to ns-3 and 5G-LENA documentation to help you enter the ns-3 and the NR world.

Download the ns-3 part of the 5G-LENA project

Download a brand new ns-3-dev repository

To download a working copy of the ns-3-dev repository, you can do the following:

```
$ git clone git@gitlab.com:nsnam/ns-3-dev.git
$ cd ns-3-dev
```

We try to keep in sync with the latest advancements in ns-3-dev. By the version 1.0, we have upstreamed all our patches to ns-3-dev, making our module independent from the ns-3 version used. However, since the version 1.3, we recommend the specific ns-3 release branch for each NR release, i.e., the ns-3 release branch with which are carried out all CI/CD tests for the specific NR release. Hence, at this step, you should check in RELEASE_NOTES.md of the NR module which is the recommended ns-3 release to use for the specific NR release, and then you can switch to the corresponding ns-3 release branch, e.g., in the following way:

```
$ git checkout ns-3.36
```

You can replace "36" with the specific release that you want to use. If the recommended ns-3 release is not available yet (such in the case that NR is released before the recommended ns-3 release), then you can use ns-3 master until ns-3 recommended release is ready.

Test the installation

To test the installation, after following the previous steps, you can do a simple configuration and compilation test:

EXAMPLE: QUICK NS-3 NR SETUP FOR WNS3 2022 TUTORIAL

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-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 70
mobility         network      nr
point-to-point  propagation  spectrum
stats            test         traffic-control
virtual-net-device
```

EXAMPLE: QUICK NS-3 NR SETUP FOR WNS3 2022 TUTORIAL

- 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-doxxygen-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

- ▼ 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

EXAMPLE: RUN THE 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:

```
[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: 0.271518 ms
Mean jitter: 0.030006 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: 7671040
Throughput: 102.280533 Mbps
Mean delay: 0.835065 ms
Mean jitter: 0.119991 ms
Rx Packets: 5993

Mean flow throughput: 56.258560
Mean flow delay: 0.553292
```


EXAMPLE: GOING THROUGH THE MAIN ELEMENTS OF THE EXAMPLE

- 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
  true]
  --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 bandwidth
  --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)

Program Options:

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

- Task: Create 4 flows.
- One possible solution:
./ns3 run "cttc-nr-demo --gNbNum=2"

```
biljkus@biljkus-Latitude-5400:~/Desktop/workspace-u
[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
  true]
  --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 effort 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 bandwidth
  --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 NrHelper logs:**

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

- **Enable GridScenarioHelper logs:**

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

- **Enable PDCP logs:**

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

- **Enable RLC logs:**

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

- **Enable gNB MAC logs:**

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

- **Enable MAC scheduler logs:**

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

Enable gNB PHY layer logs:

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

- **Enable NR AMC logs:**

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

- **Enable beamforming helper logs:**

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

-

EXAMPLE: NR TRACES

- Find the line in `cttc-nr-demo.cc` and enable the following line:
`nrHelper->EnableTraces();`
- Run again the example and look into the root project folder and there will be 23 trace files generated:
 1. `UIPathlossTrace.txt`
 2. `TxedUePhyCtrlMsgsTrace.txt`
 3. `TxedGnbPhyCtrlMsgsTrace.txt`
 4. `RxedUePhyCtrlMsgsTrace.txt`
 5. `RxedGnbPhyCtrlMsgsTrace.txt`
 6. `NrUIRlcStatsE2E.txt`
 7. `NrUIPdcPStatsE2E.txt`
 8. `NrDIRlcStatsE2E.txt`
 9. `NrDIPdcPStatsE2E.txt`
 10. `DIPathlossTrace.txt`
 11. `DICtrlSinr.txt`
 12. `TxedUeMacCtrlMsgsTrace.txt`
 13. `TxedGnbMacCtrlMsgsTrace.txt`
 14. `RxPacketTrace.txt`
 15. `RxedUePhyDIDciTrace.txt`
 16. `RxedUeMacCtrlMsgsTrace.txt`
 17. `RxedGnbMacCtrlMsgsTrace.txt`
 18. `NrDITxRlcStats.txt`
 19. `NrDIRxRlcStats.txt`
 20. `NrDIPdcPTxStats.txt`
 21. `NrDIPdcPRxStats.txt`
 22. `NrDIMacStats.txt`
 23. `DIDataSinr.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
- NR-V2X module needs to be updated to the latest NR release, and once the NR module has 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).
- For more information about NR-V2X roadmap check NR V2X Tutorial WNS3 2022

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>

5G-LENA TEAM MEMBERS

5G-LENA TEAM MEMBERS



Sandra Lagen



Katerina Koutlia



Biljana Bojovic

FORMER 5G-LENA TEAM MEMBERS



Zoraze Ali



Lorenza Giupponi



Natale Patriciello

NR MODULE REFERENCE PAPERS LIST 2022

Journal publications:

- *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](#).*
- *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](#).*

NR MODULE REFERENCE PAPERS LIST 2022

Conference papers (1):

- *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).*
- *Z. Ali, S. Lagen, L. Giupponi, On the Impact of Numerology in NR V2X Mode 2 with Sensing and Random Resource Selection, in Proceedings of IEEE Vehicular Networking Conference (VNC), Nov. 2021.*
- *S. Lagen, X. Gelabert, L. Giupponi, A. Hansson, Semi-Static Modulation Compression Optimization for Next Generation RANs, in Proceedings of IEEE International Conference on Communications (ICC), 14-23 June 2021. Available [here](#).*
- *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. Available [here](#).*
- *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](#).*
- *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. Available [here](#).*
- *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. Available [here](#).*

NR MODULE REFERENCE PAPERS LIST 2022

Conference papers (2):

- 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). Available [here](#).
- 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. Mangués, *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, Bologna (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](#).



Advanced research for everyday life



HR EXCELLENCE IN RESEARCH