The ns-3 LTE module

ns-3 annual meeting 2019
June 17-21, Florence, Italy

CTTC MONET

The ns-3 LTE module, a.k.a. LENA

LTE-EPC Network simulAtor

- LENA is a simulation platform for LTE/EPC
- LENA project, funded by Ubiquysis (now Cisco), between 2010 and 2013.
- GSoC 2010, 2012, 2013, 2014, 2015, 2017, and 2019
- Other projects:
  - Spectrum Sharing Simulator Program (LLNL) (on going)
  - ID-NRU (on going)
  - Public Safety NIST (LTE D2D)
  - ID 5G NR design in mmWave bands
  - SCALAA – Spidercloud – Licensed assisted access
  - WALAA 2 – WFA Licensed Assisted Access
- Community contributions

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LENA: An open source product-oriented LTE/EPC Network Simulator

- A Product-oriented simulator:
  - Designed around an industrial API:
    the Small Cell Forum MAC Scheduler Interface Specification
  - Full stack, end-to-end
  - Accurate model of the LTE/EPC protocol stack
  - Specific Channel and PHY layer models for LTE macro and small cells
- An Open source simulator:
  - Helps build confidence and trust on simulation model
  - Candidate reference evaluation platform
  - Based on ns-3
  - Free and open source licensing (GPLv2)
  - Widely validated through test suites, calibration campaigns
  - The most accepted open source LTE packet level simulator in terms of publication counts and citations.

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LENA High level requirements

- Support the evaluation of:
  - Radio-level performance
  - End-to-end QoE
- Allow the prototyping of algorithms for:
  - QoS-aware Packet Scheduling
  - Radio Resource Management
  - Inter-cell Interference Coordination
  - Self Organized Networks
  - Cognitive / Dynamic Spectrum Access
- Scalability requirements:
  - Several 10s to a few 100s of eNBs
  - Several 100s to a few 1000s of UEs

(Some) Important Design Choices

- FemtoForum LTE MAC Scheduler API
- Radio signal model granularity: Resource Block
  - Symbol-level model not affordable
  - Simplified Channel & PHY model
- Realistic Data Plane Protocol stack model
  - Realistic RLC, PDCP (real PDUs), S1-U, X2-U
  - Allows for proper interaction with IP networking
  - Allows for end-to-end QoE evaluations
- Simplified Control Plane model:
  - Realistic RRC model
  - Simplified S1-AP, X2-C, S11, and S5 models (UDP)
- Simplified EPC
  - One MME and multiple SGW and PGW nodes (S11, S5 support)
- Simplified UE mode of operation
  - Connected mode (full support)
  - Idle mode (simplified)

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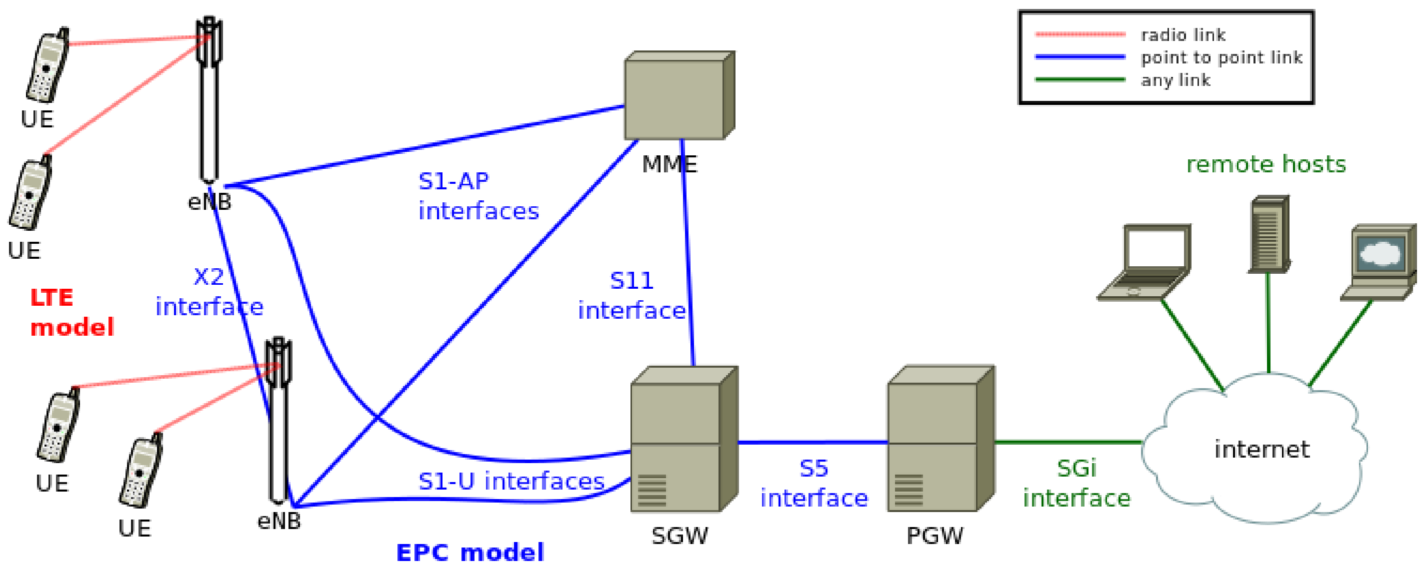
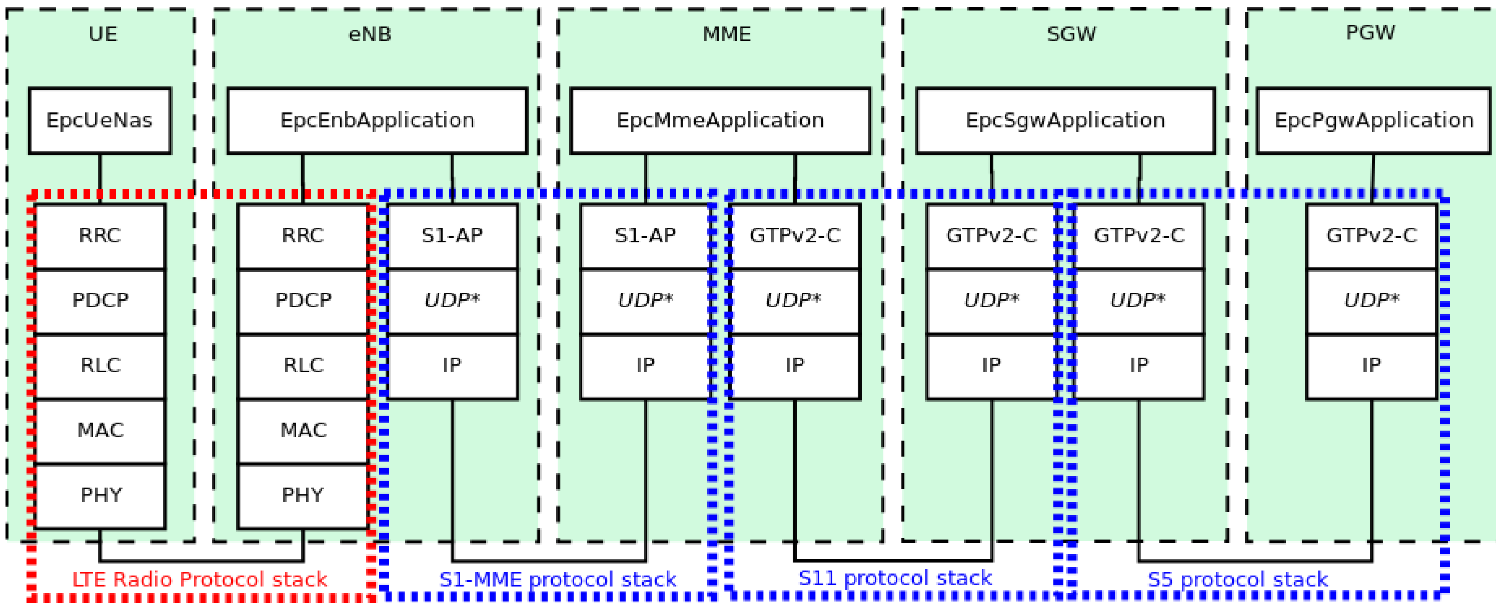
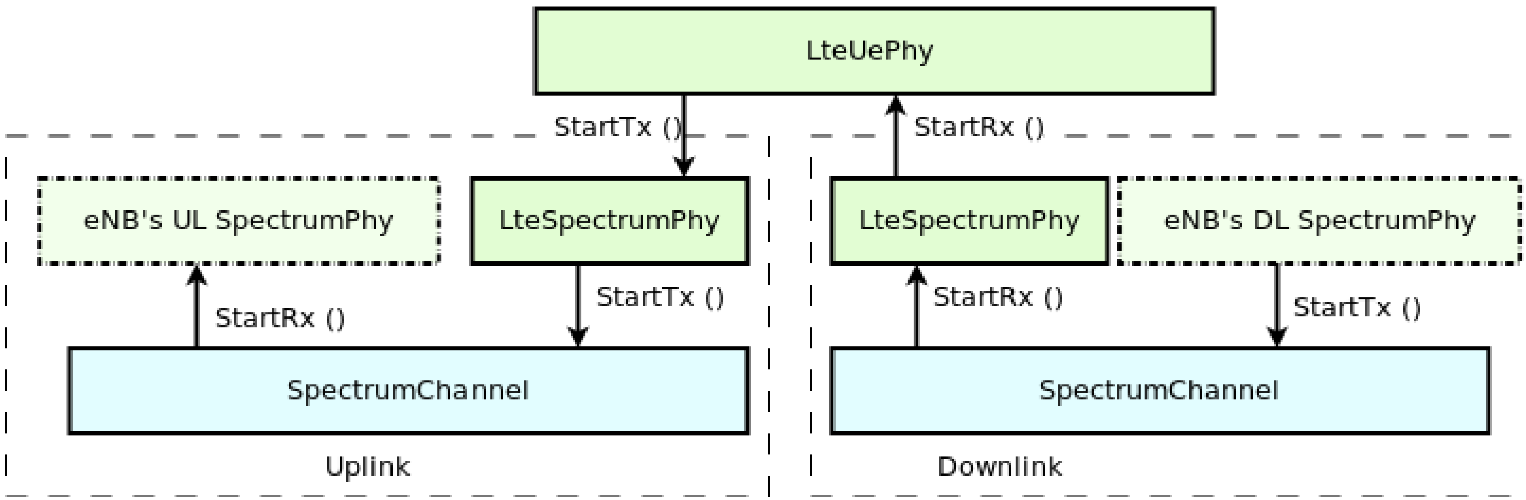
LENA model overview



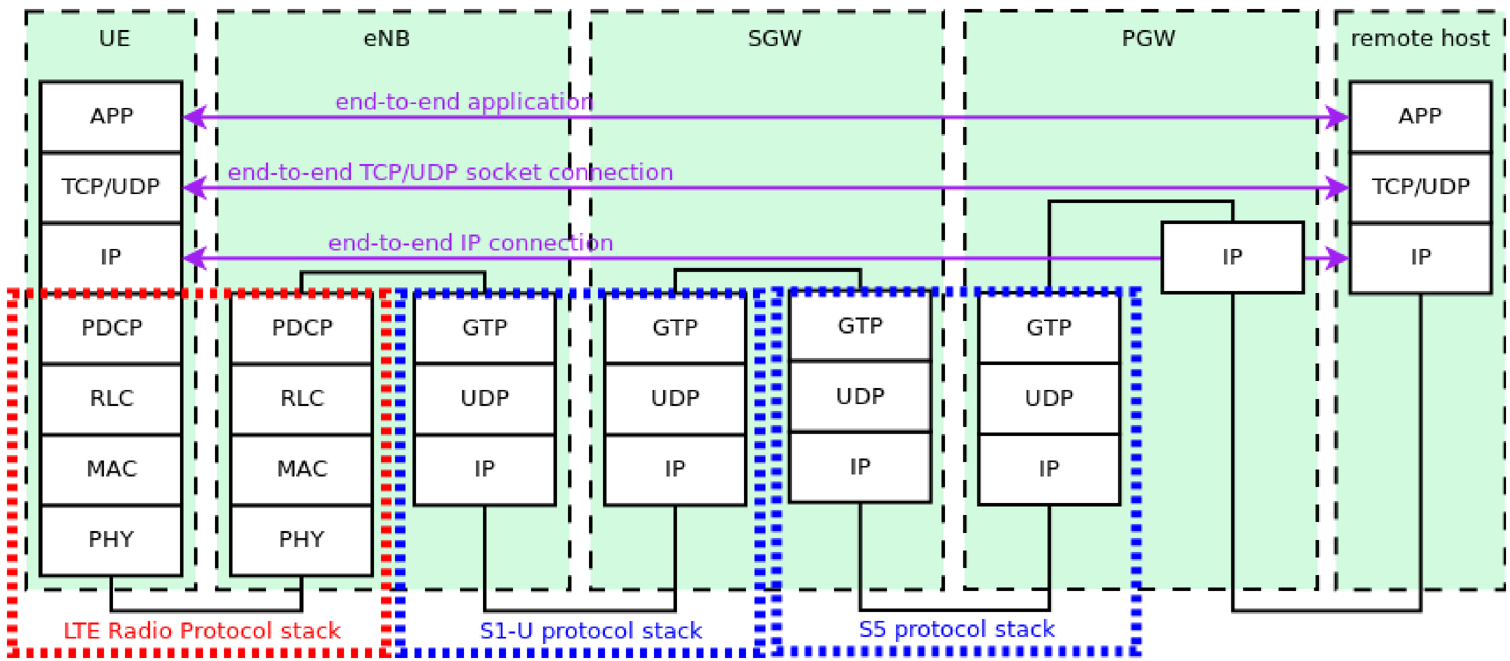
End-to-end Control Plane protocol stack



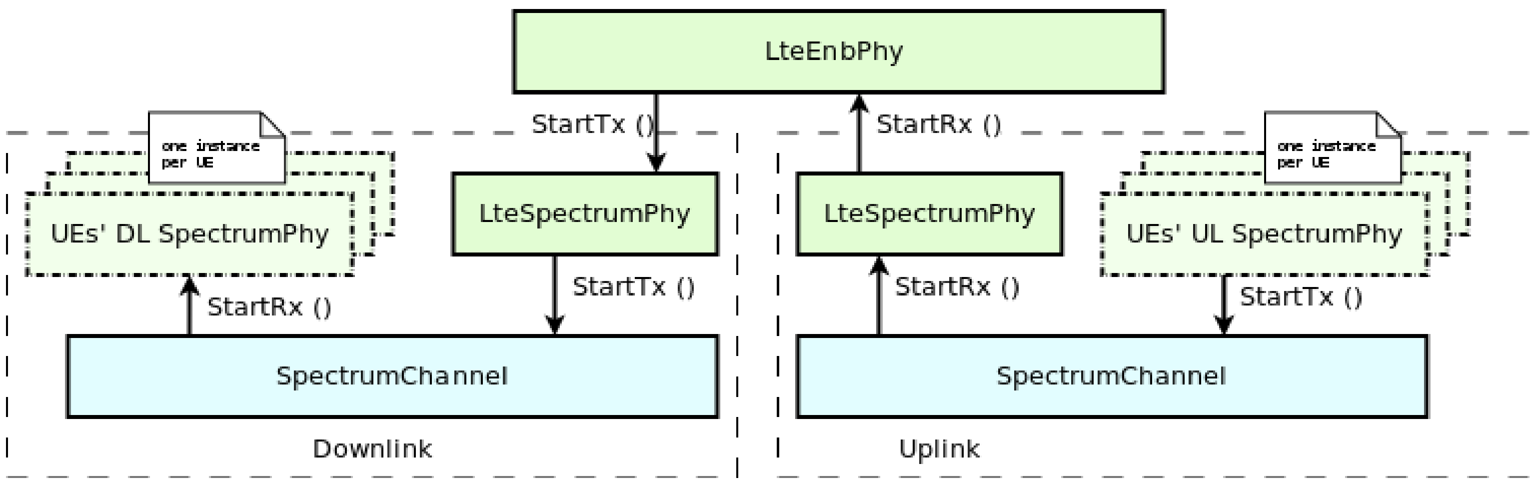
PHY and Channel architecture



End-to-end Data Plane protocol stack



PHY and Channel architecture: eNB



Radio Propagation Models

- Included new models for enabling 3GPP-like scenarios
  - New path loss models (indoor and outdoor)
    - External & internal wall losses
    - Shadowing
  - Buildings model
    - Add buildings to network topology
  - Antenna models
    - Isotropic, sectorial (cosine & parabolic shape)
  - Fast fading model
    - Pedestrian, vehicular, etc.

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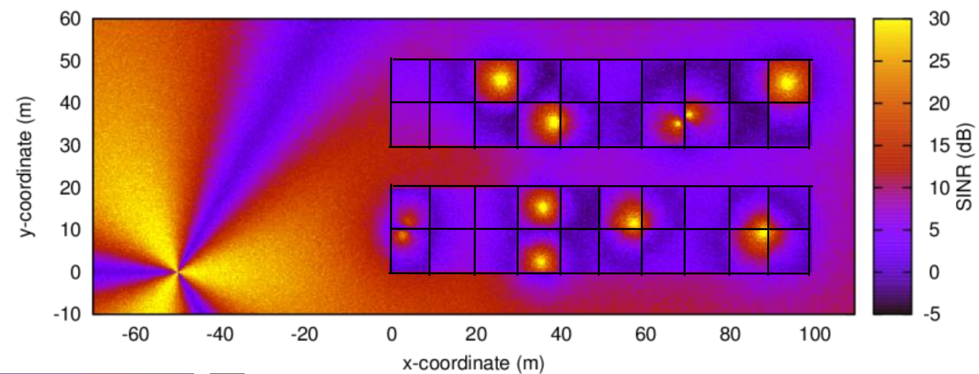
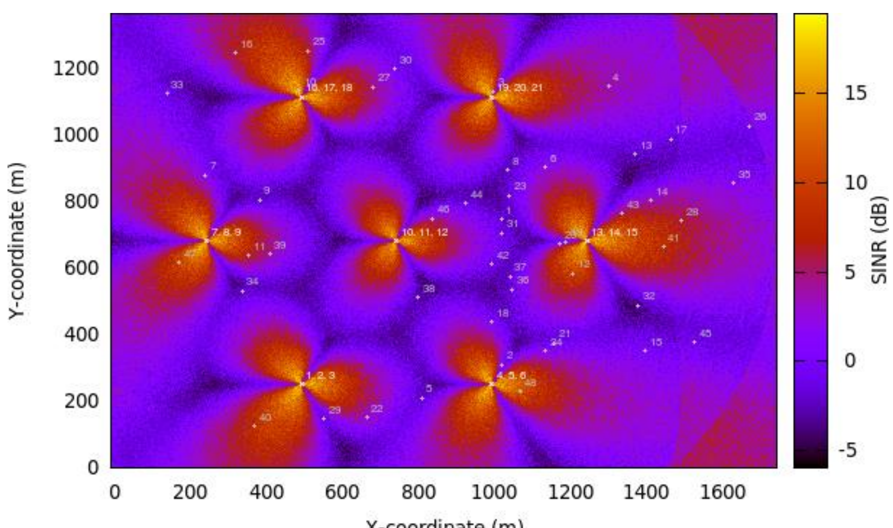
Antenna models

- LTE supports antenna modeling via ns-3 AntennaModel class.
- Isotropic [default one, for both eNB and UE]
- Sectorial (cosine & parabolic shape)

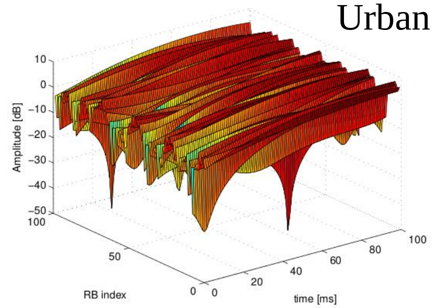




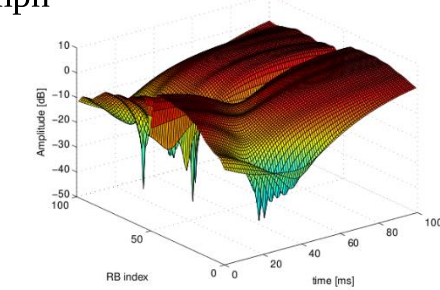
Fading model

- Fast fading model based on pre calculated traces for maintaining a low computational complexity
  - Matlab script provided in the code using rayleighchan function
  - 1 fading value per RB and TTI
- Main parameters:
  - Users' speed: relative speed between users (affects the Doppler frequency)
  - Number of taps (and relative power): number of multiple paths considered
  - Time granularity of the trace: sampling time of the trace.
  - Frequency granularity of the trace: number of RB.
  - Length of trace: ideally large as the simulation time, might be reduced by windowing mechanism.

Urban scenario 3 kmph

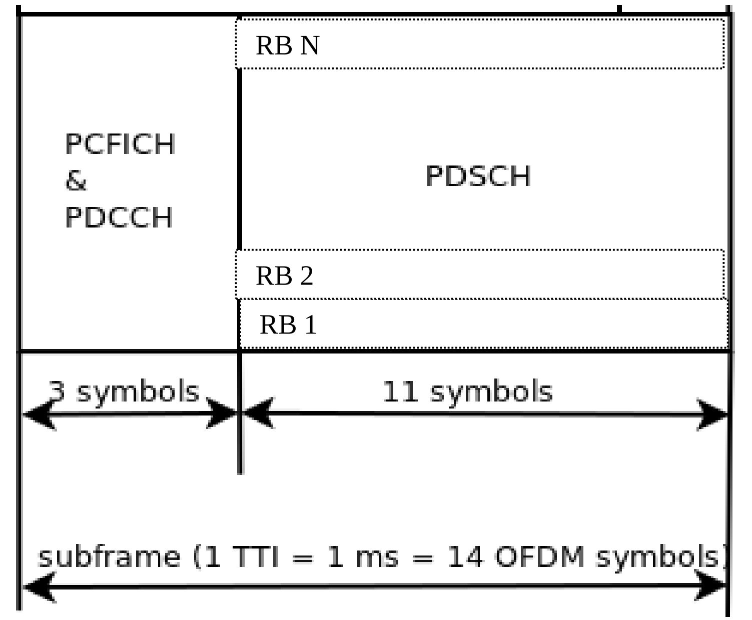


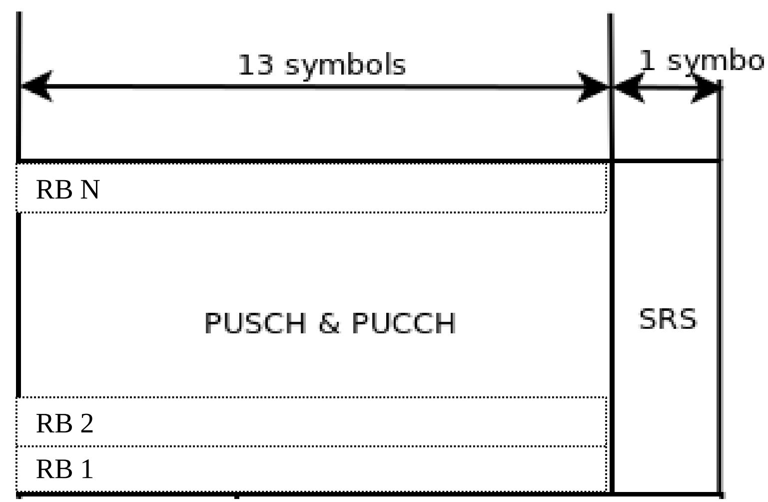
Pedestrian scenario 3 kmph



PHY model

- Only FDD is modeled
- Freq domain granularity: RB
- Time domain granularity:
  - 1 TTI (1 ms)
- The subframe is divided in frequency into DL & UL
  - DL part is made of:
    - Control (RS, PCFICH, PDCCH)
    - RS is part of the control
    - Data (PDSCH)
  - UL part is made of:
    - Control and data (PUSCH)
    - SRS (only wideband periodic)





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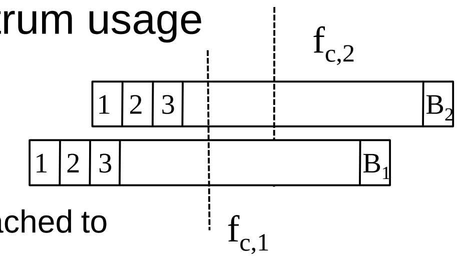
Interference and Channel Feedback

- LTE Spectrum model: (f_c, B) identifies the radio spectrum usage
  - f_c: LTE Absolute Radio Frequency Channel Number
  - B: Transmission Bandwidth Configuration in number of RB
  - Supports different frequencies and bandwidths per eNB
  - UE will automatically use the spectrum model of the eNB it is attached to



- Gaussian Interference model
  - Powers of interfering signals (in linear units) are summed up together to determine the overall interference power per RB basis
- CQI feedback
  - Periodic wideband CQIs: single value representative for the whole B.
  - Inband CQIs: a set of value representing the channel state for each RB
- In DL evaluated according to the SINR of:
  - Control channel (RS, i.e., PDCCH)
  - Data channel when available (PDSCH)
- In UL evaluated according to the SINR of
  - SRS signal periodically sent by the UEs.
  - PUSCH with the actual transmitted data.
- In UL scheduler can filter the CQI according to their nature:
  - SRS_UL_CQI for storing only SRS based CQIs.
  - PUSCH_UL_CQI for storing only PUSCH based CQIs.

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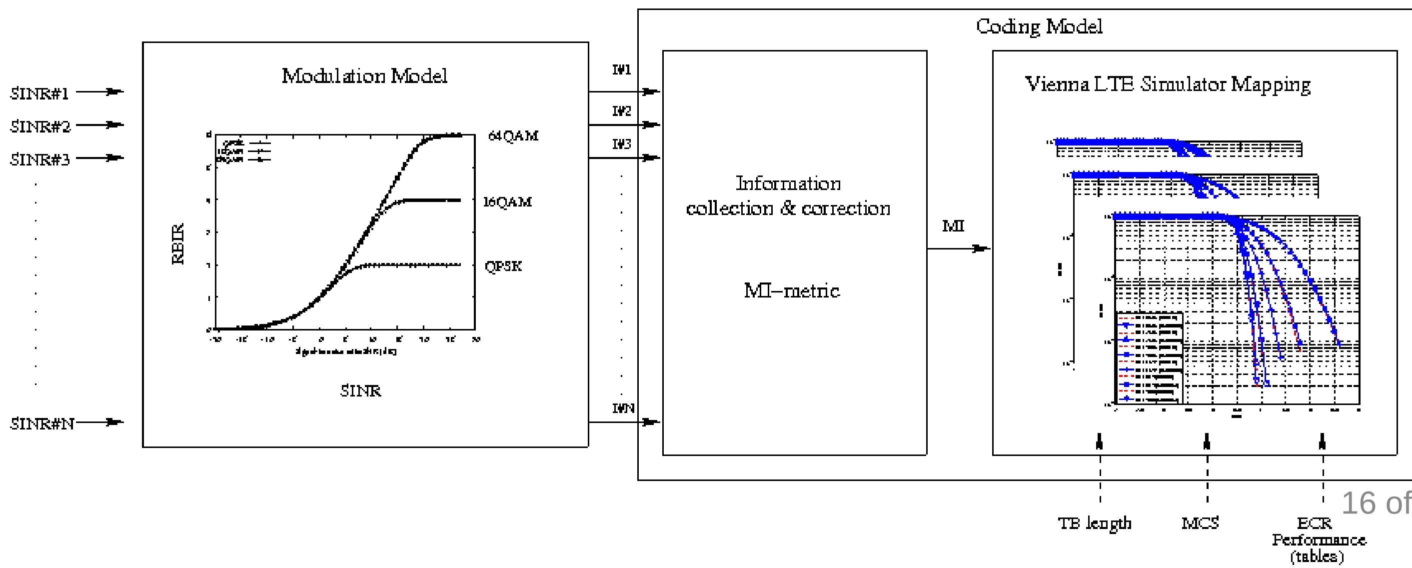
PHY Data error model

- Signal processing not modeled accurately ⇒ use error model
- Transport Block error model
- Used for PDSCH and PUSCH
- Based on Link-to-System Mapping
  - SINR measured per Resource Block
  - Mutual Information Effective SINR Mapping (MIESM)
  - BLER curves from dedicated link-level LTE simulations
  - Error probability per codeblock
  - Multiple codeblocks per Transport Block



PHY Control error model

- Error model only for downlink, while uplink has an error-free channel
- Based on an evaluation study carried out in the RAN4 (R4-081920)
- In case of error correspondent DCIs are discarded, the data will not be decoded as well

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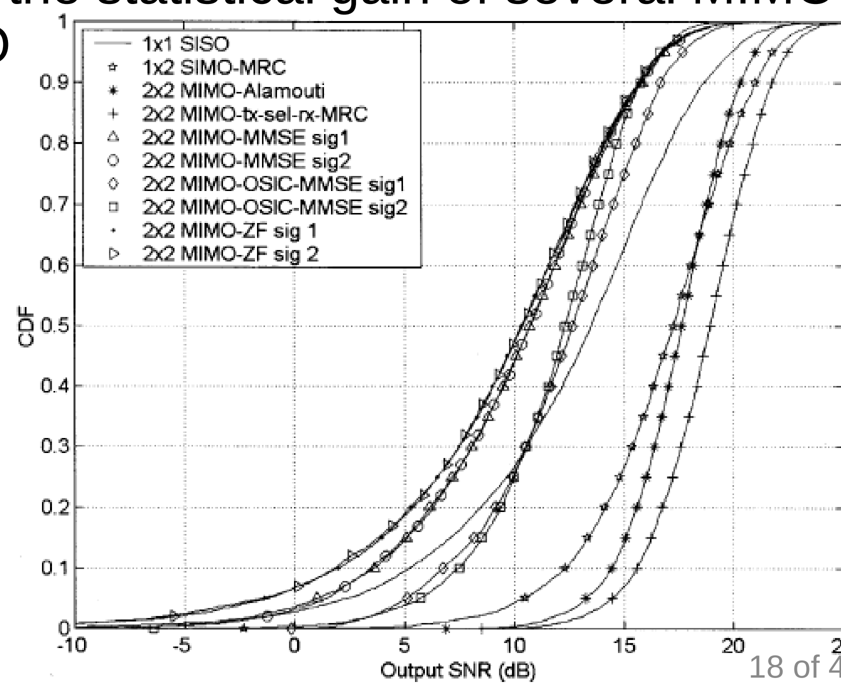
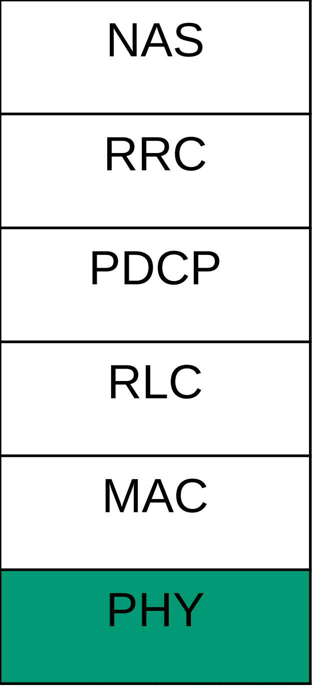
MIMO

- ns-3 provides only SISO propagation model
- MIMO has been modeled as SINR gain over SISO according to
  - S. Catreux, L.J. Greenstein, V. Erceg, “Some results and insights on the performance gains of MIMO systems,” Selected Areas in Communications, IEEE Journal on , vol.21, no.5, pp. 839- 847, June 2003
- Catreux et al. present the statistical gain of several MIMO solutions wrt the SISO





UE Measurements

- UE has to report a set of measurements of the eNBs to the eNB, and together with the associated physical cell identity (PCI)
  - Reference signal received power (RSRP) ~ “average” power across the RBs
  - Reference signal received quality (RSRQ) ~ “average” ratio between the power of the cell and the total power received across all the RBs
- Measurements are performed during the reception of the RS
- PCI is received with the Primary Synchronization Signal (PSS)
- RSRP is reported by PHY layer in dBm while RSRQ in dB every 200 ms.
- Layer 1 filtering is performed by averaging all the measurements collected during the last window slot.

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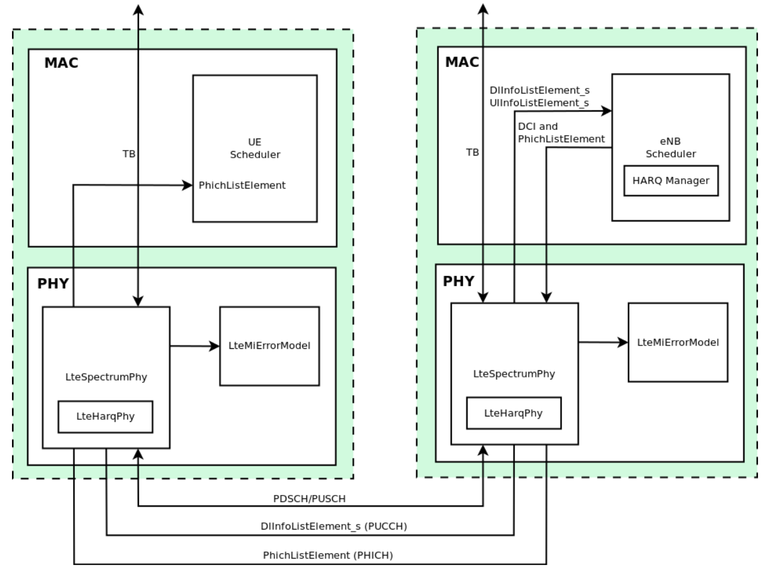
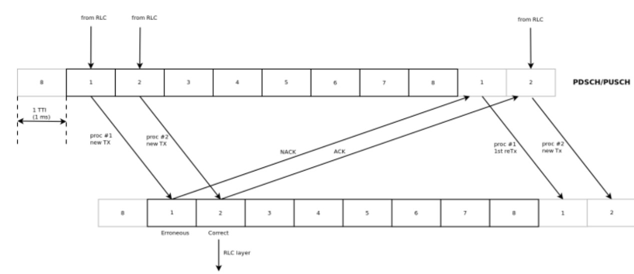
HARQ model

- Model implemented is soft combining hybrid IR Full incremental redundancy (also called IR Type II)
- Asynchronous model for DL
  - Dedicated feedback (ideal)
- Synchronous model for UL
  - After 7 ms of the original transmission
- Retransmissions managed by Scheduler
  - Retransmissions are mixed with new one (retx has higher priority)
  - Up to 4 redundancy version (RV) per each HARQ block
- Integrated with error model





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MAC & Scheduler model

- Resource allocation model:
  - Allocation type 0
  - RBs grouped into RBGs, of different size depending on the bandwidth

System Bandwidth $N_{\mathrm{RB}}^{\mathrm{DL}}$	RBG Size (P)
≤10	1
11 – 26	2
27 – 63	3
64 – 110	4

- Transport Block model
  - Mimics 3GPP structure
    - mux RLC PDU onto MAC PDU
  - Virtual MAC Headers and CEs (no real bits)
    - MAC overhead not modeled
- Modeled processing delay for both DL and UL

Adaptive Modulation and Coding (AMC)

- Two algorithms working on reported CQI feedback
  - Piro model: based on analytical BER (very conservative)

$$\mathrm{BER} = 0.00005$$
$$\Gamma = \frac{-\ln(5 * \mathrm{BER})}{1.5}$$
$$\eta_i = \log_2\left(1 + \frac{\gamma_i}{\Gamma}\right)$$

γ_i SINR of UE i

  - Vienna model: aim at max 10% BLER as defined in TS 36.213 based on error model curves
    - The scheme adapts the MCS to the actual PHY performance, based on CQI report.
    - It selects the highest MCS that has a BLER below 10%.

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MAC Scheduler implementations

- Round Robin (RR)
- Proportional Fair (PF)

LENA project

- Maximum Throughput (MT)
- Throughput to Average (TTA)
- Blind Average Throughput (BET)
- Token Bank Fair Queue (TBFQ)
- Priority Set Scheduler (PSS)

GSoC 2012

- Channel and QoS Aware Scheduler (CQA)
  - B. Bojovic, N. Baldo, A new Channel and QoS Aware Scheduler to enhance the capacity of Voice over LTE systems , In Proceedings of 11th SSD, Feb 2014, Castelldefels (Spain)
- All implementations based on the FemtoForum API
- The above algorithms are for downlink only
- For uplink, all current implementations use the same Round Robin algorithm
- Assumption: HARQ has always higher priority wrt new data

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RLC Model

- Supported modes:
  - RLC TM, UM, AM as per 3GPP specs
  - RLC SM: simplified full-buffer model
- Features
  - PDUs and headers with real bits (following 3GPP specs)
  - Segmentation
  - Fragmentation
  - Reassembly
  - SDU discard
  - Status PDU (AM only)
  - PDU retx (AM only)
- Unsupported features
  - Fragmentation of ReTx PDUs (resegmentation)

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PDCP model

- Simplified model supporting the following:
  - Headers with real bytes following 3GPP specs
  - Transfer of data (both user and control plane)
  - Maintenance of PDCP SNs (sequence numbers)
  - Transfer of SN status (for handover)
- Unsupported features
  - Header compression and decompression using ROHC
  - In-sequence delivery of upper layer PDUs at re-establishment of lower layers
  - Duplicate elimination of lower layer SDUs at re-establishment of lower layers for radio bearers mapped on RLC AM
  - Ciphering and deciphering of user plane data and control plane data
  - Integrity protection and integrity verification of control plane data
  - Timer based discard

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RRC Model features

- Initial cell selection
  - Cell search (based on RSRP of the received PSS)
  - Broadcast of system information (MIB, SIB1, SIB2)
  - Cell selection evaluation
  - Simplified RLF model (detection at the UE)
- RRC Connection Establishment
- RRC Connection Reconfiguration, supporting:
  - SRB1 and DRB setup
  - SRS configuration index reconfiguration
  - PHY TX mode (MIMO) reconfiguration
  - Mobility Control Info (handover)
  - Secondary carrier configuration
- UE Measurements
  - Event-based triggering supported (events A1 to A5)
  - Assumption: 1-to-1 PCI to EGCI mapping
  - Only E-UTRA intra-frequency; no measurement gaps

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RRC Model architecture

- LteUeRrc: UE RRC logic
- LteEnbRrc + UeManager: eNB RRC logic
- Two models for RRC messages
  - Ideal RRC
    - SRBs not used, no resources consumed, no errors
  - Real RRC
    - Actual RRC PDUs transmitted over SRBs
    - ASN.1 encoding

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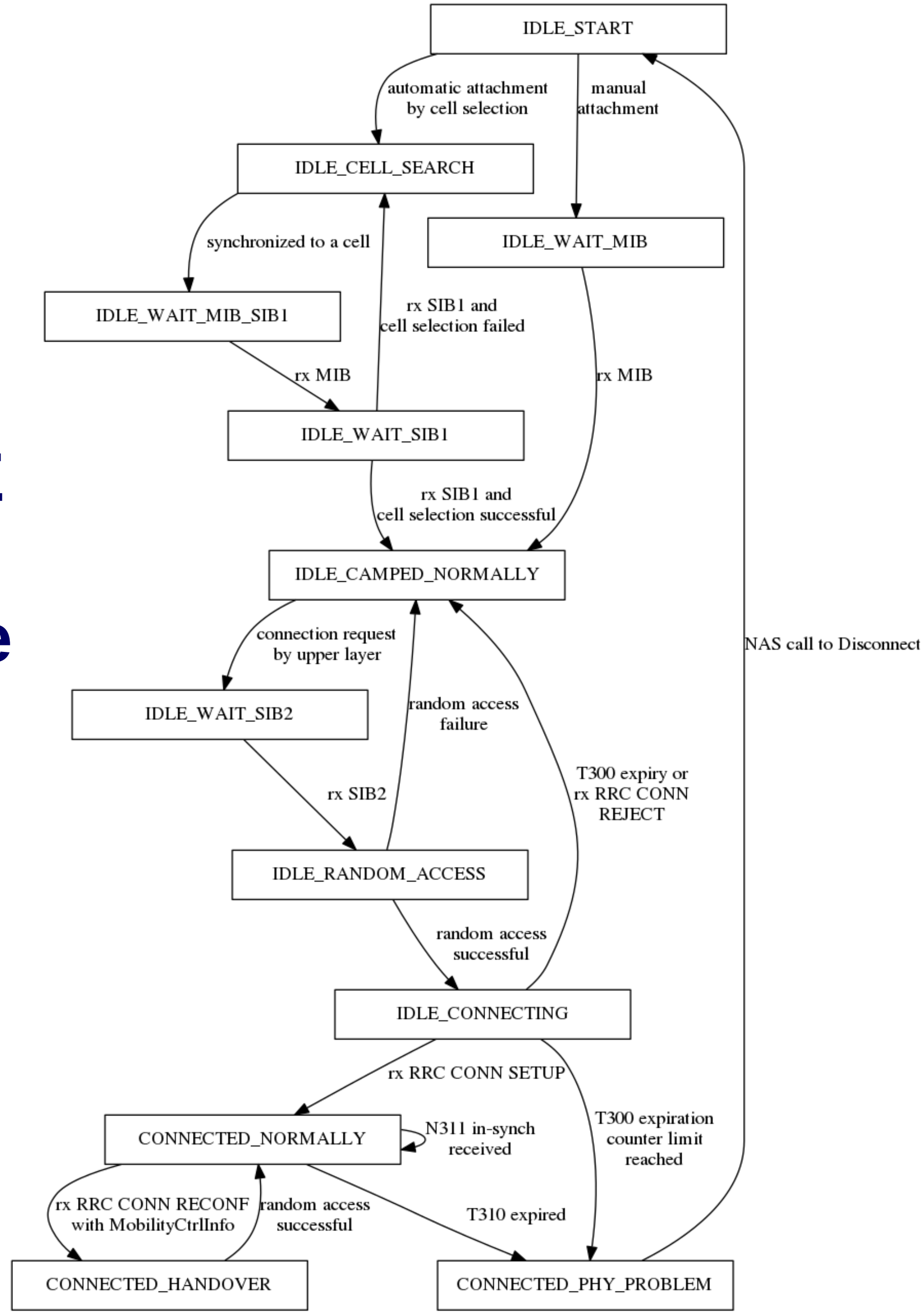
RRC UE state machine



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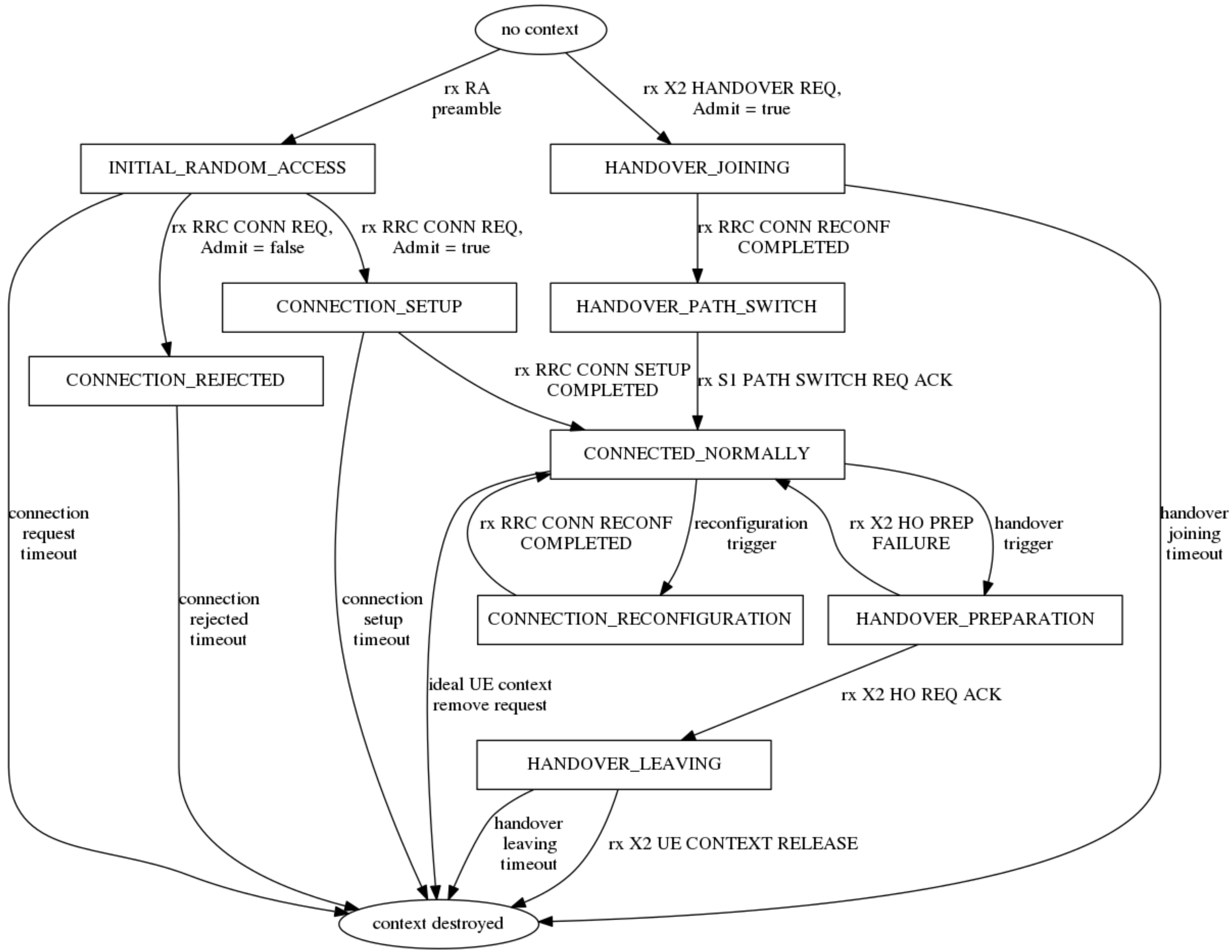
RRC eNB State Machine



Random Access model

- Random Access preamble transmission
  - Ideal model: no propagation / error model
  - Simplified collision detection
  - No capture effect
- Random Access Response (RAR)
  - Consumes no resources
  - Modeled as control message, subject to error model
  - In real system is a special PDU sent on DL-SCH
  - Resource consumption can be modeled by enhanced scheduler
- Message3 – RRC connection request
  - UL grant allocated by Scheduler
  - RLC TM PDU with actual bytes, subject to error model
- Contention resolution is not modeled

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Random Access model

- Supported modes:
  - Contention based (for connection establishment)
  - Non-contention based (for handover)

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NAS model

- It is a protocol which allows UE to talk to MME
- Supported NAS states
  - EMM (EPS Mobility management) Registered, ECM (EPS connection management) connected, RRC connected
  - EMM Registered, ECM idle, RRC idle
- Logical interaction with RRC
  - NAS PDUs not implemented
- Functionality
  - UE Attachment (transition to NAS Active state)
  - UE Removal (transition to NAS OFF state)
  - EPS Bearer activation
  - Multiplexing of data onto active EPS Bearers
    - Based on Traffic Flow Templates
    - Both UDP and TCP over IPv4 and IPV6 are supported

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NAS model

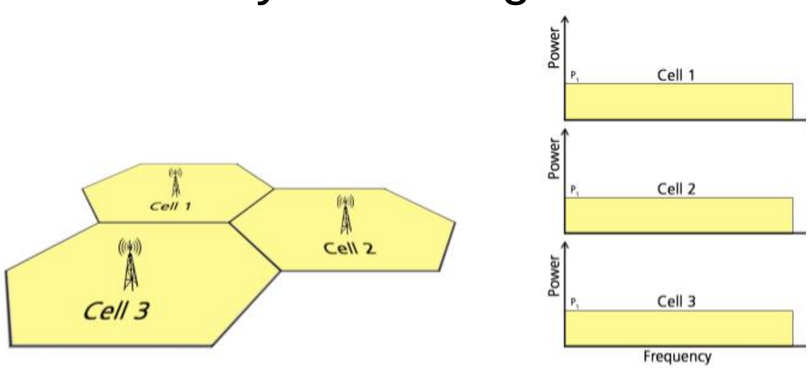
- Unsupported features
  - PLMN and CSG selection
  - Tracking area update, paging

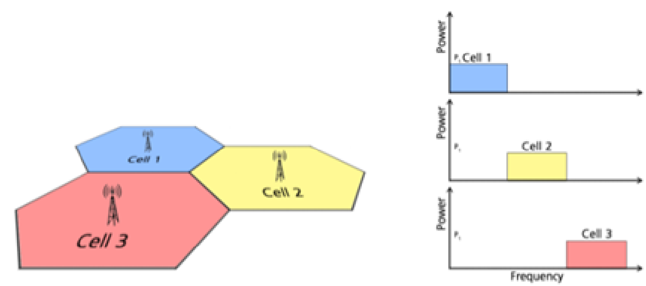
Handover Support

- API for Handover Algorithms (GSoC 2013)
  - Measurement configuration
  - Measurement report handling
  - Handover triggering
- Available handover algorithms:
  - No-op
  - A2-A4-RSRQ
  - Strongest cell handover (A3-based)
  - <your algorithm here>

FFR Algorithms

- GSoC 2014
- FFR algorithms fit in Self Organized Network algorithms
- The LTE standard does not provide the design of FFR algorithms (left to vendor)
- Usually eNB uses same carrier frequency and system bandwidth to serve all of its users: **FFR= 1**
- FFR divides available bandwidth into sub-bands with different FFR and different TX power setting
  - Combination of scheduling and power control functionalities
- Currently 7 FFR algorithms are implemented





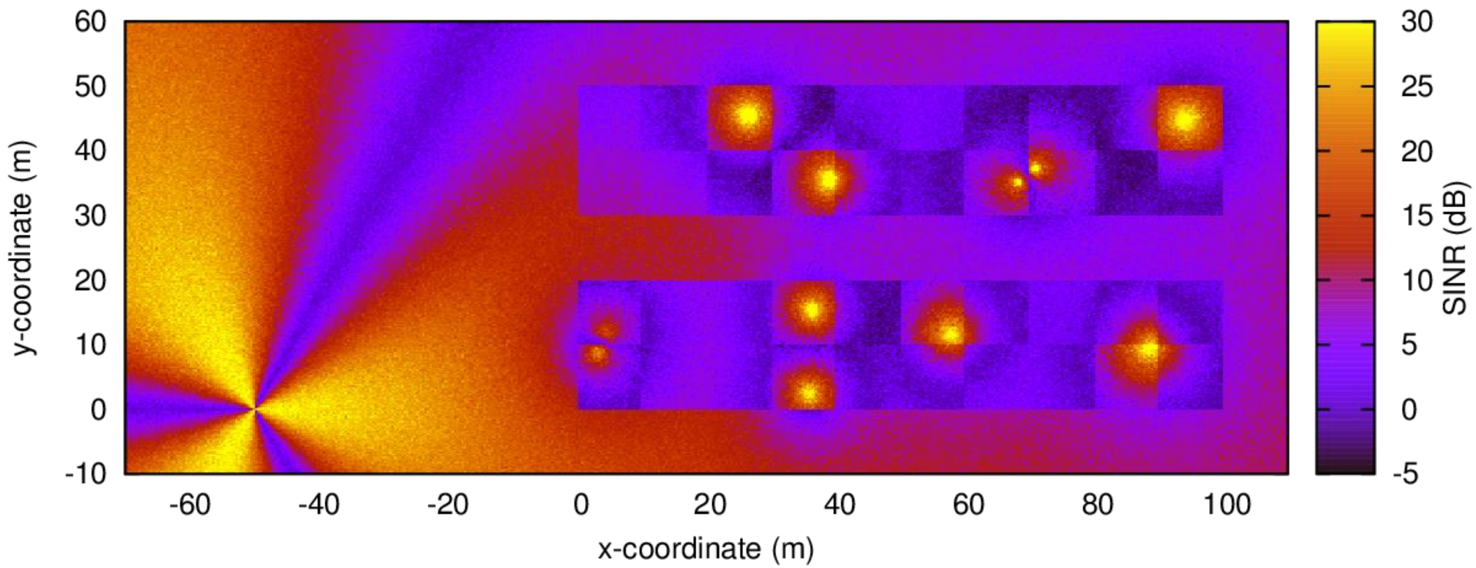
Carrier Aggregation

- Funded and initiated through GSoC2015, finalized with Spidercloud Wireless support.
- Supported for downlink only
- Component Carriers are divided in:
  - 1 Primary Component Carrier (PCC)
  - Several Secondary Component Carriers (SCCs)
- The SCCs include the legacy LTE stack from MAC to PHY layer
- SCCs can be created only in LTE bands
- *LteEnbComponentCarrierManager* API is in charge of dispatching data among CCs:
  - Load balancing procedures among CCs can be implemented

Simulation Ouput

- Lots of KPIs available at different levels:
  - Channel
    - SINR maps
    - pathloss traces
  - PHY
    - TB tx / rx traces
    - RSRP/RSRQ traces
  - MAC
    - UL/DL scheduling traces
  - RLC and PDCP
    - Time-averaged PDU tx / rx stats
  - IP and application stats
    - FlowMonitor, PCAP traces (P2P links only), get stats directly from app, etc.

Example: 3GPP dual stripe scenario



- Points are modelled as nodes
- SINR is evaluated considering the strongest signal as the one of the serving eNB

Testing

- Huge effort in testing:
  - Unit tests
    - Checking that a specific module works properly
  - System test
    - Checking that the whole LTE model works properly
  - Validation tests
    - Validating simulation output against theoretical performance in a set of known cases
  - Valgrind test coverage
    - Systematically check for memory errors
      - memory corruption, leaks, etc. due to programming errors
  - Test code build
    - Provided by ns-3 project for stable LTE code
    - Verify correct build with all supported compilers and platforms using GitLab CI
      - https://gitlab.com/nsnam/ns-3-dev/tree/master/utils/tests

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Documentation

- LTE module documentation
- Part of the ns-3 models library docs
- 202 pages, comprises of:
  - Design documentation
  - User documentation
  - Test documentation
  - Profiling documentation

- https://www.nsnam.org/docs/models/html/lte.html

Further branches

- NR
  - Developed in collaboration with Interdigital and CTTC (since 2016)
  - Some features to be discussed during this WS
  - https://5g-lena.cttc.es/
- D2D
  - Developed by NIST
  - Upgraded in collaboration with CTTC/Uni Washington (2017-2019)
  - In-coverage and out-of-coverage scenarios supported
  - Support for direct communication, synchronization and neighbour discovery features
  - https://apps.nsnam.org/app/publicsafetylte/
- Licensed Assisted Access (LAA)
  - Developed in collaboration with WFA and University of Washington (2015-2016)
  - Includes Rel.13 features
  - Support for Supplemental Downlink in unlicensed spectrum
  - Does not support partial subframe
  - Available: http://bitbucket.org/cttc-lena/ns-3-lena-dev-lte-u
- LTE-U
  - Developed in collaboration with Spidercloud Wireless (2015-2016)
  - Includes LTE-U Forum specs
  - Support for Supplemental Downlink in unlicensed spectrum
  - Available: http://bitbucket.org/cttc-lena/ns-3-lena-dev-lte-u

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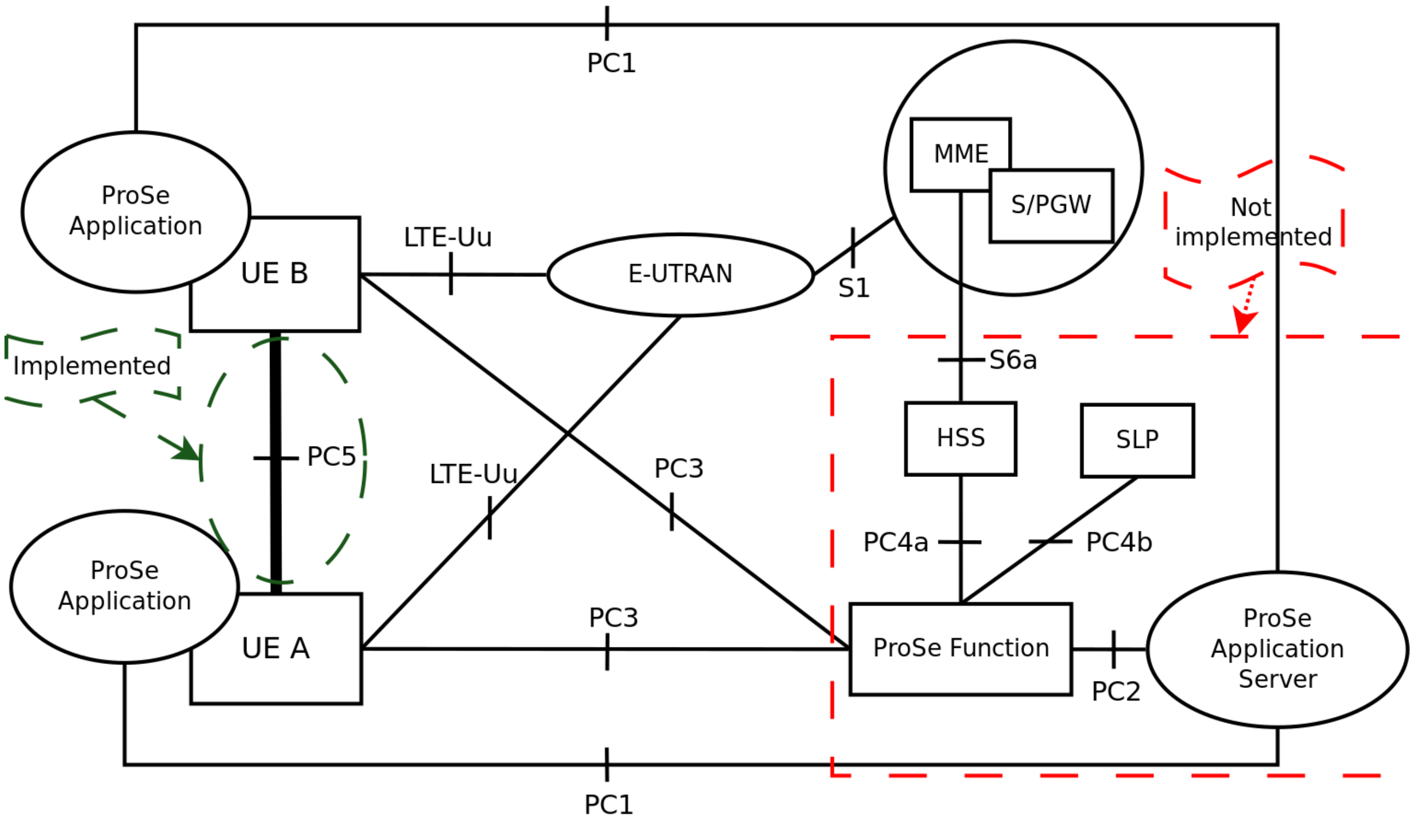
The ns-3 LTE D2D architecture

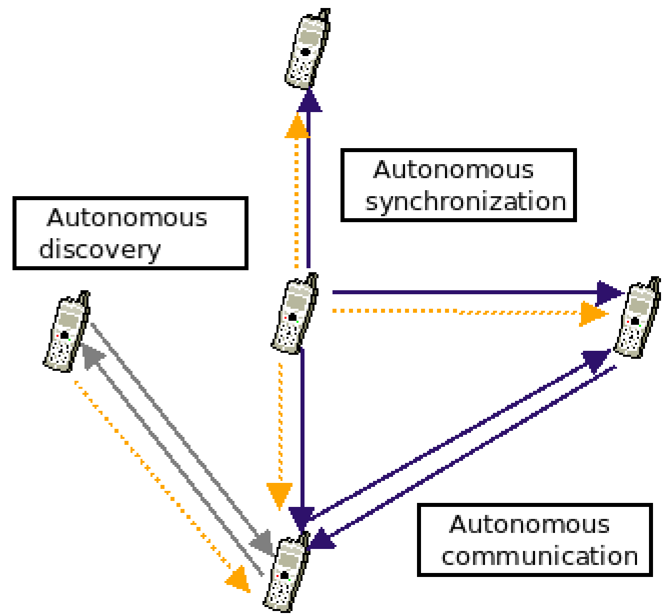


The ns-3 LTE D2D architecture

- Four scenarios were identified by 3GPP.
  - 1A. Out-of-Coverage
  - 1B. Partial-Coverage
  - 1C. In-Coverage-Single-Cell
  - 1D. In-Coverage-Multi-Cell
- Fully tested and simulated 1A and 1C
- Aligned with latest ns-3-dev
- Documented following the ns-3 guidelines

The ns-3 LTE D2D architecture

- Out-of-Coverage scenario
  - Direct communication
    - Resource allocation Mode 2
  - Direct discovery
    - Resource allocation Type 1
  - Synchronization
    - Autonomous

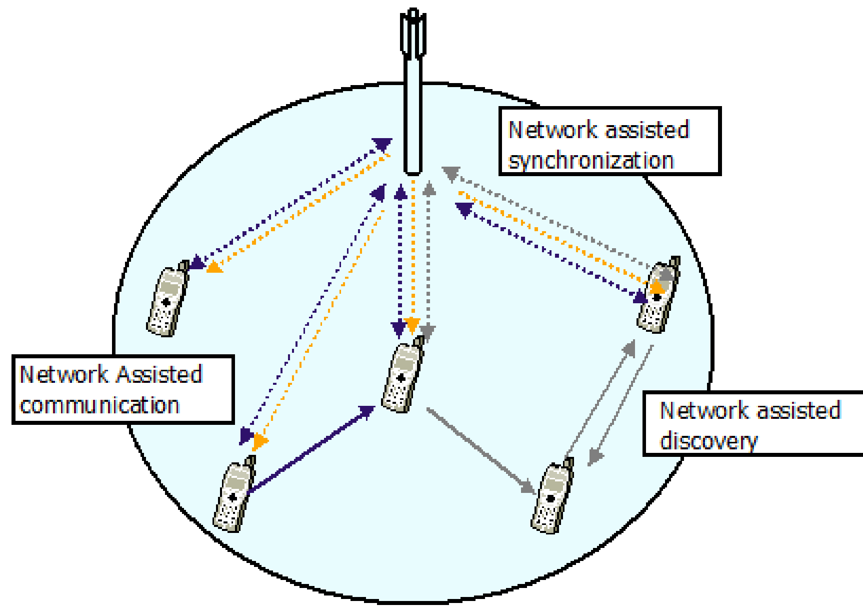


	Direct communication	Direct discovery	Synchronization
Control			
Data			

Source: Richard Rouil, Fernando J. Cintrón, Aziza Ben Mosbah and Samantha Gamboa. Implementation and Validation of an LTE D2D Model for ns-3 WNS3 2017

The ns-3 LTE D2D architecture

- In-Coverage scenario
  - Direct communication
    - Resource allocation Mode 1 and 2
  - Direct discovery
    - Resource allocation Type 1
  - Synchronization
    - Network assisted



	Direct communication	Direct discovery	Synchronization
Control			
Data			

Source: Richard Rouil, Fernando J. Cintrón, Aziza Ben Mosbah and Samantha Gamboa. Implementation and Validation of an LTE D2D Model for ns-3 WNS3 2017

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