NR module

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Outline

5G-LENA history

- We started working on an extension of ns-3, targeting NR modeling in 2017, in the context of a collaboration with **InterDigital**.
- The objective was to build a 5G simulator:
  - Wideband: FR1 and FR2.
  - Coexistence frameworks below and above 7 GHz
    - Unlicensed 2.4 GHz, 5 GHz, 60 GHz
    - Shared 3.5 and 37 GHz
- In 2017, we opted to fork from the status of *mmWave module* (effort of NYU and Uni Padova, fork from LTE), instead of LTE.
  - It was more advanced in terms of beamforming, TDD, 3GPP channel model.
  - Already prepared to work at FR2 bands.
- At the moment the simulator relies on LTE for layers above MAC (RLC, PDCP, NAS, RRC and EPC).
- Has completely new PHY and MAC.

Project activities

- Activities presented in these slides have been funded by various projects:
  - S3: funded by **US Department of Defense**, through **Lawrence Livermore National Lab**, to study impact on military assets of commercial networks in AWS-3 bands released for spectrum sharing purposes.
  - NR V2X: funded by the **National Institute of Standards and Technology (NIST)** to model, simulate and research in the area of NR V2X.
  - NR-U: We worked with **InterDigital** on NR-U coexistence with WiGig during a couple of years.

Releases

- We did the first Release NR-v0.1 in February 2019.
- As of today the code went through 4 releases, including the following features:
  - NSA architecture: 5G RAN and 4G EPC.
  - Flexible and automatic configuration of the NR frame structure through multiple numerologies.
  - Orthogonal Frequency-Division Multiple Access (OFDMA)-based access with variable TTIs.
  - Restructuring and redesign of the MAC layer, including new flexible MAC schedulers that simultaneously consider time- and frequency-domain resources (resource blocks and symbols) both for Time-Division Multiple Access (TDMA) and OFDMA-based access schemes with variable TTI.
  - UpLink (UL) grant-based access scheme with scheduling request and 3GPP-compliant buffer status reporting.
  - NR-compliant processing timings (K0, K1, K2).
  - New Bandwidth Part (BWP) managers and the architecture to support operation through multiple BWPs.
  - New PHY layer abstraction, considering LDPC codes for data channels.

Latest releases

- September 2020 (NR-v1.0).
  - FDD duplexing mode.
  - Channel model aligned with ns-3-dev, and able to simulate 0.5-100 GHz frequency ranges.
  - Realistic MAC headers.
  - Added various trace sources (PowerSpectralDensity, SlotDataStats, etc.)
  - Removed PhyMacCommon, moved its attribute among the stack, to prepare for future works at RRC level.
- March 2021 (NR-v1.1).
  - MIB/SIB scheduled and take real space
  - Uplink Power control
  - Realistic beamforming
  - SRS modelling
- Other scheduled features:
  - X2/Xn interface
  - Improvements at RRC
  - Interference management/coordination (including ICIC, notching)

Helpers

Multiple helpers available to facilitate the usage.

- Helpers to build communication models, e.g. **NR helper**, EPC, beamforming, SpectrumValue, CcBwpCreator.
  - In recent release, improved usability of NR helper, to allow Multi-Cell Configurations
- Topology helpers, e.g. grid-scenario, hexagonal-grid-scenario, file-scenario.
- Stats helpers
- Radio Environment Map Helper (REM)
  - **BeamShape**: Shows the SNR (Signal to Noise Ratio)/SINR (Signal to Interference and Noise Ratio)/IPSD (Interference Power Spectral Density) of pre-configured beams
  - **CoverageArea**: Shows the SNR/SINR/IPSD of the best beam in each map point to show how well an area is covered by a gNB.
    - Best-case SNR and Worst-case SINR.

REM Helper examples at 2 GHz

- Inter-site distance: 500 mt (small cells), 1732 mt (Urban), 7 Km (Rural).
- Transmit power: 30 dBm (small cells), 43 dBm (Urban), 49 dBm (Rural).
- Propagation model: 3GPP TR 38.901
- Antenna type 5x1, directional element
- Numerology 0
- Frequency band: 2 GHz
- Bandwidth: 20 MHz
- check rem-example.cc

REM Helper examples at 2 GHz

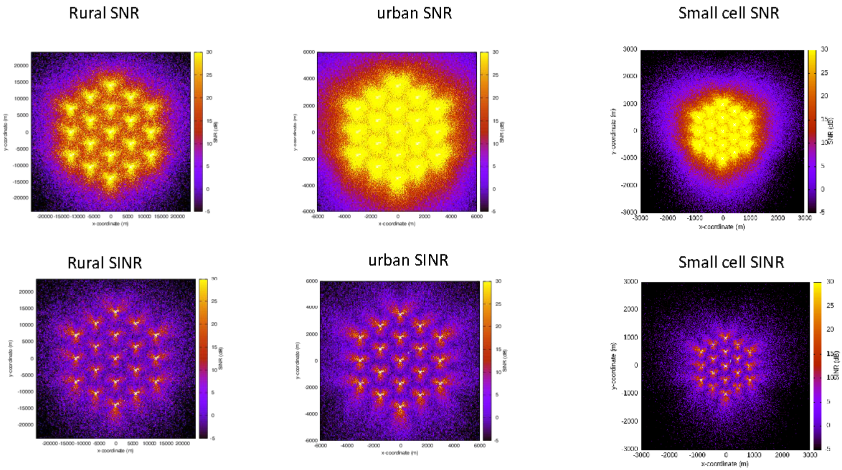


Figure: SNR and SINR REM for Rural, Urban and small cell scenarios, with 3-sectorial 21 sites deployments

REM Helper examples at 2 GHz

- Besides SNR and SINR, we also support IPSD (Interference Power Spectral Density) to visualize UL aggregated interference, at the UE height.

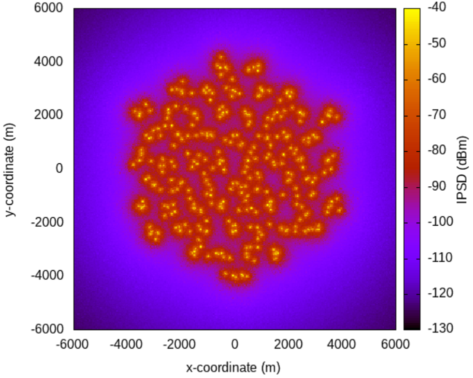


Figure: IPSD for Rural 3-sectorial 21 sites deployments

REM Helper examples at 28 GHz - Beam shape

- Scenario path: nr/examples/rem-example.cc; **BeamShape example**
- Devices: 1 gNB and 1 UE (left), 2 gNBs and 1 UE per gNB (right).
- gNB transmit power: 1 dBm
- gNB1 (0, 0, 1.5); gNB2 (20, -30 , 1.5); UE1 (10, 10, 1.5); UE2 (25, -15 , 1.5).
- Antenna model: 3GPP, 8x8 at gNB; ISO, 1x1 at UE.
- Frequency/bandwidth/numerology: 28 GHz and 100 MHz; numerology 4.

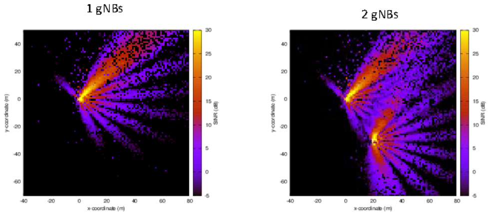


Figure: SINR for 1 gNB and 2 gNBs setup at 28 GHz, BeamShape example

REM Helper examples at 28 GHz - Coverage area

- Scenario path: nr/examples/rem-example.cc; **CoverageArea example**
- Devices: 1 gNB and 1 UE (left), 2 gNBs and 1 UE per gNB (right).
- gNB transmit power: 1 dBm
- gNB1 (0, 0, 1.5)/gNB2 (20, -30 , 1.5)/UE1 (10, 10, 1.5)/UE2 (25, -15 , 1.5).
- Antenna model: 3GPP, 8x8 at gNB; ISO, 1x1 at UE.
- Frequency/bandwidth/numerology: 28 GHz and 100 MHz; numerology 4.

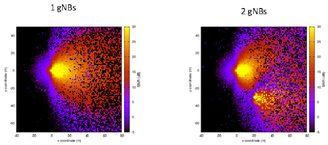


Figure: SINR for 1 gNB and 2 gNBs setup at 28 GHz, CoverageArea example

REM Helper examples at 28 GHz - Coverage Area with buildings

- Scenario path: nr/examples/rem-example.cc; **CoverageArea example, with buildings**.
- Devices: 1 gNB and 1 UE (left), 2 gNBs and 1 UE per gNB (right).
- 1 building in 1 gNB case / 2 buildings in 2 gNBs case.
- gNB transmit power: 1 dBm
- Antenna model: 3GPP, 8x8 at gNB; ISO, 1x1 at UE.
- Frequency/bandwidth/numerology: 28 GHz and 100 MHz; numerology 4.

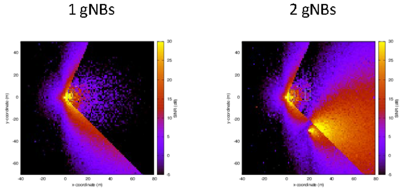


Figure: SINR for 1 gNB and 2 gNBs setup at 28 GHz, CoverageArea example, with buildings

Section 1

NR model

Subsection 1

Assumptions and Architecture

Modelling assumptions

- NSA and for layers above MAC we rely on LTE.
- OFDMA-based access with variable TTI.
  - Radio signal model granularity in time domain: Symbol.
  - Radio signal model granularity in frequency domain: Resource Block.
- PHY layer abstraction: considering LDPC codes for data channels
- Duplexing schemes: TDD/FDD
- Realistic Data Plane Protocol stack model
  - Realistic RLC, PDCP, S1-U, X2-U
  - RLC allows for proper interaction with IP networking
  - Allows for end-to-end QoE evaluations
- Simplified Control Plane model
  - Currently working on RRC
  - Realistic S1-AP, X2-C, S5 and S11 models.
- Simplified EPC
  - One MME and one SGW and PGW.
- Focus on RRC connected mode (EMM Registered, ECM connected).
- Even if Handover management is supported in LTE, more work is required for using it in 5G-LENA.

5G-LENA Model Overview

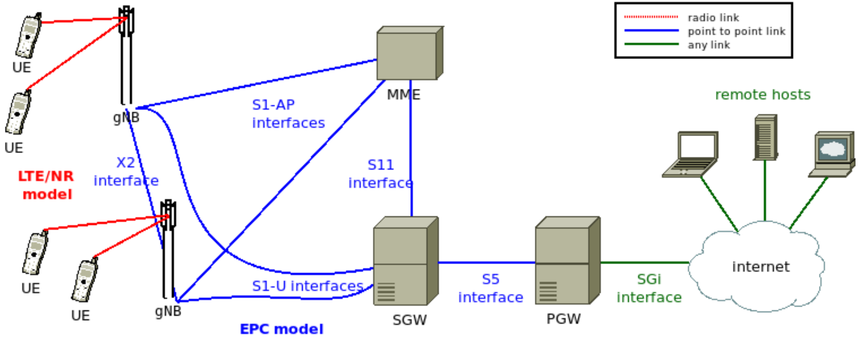


Figure: End-to-end overview

End-to-end Data Plane protocol stack

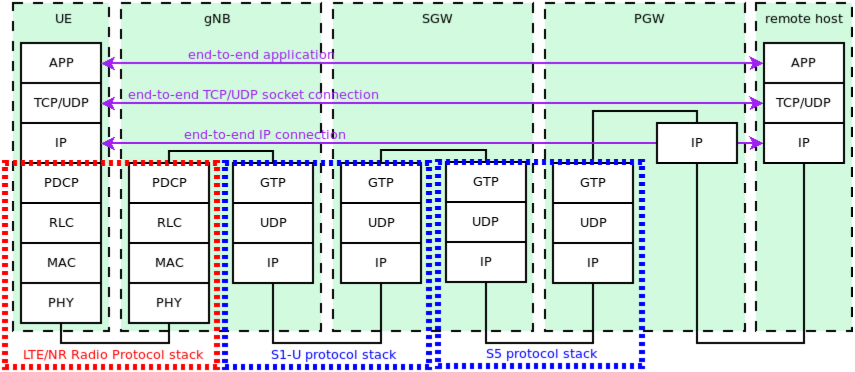


Figure: Data Plane

End-to-end Control Plane protocol stack

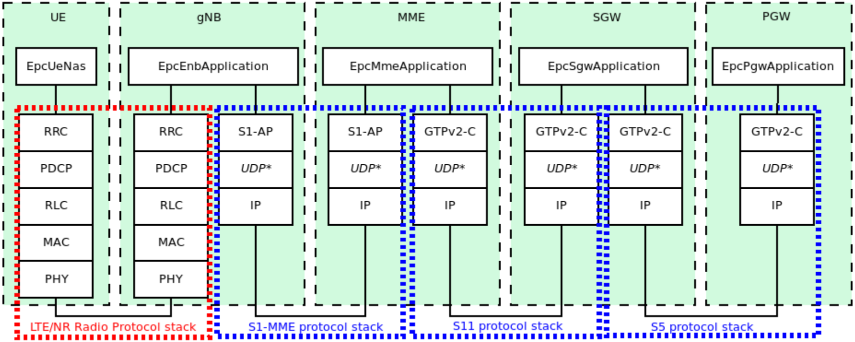


Figure: Control Plane

Subsection 2

PHY

NR Bands

- 5G-LENA is flexible as NR to work from 400 MHz to 100 GHz
- We have tested FR1, FR2, and 60 GHz

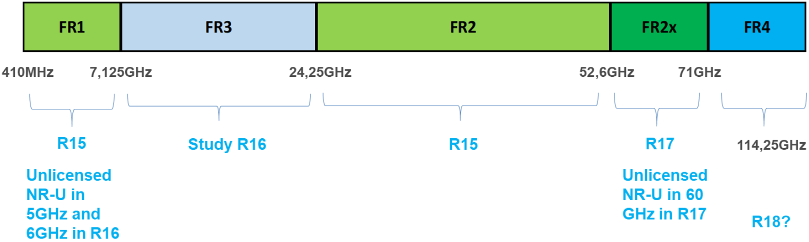


Figure: Current and foreseen Frequency Ranges

Propagation and channel models

- For evaluation of NR 3GPP has adopted TR 38.901 3D spatial channel model (SCM)
  - stochastic SCM that can model interactions with beamforming vectors
  - valid for the 0.5-100 GHz frequency range
  - SCM:
    - models the channel through a channel matrix $\mathbf{H}(t, \tau)$, with as many rows and columns as the number of transmit antennas (U) and receive antennas (S).
    - each entry $H_{u,s}(t, \tau)$ corresponds to the impulse response of the channel between the s-th element of the gNB antenna and the u-th element of the UE antenna at delay τ and time t.
    - $H_{u,s}(t, \tau)$ is generated by the superposition of N different clusters, representing groups of multipath components (M rays) that arrive and/or depart the antenna arrays with certain azimuth/zenith angles (AoD/AoA/ZoD/ZoA)
  - Different random distributions' parameters for four different scenarios:
    - Rural Macro
    - Urban Macro
    - Urban Micro Street-Canyon
    - Indoor Hotspot Mixed and Open Office
  - For each scenario, it provides the characterization of the LOS/NLOS channel condition, the propagation loss, and the small scale fading.

Propagation and channel models

- Channel generation procedure, including large (pathloss and shadowing) and small scale (fast fading) propagation phenomena

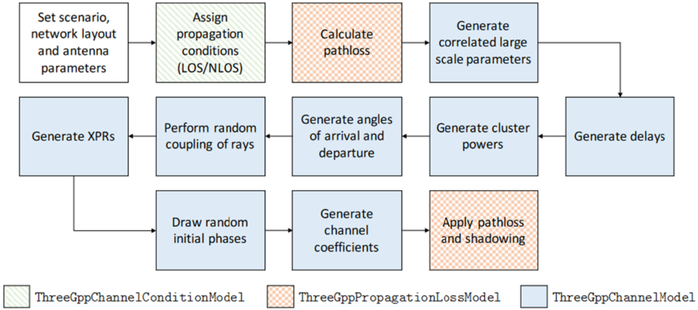


Figure: Channel generation procedure

- The code follows step-by-step TR 38.901, except for polarization and optional components (e.g., outdoor-to-indoor penetration loses, oxygen absorption)

Propagation and channel models

- LOS/NLOS channel condition:
  - probabilistic model, based on distance and propagation environment (scenario, buildings)
- Pathloss:
  - $PL = A\log_{10}(d) + B + C\log_{10}(f_C) + X$ [dB], where A, B, C and X take different values depending on the propagation conditions (scenario, LOS/NLOS channel state, break point distance)
- Shadowing:
  - statistical characterization of attenuation generated by e.g. obstacles.
  - log-normal shadowing component, added to the mean pathloss, whose standard deviation depends on the propagation conditions
- Fast fading:
  - signal phase and amplitude variations due to small changes in the spatial separation between the tx and the rx, and to Doppler effect.
  - $H_{u,s}(t,\tau) = \sum_{n=1}^{N} \sqrt{\frac{P_n}{M}} e^{j2\pi\nu_n t}\delta(\tau - \tau_n) \sum_{m=1}^{M} H_{u,s,n,m}$
  - rays of the same cluster have same power and delay
  - assumes same Doppler shift for all rays of each cluster (simplification)
  - $H_{u,s,n,m}$ depends on the angles of arrivals and departures, initial phases of the rays, and antenna field patterns

Antennas

- Antenna arrays:
  - Uniform planar arrays (UPA)
    - specified by the number of antenna elements in each dimension
  - Antenna elements are vertically polarized
  - 1 UPA (sector) per gNB
  - 1 UPA (panel) per UE
- Antenna elements:
  - isotropical radiation, or
  - directional radiation (based on the 3GPP model in TR 38.901)

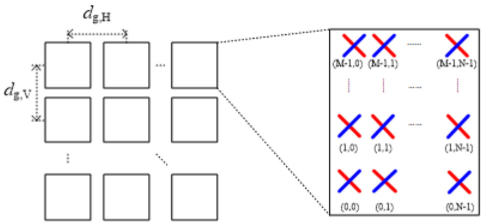


Figure: Cross-polarized panel array antenna model in TR 38.901

Beamforming

- MIMO allows to:
  - Increasing the data rate by sending multiple simultaneous data streams (spatial multiplexing).
  - Increasing the robustness of the data transmission by sending replicated data (transmit diversity).
  - Providing array gain into specific spatial areas by properly designing the antenna weights or beamforming vectors (Beamforming).
- Beamforming (BF) is particularly essential at high carrier frequencies within the mmWave region to combat the high pathloss propagation losses and blocking effects.
- A single spatial stream is sent per receiver and the multiple antennas are used to concentrate the radiated power towards the receiver's location, thus improving the received SINR and the probability of error at the target receiver, and the generated interference towards other users.
- 3GPP LTE covers BF in the so-called Transmission Mode 7.

Beamforming

- 3GPP NR has introduced CSI RSs and SS blocks for beam management in the DL and SRSs for beam management in UL.
- In TDD systems, SRS can be used for beam managementin both DL and UL directions because, due to channel reciprocity, beam reciprocity can be assumed.
- Since Feb 2021, the models support both ideal and realistic beamforming.
- Specified by means of beamforming (BF) vectors.
- BF methods have their own beam update periodicity, which may vary from channel update period.
  - The PSD of a received signal is: $S_{rx}(t,f) = S_{tx}(t,f)\mathbf{w}_{rx}^{T}\mathcal{H}(t,f)\mathbf{w}_{tx}$, being $\mathcal{H}(t,f)$ the channel matrix in the frequency domain

Ideal beamforming models

- Ideal methods:
  - No physical resource is employed,
  - ideal channel state acquisition is assumed,
  - they are computed offline (no real training, no BF overhead)
- Two main methods available:
  - 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)
- Quasi-omni BF is supported, and combinations with previous methods
- Helper available (ideal-beamforming-helper), example of configurations in many examples.

Realistic beamforming model

- NR-compliant SRS signals transmissions and receptions are included.
- Based on SRS reception, an abstraction model allows to estimate the channel matrix.
- The abstraction model is used, to avoid the related signal processing operations and reduce its computational complexity.
- Using the SRS-based channel estimation, the BF vectors can be determined at the gNB side.
- Helper (realistic-beamforming-helper) and example (cttc-realistic-beamforming)

Beamforming models

- All are analog beamforming methods, since they only change the phases of the BF weights.
- However, the BF vectors are general enough to support changing also the amplitudes of the different BF weights (and so, could support hybrid and digital beamforming).
- Limitations:
  - 5G-LENA does not support MIMO with multiple streams per UE. We have a limitation due to the PHY abstraction model: a single stream can be transmitted per UE.
  - As of today, 5G-LENA does not support MU-MIMO. MU-MIMO could be supported from the PHY abstraction perspective, but extensions at MAC layer and spectrum-interference computations would be needed.

Frame structure model

- Subcarrier Spacing can range from 15 kHz to 240 KHz (120 KHz for data). We also support 480 KHz.
- Flexible numerology results in flexible time/freq-slot structure
- Number of symbols per slot: 14 for Normal CP, and 12 for Extended CP
- Dynamic TDD: Up/down at symbol level.

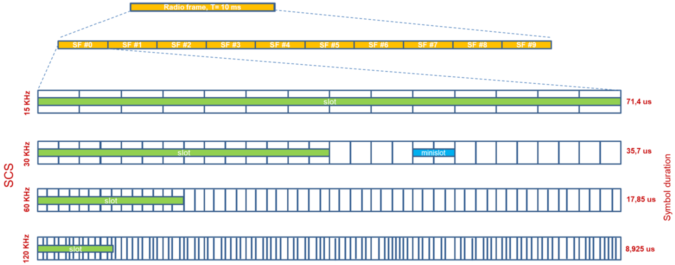


Figure: NR frame structure

Frame structure model

	n=0	n=1	n=2	n=3	n=4	n=5
Subcarrier spacing (SCS)	15 kHz	30 kHz	60 kHz	120 kHz	240 kHz	480 kHz
OFDM symbol length	66.67 us	33.33 us	16.67 us	8.33 us	4.17 us	2.08 us
Cyclic prefix (CP)	~4.8 us	~2.4 us	~1.2 us	~0.6 us	~0.3 us	~0.15 us
Frame length	10 ms	10 ms	10 ms	10 ms	10 ms	10 ms
Number of subframes per frame	10	10	10	10	10	10
Subframe length	1 ms	1 ms	1 ms	1 ms	1 ms	1 ms
Number of slots per subframe	1	2	4	8	16	32
Slot length	1 ms	500 us	250 us	125 us	62.5 us	31.25 us
Number of OFDM symbols per slot	14	14	14	14	14	14
Number of subcarriers in a PRB	12	12	12	12	12	12
PRB width	180 kHz	260 kHz	720 kHz	1.44 MHz	2.88 MHz	5.76 MHz

	SCS	SF	slots	Slots/SF	Symb/slot	Use
μ = 0	15 kHz	10	10	1	14	Data, FR1
μ = 1	30 kHz	10	20	2	14	Data, FR1
μ = 2	60 kHz	10	40	4	14	Data FR1, FR2, no sync
μ = 3	120 kHz	10	80	8	14	Data FR2
μ = 4	240 kHz	10	160	16	14	No data
μ = 2 (ext. CP)	60 kHz	10	40	4	12	Data FR1, FR2

Figure: 6 frame structures available in the simulator

Frequency Division Multiplexing (FDM) of numerologies

- Bandwidth part (BWP) concept:
  - NR needs to be deployed over very large bandwidths.
  - Very large bandwidth at the UE side is too expensive for RF, power levels.
- FDM of numerologies through different BWPs, for the trade-off latency vs. throughput for different types of traffic.
- The user can configure FDM bands statically before the simulation starts
  - Channel model does not allow run time configurations.
- Examples: cttc-3gpp-channel-nums, cttc-3gpp-channel-simple-fdm.

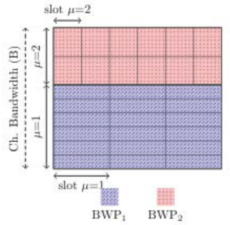


Figure: FDM of numerologies

PHY model

- The modeling of PHY processing is replaced by an abstraction model, implemented through an interface that is known as link-to-system mapping (L2SM).
- Both FDD and TDD duplexing modes are supported.
  - A gNB can be configured with multiple carriers, some being FDD and other TDD
  - Each carrier can be further split into various BWPs (Bandwidth Parts), under the assumption that all the BWPs are orthogonal in frequency, to enable compatibility with the channel instances.
- Frequency domain granularity: Resource Block (RB).
- Time domain granularity: Symbol.
- NR allows different slot types:
  - *DL-only ("DL" slots)*: the first symbol is reserved for DL CTRL, and the rest of the symbols are available for DL data.
  - *UL-only ("UL" slots)*: the last symbol is reserved for UL CTRL, and the rest of the symbols are available for UL data.
  - *Flexible ("F" slots)*: the first and the last OFDM symbols are reserved for DL CTRL and UL CTRL, respectively (e.g., DCI and UCI). The symbols in between can be dynamically allocated to DL and UL data (dynamic TDD).

Duplexing schemes: TDD and FDD

- TDD:
  - Flexible slots have a certain number of DL symbols, a guard band, and a certain number of UL symbols.
  - TDD pattern is defined by the user through a string of slot types, e.g., FFFFFFFFFF
  - There are no limitations in the implementation of the gaps in between two DL slots, or two UL slots.
  - Gaps in between two DL slots, or two UL slots, have to be checked to respect CTRL timings.
- 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.
    - DDDDDD...
    - UUUUUU...
  - The user would 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.
  - Paired BWPs have to be configured with the same numerology.
- Example: cttc-3gpp-channel-nums-fdm

SRS transmissions and receptions

- In 5G NR:
  - SRS is a reference signal sent in the UL to measure the channel quality.
  - SRS receptions at the gNB provide information about the combined effect of multipath fading and power loss of the transmitted signal from the UE.
  - Based on SRS reception, the gNB takes decisions for resource allocation and scheduling, link adaptation, beam management, etc.
  - SRS transmissions can be periodic, aperiodic, or semi-persistent
  - SRS parameters, i.e. periodicity and offset, can be configured:
    - by RRC and notified to UE (used in 4G LENA, more static);
    - by gNB MAC scheduler. The UE is notified through DCI format 2_3, about resources where SRS should be transmitted.
  - In time domain, the range for SRS transmission is from 8th to 13th OFDM symbol. 14th symbol is for PUCCH.
  - Within this 6 OFDM symbol region, SRS transmissions can take maximum 4 OFDM symbols.
  - To allow frequency multiplexing, SRS is typically transmitted over only a subset of subcarriers defined by the configuration, e.g., 2nd or 4th subcarrier.

SRS transmissions and receptions

- In 5G LENA:
  - Minimum transmission granularity in 5G-LENA is a RB in frequency domain, all subcarriers are used for SRS transmission.

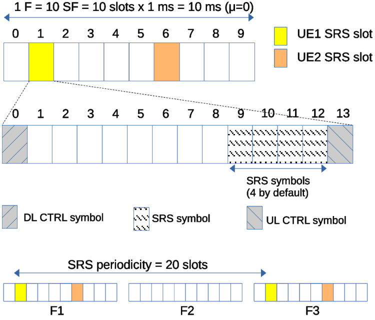


Figure: Example of SRS transmissions of 4 different UEs (max 1 UE SRS transmission per slot, per 5G-LENA design). SRS periodicity equal to 20 slots. Numerology is $\mu = 0$. TDD pattern structure is [DL S UL UL UL]. SRS transmissions occur in S slots (i.e., slots number 1 and 6).

Interference and channel feedback models

- 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 and interference signals derive from the PDSCH.

CQI feedbacks

- 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-LENA supports CQI Table1 and CQI Table2 (i.e., Table 5.2.2.1-1 and Table 5.2.2.1-2)
- 5G-LENA 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.

Power allocation

- The model supports two power allocation conventions:
  - Uniform power allocation:
    - The transmission power is uniformely allocated over all RBs of the bandwidth.
    - Power per RB is fixed.
    - If a RB is not allocated to any data transmission, the transmitted power is 0, and no interference is generated in that RB.
  - Uniform power allocation used:
    - The transmission power is uniformely allocated only over the RBs used for transmission.
    - Power per RB is fixed.
- Uplink power control is supported:
  - for UL DATA, UL CTRL and SRS.
  - Both closed and open loop modes are supported.

PHY data error models

- The model is defined at TB (Transport Block) level.
- A TB can span several RBs/symbols, and its size is a function of the number of allocated RBs/symbols and the MCS.
- The TB is an entity that is either received or not.
- A Link to System Mapping (L2SM) approach derives the error probability of the TB, based on the SINR, the transport block size, the MCS index, and the HARQ history.
- These aspects are captured in a pre-computed table, so saving execution time of the PHY processing.
- L2SM includes two key blocks:
  - The compression of the given set of per sub-carrier SINRs into a single scalar value (effective SINR)
  - The computation of the transport BLER corresponding to the derived effective SINR, by using SINR-BLER lookup table.
- Example of interest: cttc-error-model-amc

L2SM for PHY abstraction

- The used technique for SINR compression is Exponential Effective SINR Metric (EESM).
- A proprietary NR-compliant link simulator provided by Interdigital is used to generate SINR-BLER curves for various settings.

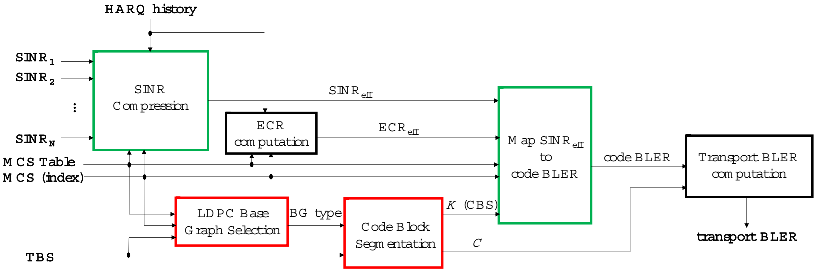


Figure: Schematic of the PHY NR abstraction

L2SM for PHY abstraction

- PHY abstraction for DL and UL data channels:
  - BLER-SINR curves provided by InterDigital, for block size, base graph type, MCS table and MCS index
  - SINR compression optimized based on link-level simulations, and valid for all NR frequency ranges and numerologies
  - MCS/CQI table 1 (up to 64QAM) and MCS/CQI table 2 (up to 256QAM), as per TS 38.214
  - LDPC base graph selection (BG1 and BG2), as per TS 38.212
  - Code block segmentation for LDPC, as per TS 38.212
  - It is used for error modeling, and can be used for AMC (if configured; otherwise, Shannon-based formula to determine CQI and then MCS, or fixed MCS)
- PHY abstraction for DL and UL control channels: No error model

Supported MCS tables

MCS Index	Modulation Order	Effective Code Rate	Spectral efficiency
0	2	0.12	0.2344
1	2	0.15	0.3066
2	2	0.19	0.3770
3	2	0.25	0.4902
4	2	0.30	0.6016
5	2	0.37	0.7402
6	2	0.44	0.8770
7	2	0.51	1.0273
8	2	0.59	1.1758
9	2	0.66	1.3262
10	4	0.33	1.3281
11	4	0.37	1.4766
12	4	0.42	1.6953
13	4	0.48	1.9141
14	4	0.54	2.1602
15	4	0.60	2.4063
16	4	0.64	2.5703
17	6	0.43	2.5664
18	6	0.46	2.7305
19	6	0.50	3.0293
20	6	0.55	3.3223
21	6	0.60	3.6094
22	6	0.65	3.9023
23	6	0.70	4.2129
24	6	0.75	4.5234
25	6	0.80	4.8164
26	6	0.85	5.1152
27	6	0.89	5.3320
28	6	0.93	5.5547

MCS Index	Modulation Order	Effective Code Rate	Spectral efficiency
0	2	0.12	0.2344
1	2	0.19	0.3770
2	2	0.30	0.6016
3	2	0.44	0.8770
4	2	0.59	1.1758
5	4	0.37	1.4766
6	4	0.42	1.6953
7	4	0.48	1.9141
8	4	0.54	2.1602
9	4	0.60	2.4063
10	4	0.64	2.5703
11	6	0.46	2.7305
12	6	0.50	3.0293
13	6	0.55	3.3223
14	6	0.60	3.6094
15	6	0.65	3.9023
16	6	0.70	4.2129
17	6	0.75	4.5234
18	6	0.80	4.8164
19	6	0.85	5.1152
20	8	0.67	5.3320
21	8	0.69	5.5547
22	8	0.74	5.8906
23	8	0.78	6.2266
24	8	0.82	6.5703
25	8	0.86	6.9141
26	8	0.90	7.1602
27	8	0.93	7.4063

Figure: Supported MCS tables

BLER-SINR curves

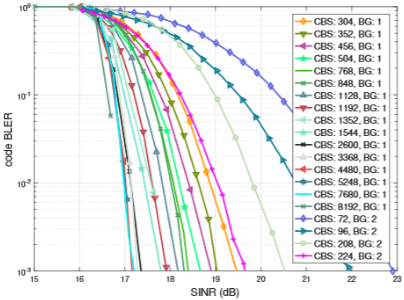


Figure: MCS23 of MCS Table1

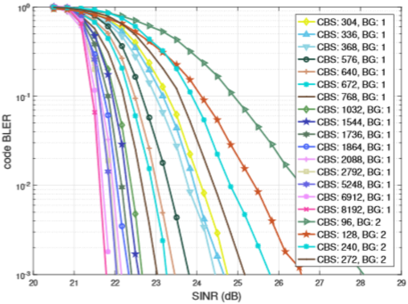


Figure: MCS21 of MCS Table2

PHY abstraction for HARQ

- Two methods: Chase Combining (CC) and Incremental Redundancy (IR)
  - HARQ-IR changes SINR and ECR (Effective Code Rate).
  - HARQ-CC changes only SINR.
- In both cases we consider the bits to be combined, to enable flexible NR scheduling decisions in time/freq domains.
- 5G-LENA supports 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.

Subsection 3

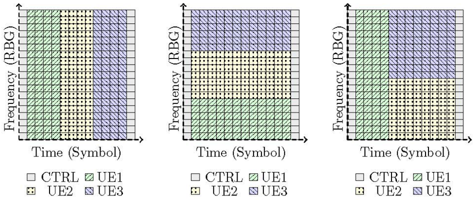
MAC

MAC

- 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 (Respurce 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 lenght 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

MAC

- **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.



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

Figure: Access schemes

Adaptive modulation and coding (AMC) model

- 5G-LENA 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).
    - Shannon-based: chooses the highest MCS that gives a spectral efficiency lower than the one provided by the Shannon rate.
  - In the Error model-based AMC, the PHY abstraction model is used for link adaptation.

Transport Block (TB) model and MAC PDU

- The model multiplexes RLC PDUs onto a MAC PDU
- Only one MAC PDU can be transmitted per TB per MAC entity.
- Differently from LTE models, we are progressing towards a real model of headers and control elements (CE). However, the LteRadioBearerTag packet tag inhereted by LTE to multiplex different logical channels to and from the RLC layer is still present.
- The incorporation of real MAC headers is included in the latest release.
- The LCID (Logical Channel ID) subheader contains information on the LCID of the following data.
- The Buffer Status Report is a MAC CE. The only one we model at the moment

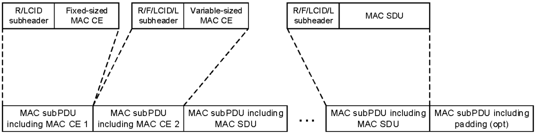


Figure: MAC PDU extracted from TS 38.321

Transport Block Size (TBS)

- It is based on TS 38.214, Section 5.1.3.2 (DL) and 6.1.4.2 (UL).
- It depends on MCS table, MCS index and resource allocation (in terms of OFDM symbols and RBs).
- TBS is computed as follows.

$$N_{info} = R \times Q \times n_s \times n_{rb} \times (12 - n_{refSc}) \tag{1}$$

- 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, to obtain the TBS:
  - The CRC attachment to the TB is subtracted (24 bits).
  - In case of code block segmentation, the code block CRC attachments are subtracted.

Schedulers

- 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.
- Schedulers API follows the FemtoForum specification for LTE MAC Scheduler Interface
- The core class of the NR module schedulers design is NrMacSchedulerNs3.

Schedulers

- Support of:
  - 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.
- Policies: RR, PF, MR
  - 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.
- Creation of DCIs: per slot, specifying the starting symbol, the duration (in number of symbol), and the RBG (Resource Block Group) bitmask.
- Timings: at slot x, scheduler takes DL scheduling decisions for slot x+L1L2CtrlLatency, and UL scheduling decisions for slot x+L1L2CtrlLatency+K2
- Intrusive code redesign was performed, following the principle of reducing duplication of codes among schedulers (big problem in LTE maintenance).

LTE/NR scheduling times

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

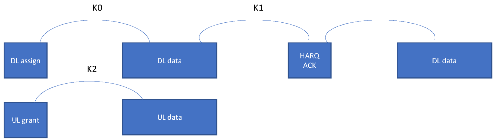


Figure: Implemented processing times

LTE/NR scheduling times

	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]

Figure: Default values of processing times

UL Scheduling Request (SR)

The procedure can be summarized as follows:

- In slot *n*, when the UE sees data to transmit in the RLC queue, it prepares a SR to be sent to the eNB MAC, informing of data to transmit.
- It takes 1 slot for the SR to reach the UE PHY and 2 slots to reach the air.
- The gNB receives the SR in n+3.
- The 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+N2.
- The UE receives the UL DCI at n+4+L1L2, and prepares the data plus the BSR that have to be sent N2 slots later.
- At slot n+4+L1L2+N2+1 the scheduler knows there is more data in UE's queue, and prepares the allocation for the UE to transmit such data at (n+4+L1L2+N2+1)+L1L2+N2

Component Carriers and Bandwidth Parts

- NR devices have an architecture that can be used for:
  - Carrier Aggregation (multiple CCs)
  - FDM of numerologies: with orthogonal allocation of multiple BWPs.
  - The gNB can simultaneously transmit and receive from multiple BWPs.
  - The UE is active in a single BWP at a time.
- Proxy CC manager:
  - It allocates flows to CC based on their CQI (FDM of numerologies strategy for multiple BWPs)
  - Other rules for CC manager can be implemented.
- Each CC has its own MAC and PHY instances:
  - They can be configured with a different scheduler policy and different PHY parameters (i.e., BW, numerology, power, etc.)
- A CC is defined as primary (CC0) and SIB/MIB are sent through it to enable UEs attachment.
- Each CC has its own control and data channels.
- HARQ processes are maintained per CC.

CC/BWP architecture

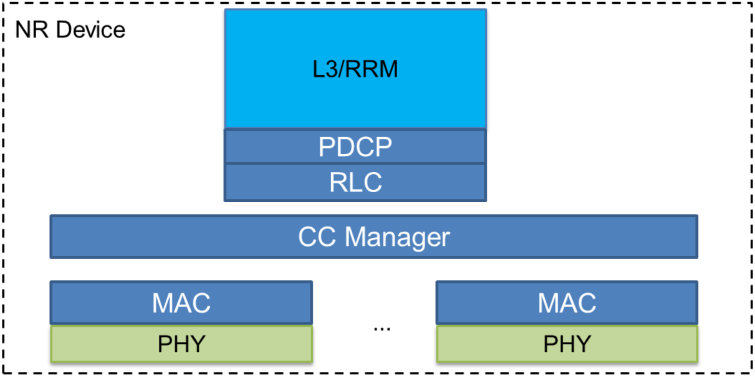


Figure: Architecture of CC/BWP manager

NR CA/BWP example

- cttc-lte-ca-demo.cc
- One operation band @28GHz
- Two contiguous Component Carriers (CCs)
  - Primary CC: 2 BWPs with numerologies 3 and 4, and 20 and 40 MHz bandwidth.
  - Secondary CC: 1 BWP (whole carrier bandwidth), 100 MHz, numerology 3
  - 2 UEs

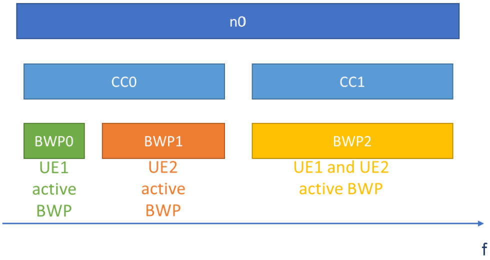


Figure: Example of CA functionality with FDM of numerologies per BWP

Subsection 4

Validation

Calibration Campaign for FR2 (mmWave) bands

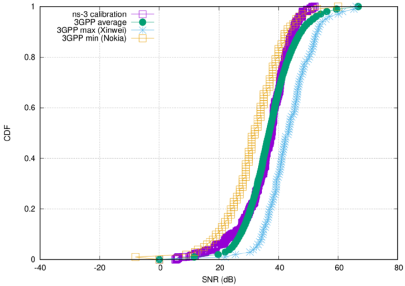
- The simulator is calibrated according to Phase 1 indoor hotspot system-level calibration for multi-antenna systems, as per Annex A.2 in [TS 38.802].
- The deployment scenario is composed of 12 sites at 20 m distance, and 120 UEs (100% indoor) randomly dropped in a 50 m x 120 m area.

Parameter	Value
Carrier freq.	30 GHz
Bandwidth	40 MHz
SCS	60 kHz ($\mu = 2$)
Channel	Indoor TR 38.900
BS Tx Power	23 dBm
BS Antenna	M=4, N=8, 1 sector, height=3 m, vertical polarization
UE Antenna	M=2, N=4, 1 panel, height=1.5 m, vertical polarization
BS noise figure	7 dB
UE noise figure	10 dB
UE speed	3 km/h
Scheduler	TDMA PF
Traffic model	Full Buffer

Figure: Simulation parameters

Selected Results

- As reference curves, we use the results provided by the companies in [R11709828].



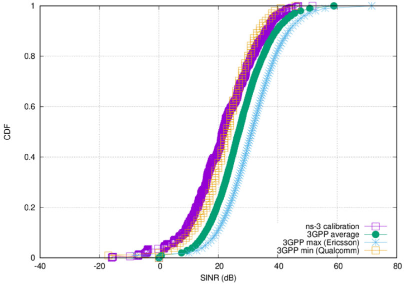


Figure: Simulation results

Calibration Campaign for FR1 bands

- We calibrated also LTE configuration to 4G LENA.
- 4G LENA was previously calibrated by different users, and by NIST through typical 3GPP procedures.

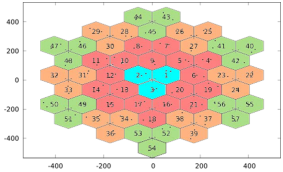
LTE Configuration

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

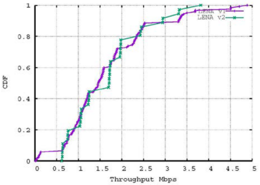
Figure: LTE in LENA vs. 5G-LENA

Calibration results

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

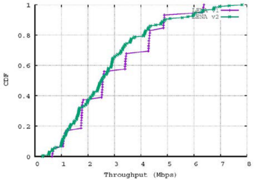


Figure: Simulation results

Section 2

Latest extensions to NR module

Subsection 1

NR-U

NR-U Extension

- Collaboration with Interdigital 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.

NR-U System design

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

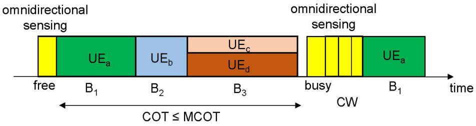
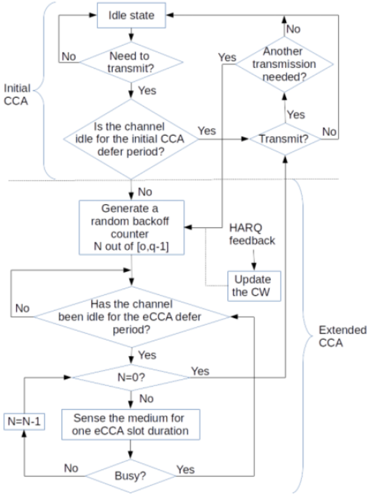


Figure: NR-U frame

Listen Before Talk (LBT)



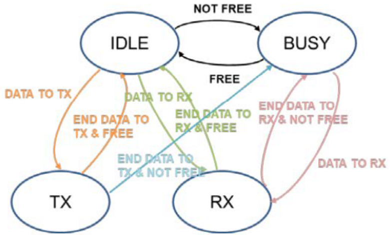


Figure: Listen Before Talk

NR-U Functional Architecture

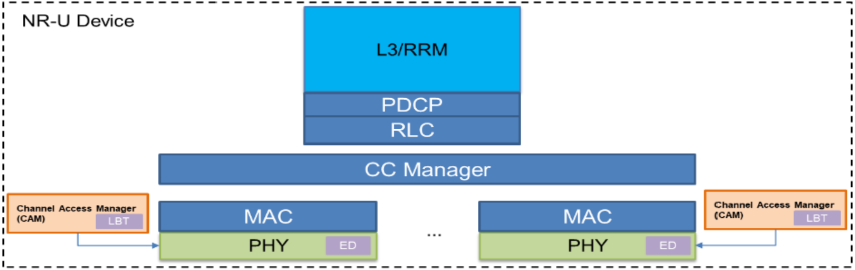


Figure: NR-U architecture

Subsection 2

NR-V2X

NR-V2X Extension

- Collaboration with NIST started due to our previous experience with studies on D2D.
- 1 year grant between fall 2019 and fall 2020.
- Objectives:
  - Extend 5G-LENA simulator with V2X capabilities.
  - NR V2X evaluations on high fidelity, full stack network simulator.
- Output:
  - Open source network simulator for NR V2X evaluations (first release planned for: 1Q 2021).

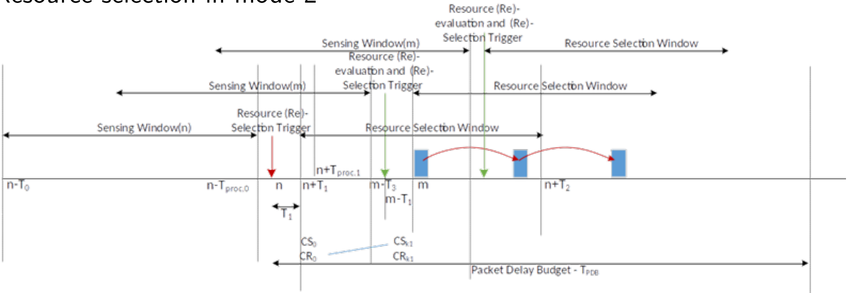
Focus and Base codes

- V2X extension for NR in development, based on the (on-going) standardization in 3GPP Rel-16.
  - Broadcast, groupcast, unicast
  - FR1 (numerologies 0, 1, 2), FR2 (numerologies 2, 3)
  - Out-of-coverage scenario, in-coverage
  - Mode 2 resource allocation (UE selected), mode 1 (gNB scheduled)
  - Omnidirectional tx/rx for SL
  - Sensing-based and random-based semi-persistent scheduling (basic service messages), per-packet scheduling
  - Time multiplexing of PSCCH and PSSCH, frequency multiplexing
  - Blind retransmissions, no feedback. HARQ, feedback channel (PSFCH)
- Base codes: D2D (NIST), C-V2X (TU Dortmund Univ.), milliCar (Univ. Padova).
  - C-V2X code includes sensing-based SPS, but FDD
  - milliCar code includes V2V-Highway and V2V-Urban channel models (TR 37.885), but TDMA

MAC

- Mode 1: gNB schedules SL resource(s) to be used by UE for SL.
- Mode 2: UE determines SL transmission resource(s) within SL resources configured by gNB/network or pre-configured.

Resource selection in mode 2



- 1st step: Sensing procedure (SCI decoding and/or SL measurements, during sensing window [n-T_0, n-$T_{proc,0}$])
- 2nd step: Resource (re)-selection procedure, including:
  - identification of candidate resources within the resource selection window [n+T_1, n+T_2]
  - resource selection for (re-)transmission(s) from the identified candidates

Section 3

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