THE NS-3 LTE MODULE

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How the LTE module was developed

- Google Summer of Code 2010
- LENA project
  - CTTC-Ubiquisys, Jan 2011 to Jun 2013
- Google Summer of Code 2012, 2013, 2014
- Other projects, including.:
  - SYMBIOSIS project
  - FP7 ICT-COMBO project
- Community contributions

The LENA project: 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
  - Allows testing of real code in the simulation
  - Accurate model of the LTE/EPC protocol stack
  - Specific Channel and PHY layer models for LTE macro and small cells
- An Open source simulator:
  - Development open to the community
  - Fosters early adoption and contributions
  - Helps building confidence and trust on simulation model
  - Candidate reference evaluation platform
  - Based on ns-3
  - Free and open source licensing (GPLv2)

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

Target applications for LENA include
the design and performance evaluation of:

- DL & UL LTE MAC Schedulers
- Radio Resource Management Algorithms
- Inter-cell interference coordination solutions
- Load Balancing and Mobility Management
- Heterogeneous Network (HetNets) solutions
- End-to-end QoE provisioning
- Multi-RAT network solutions
- Cognitive LTE systems

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

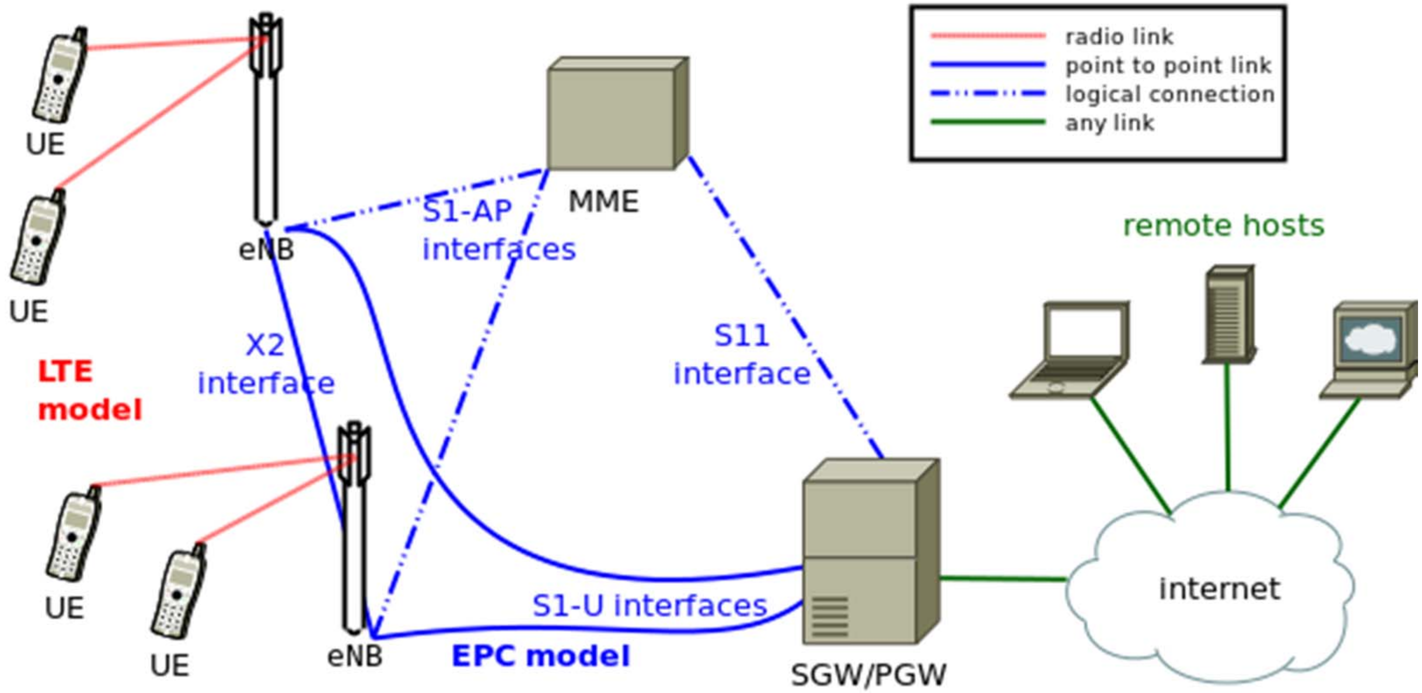
Design approach

- Simulation is a tradeoff between:
  - Detail of the model
  - Implementation complexity and run-time scalability
- Choose min detail that satisfies requirements
  - Minimize implementation complexity
  - Minimize difficulty in using the simulator

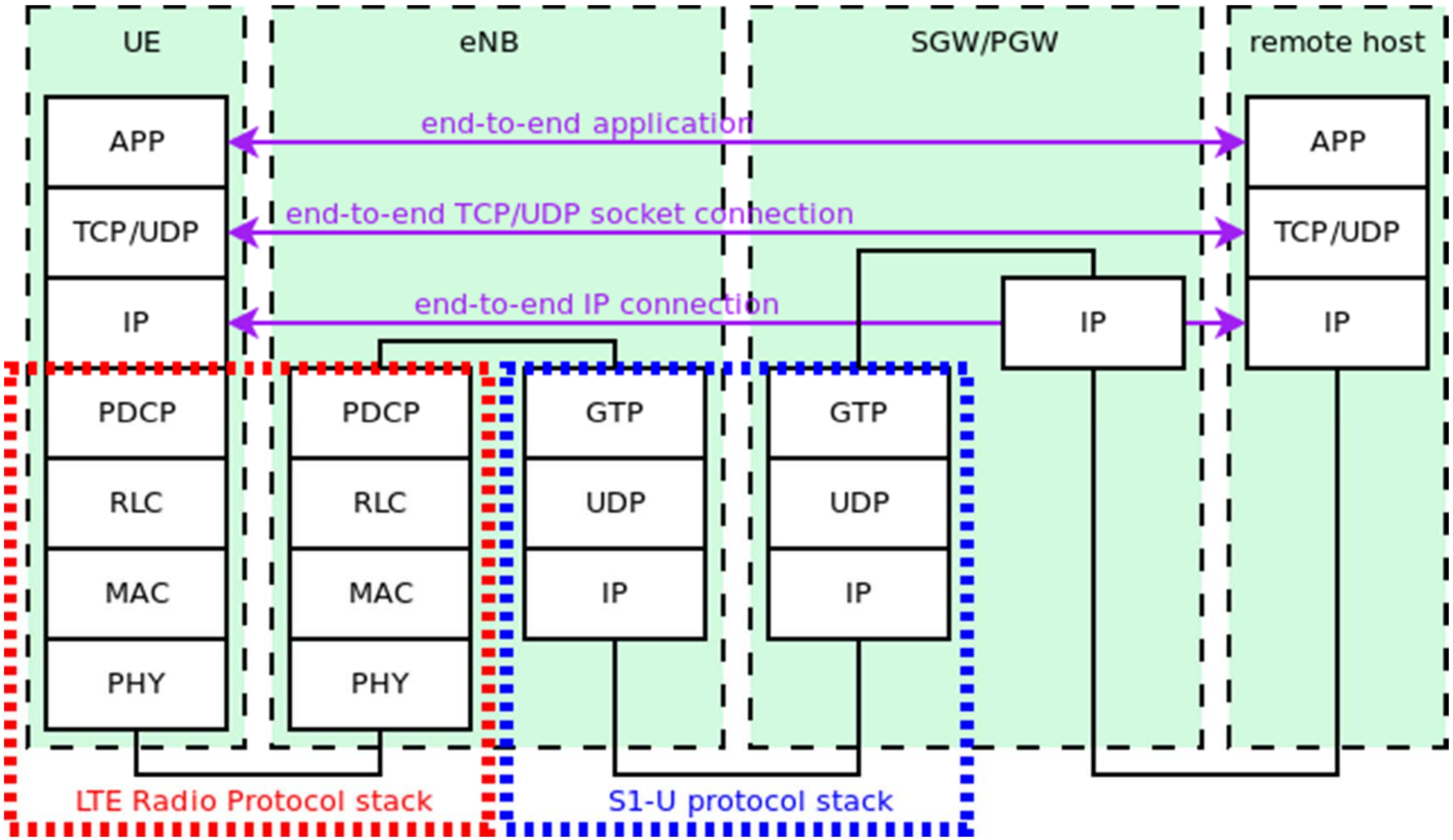
(Some) Important Design Choices

- 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, S1-U, X2-U
  - Allow proper interaction with IP networking
  - Allow end-to-end QoE evaluations
- Hybrid Control Plane model:
  - Realistic RRC model
  - Simplified S1-C, X2-C and S11 models
- Simplified EPC
  - One MME and one SGW
  - SGW and PGW in the same node (no S5/S8 interface)
- Focus on connected mode
  - RRC connected, EMM Registered, ECM connected

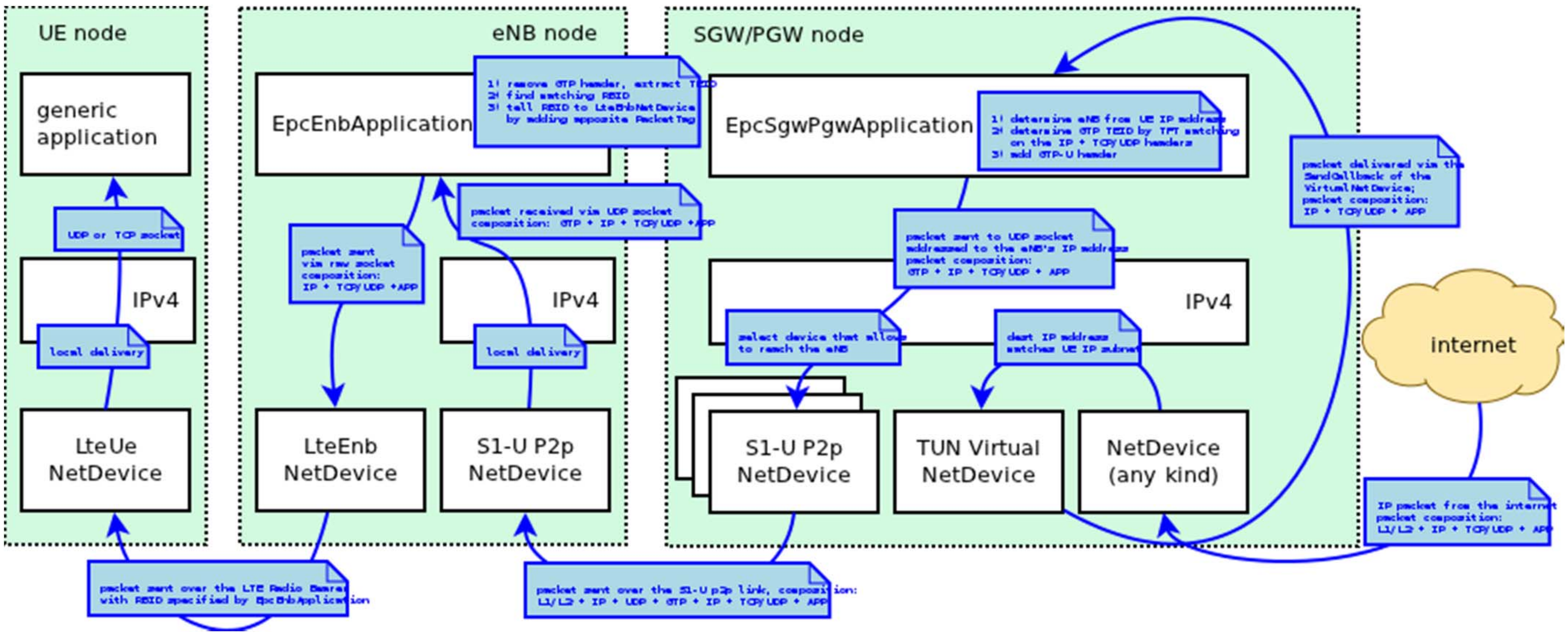
LENA model overview



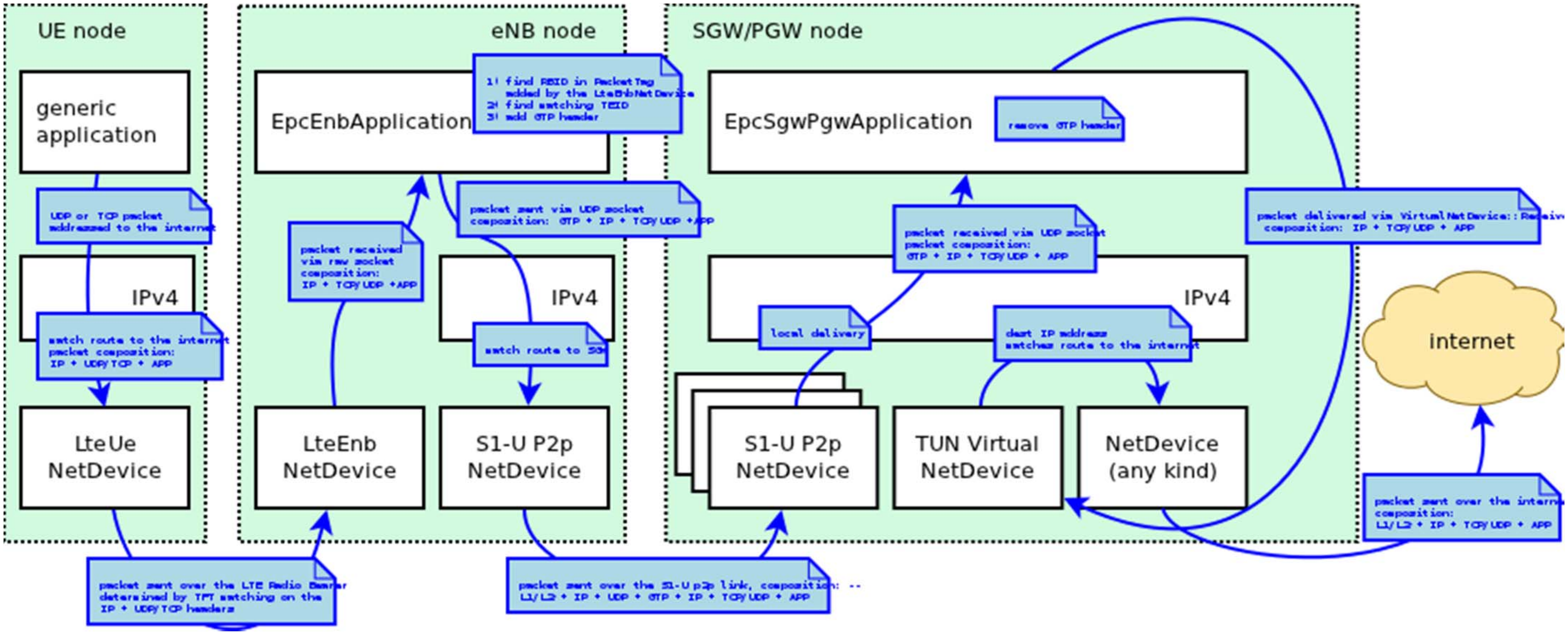
End-to-end Data Plane protocol stack



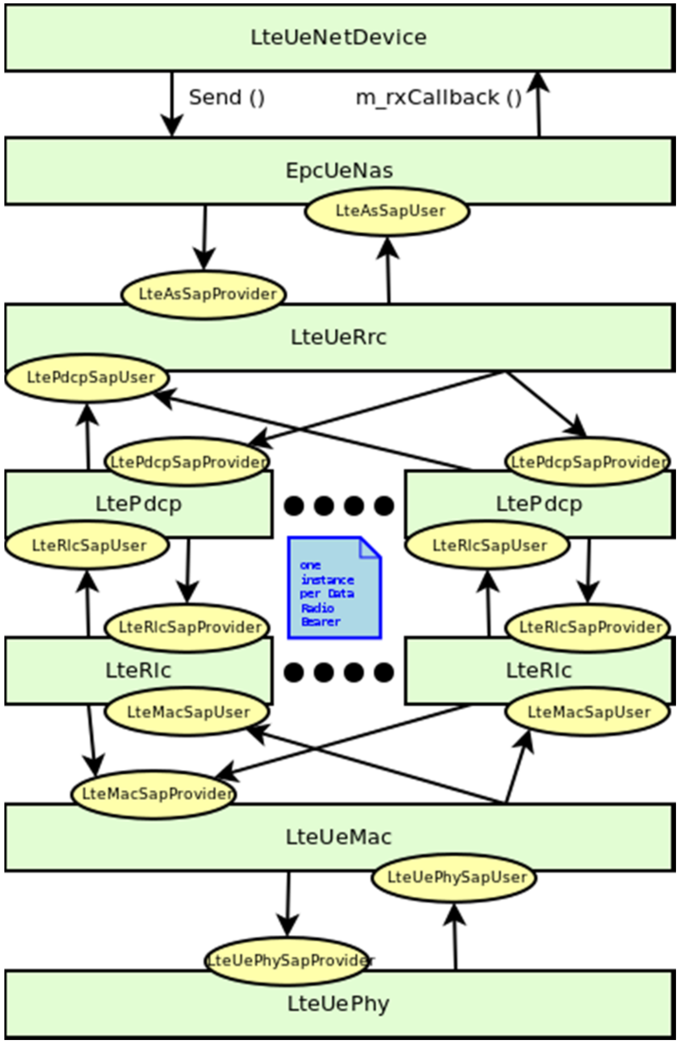
End-to-end Data Plane architecture: data flow in downlink



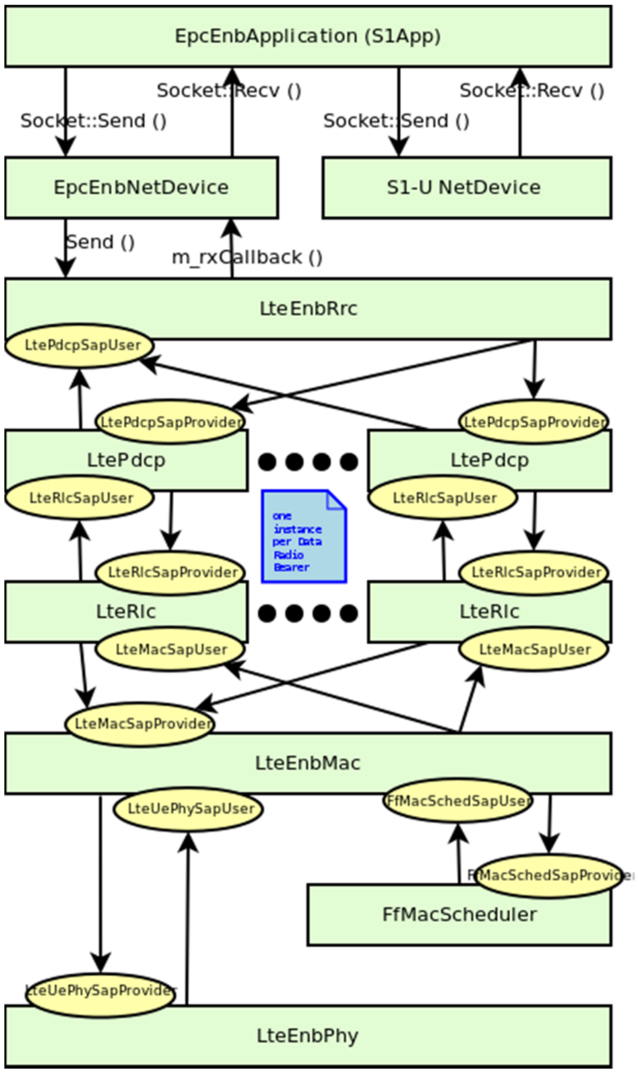
End-to-end Data Plane architecture: data flow in uplink



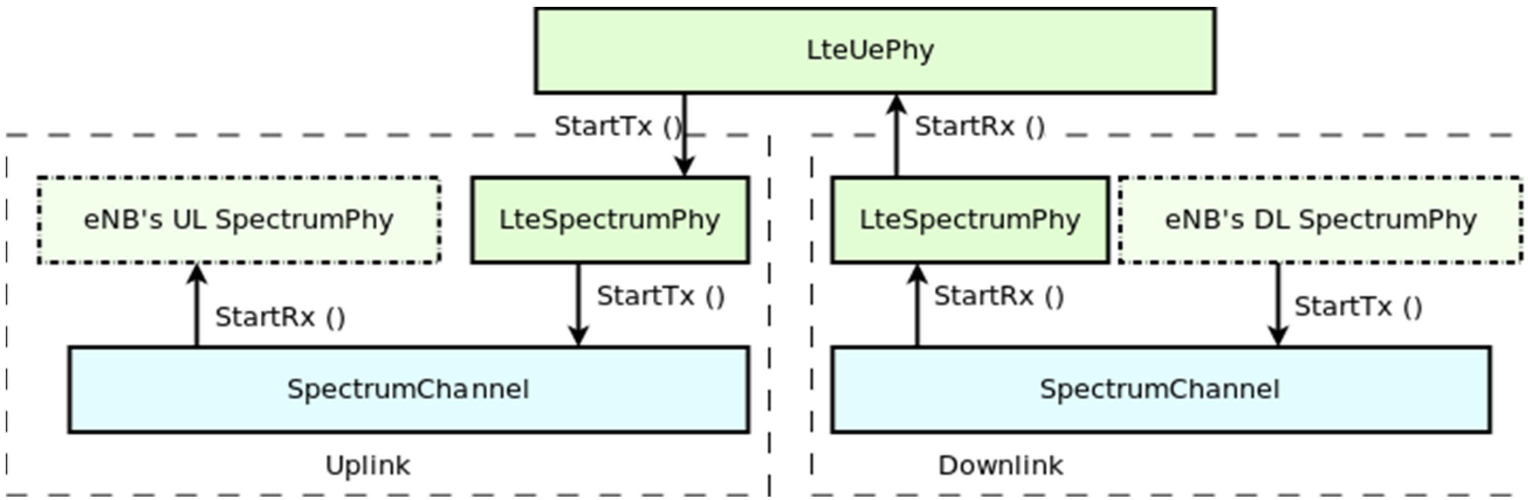
LTE Data Plane protocol stack: UE



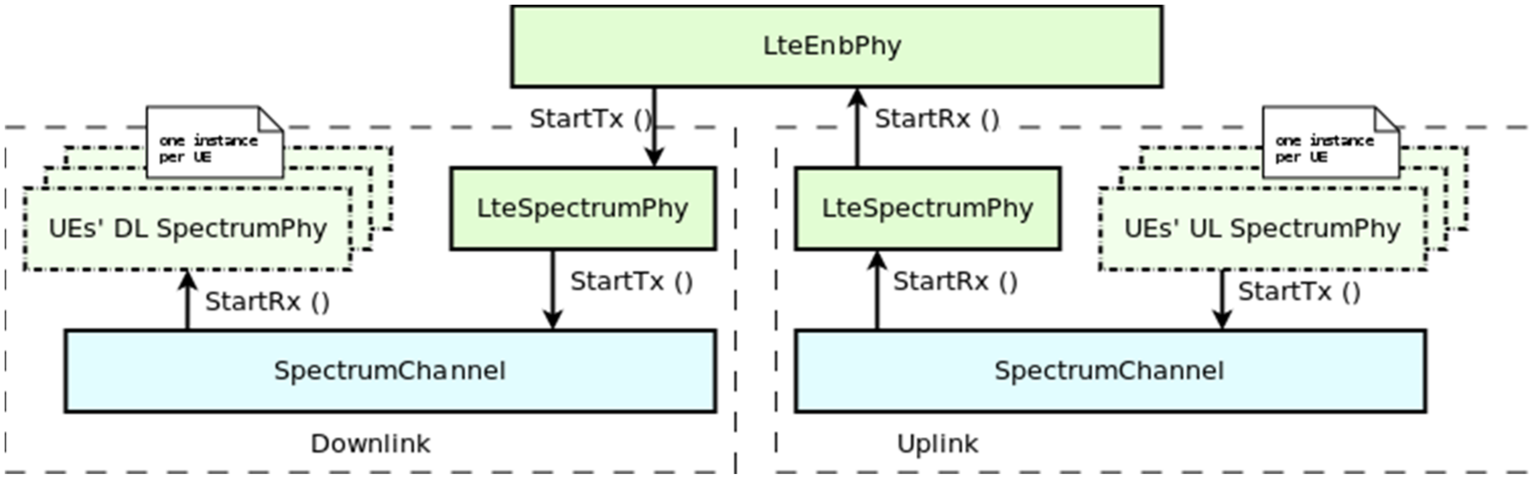
LTE Data Plane protocol stack: eNB



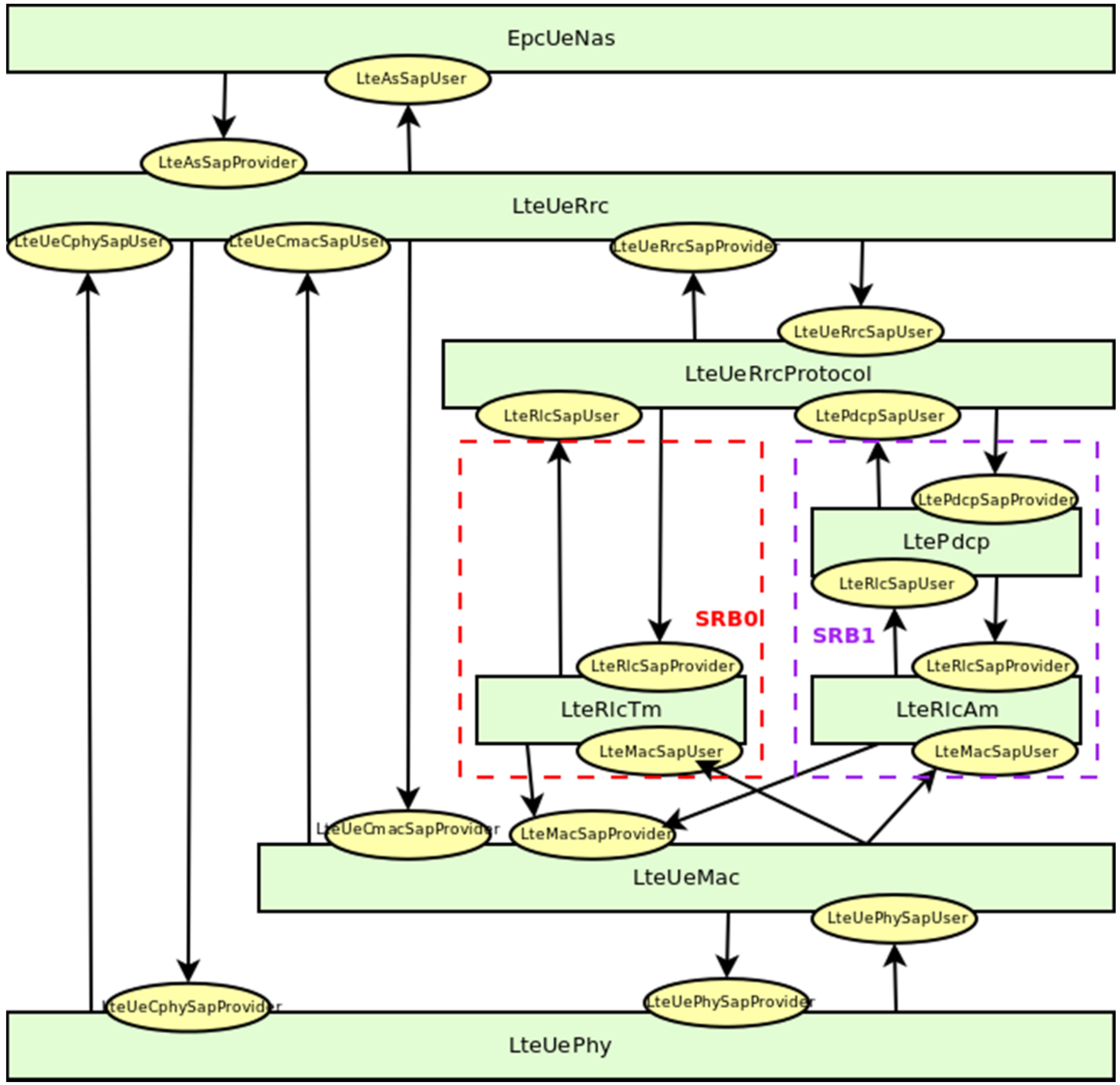
PHY and Channel architecture: UE



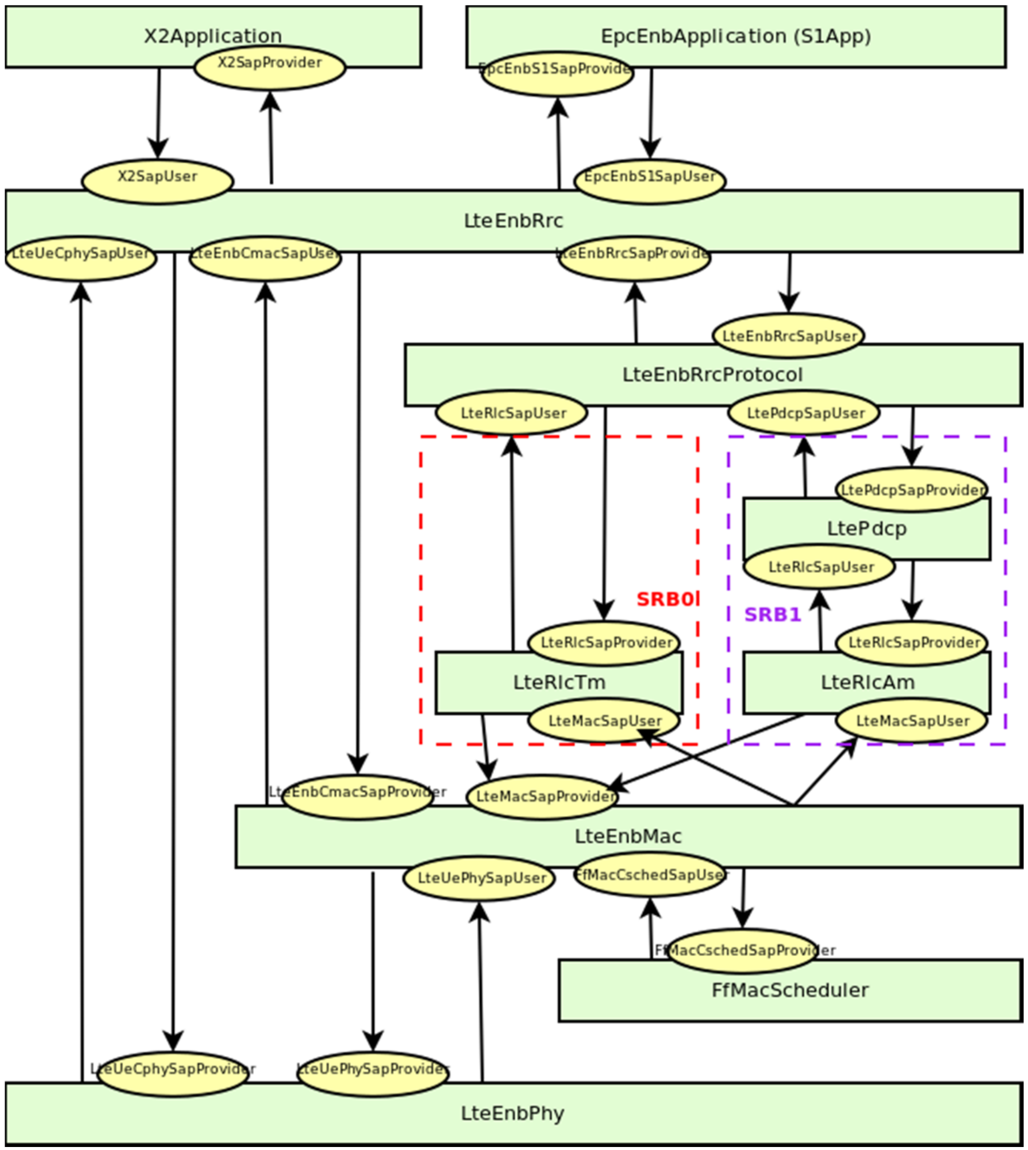
PHY and Channel architecture: eNB



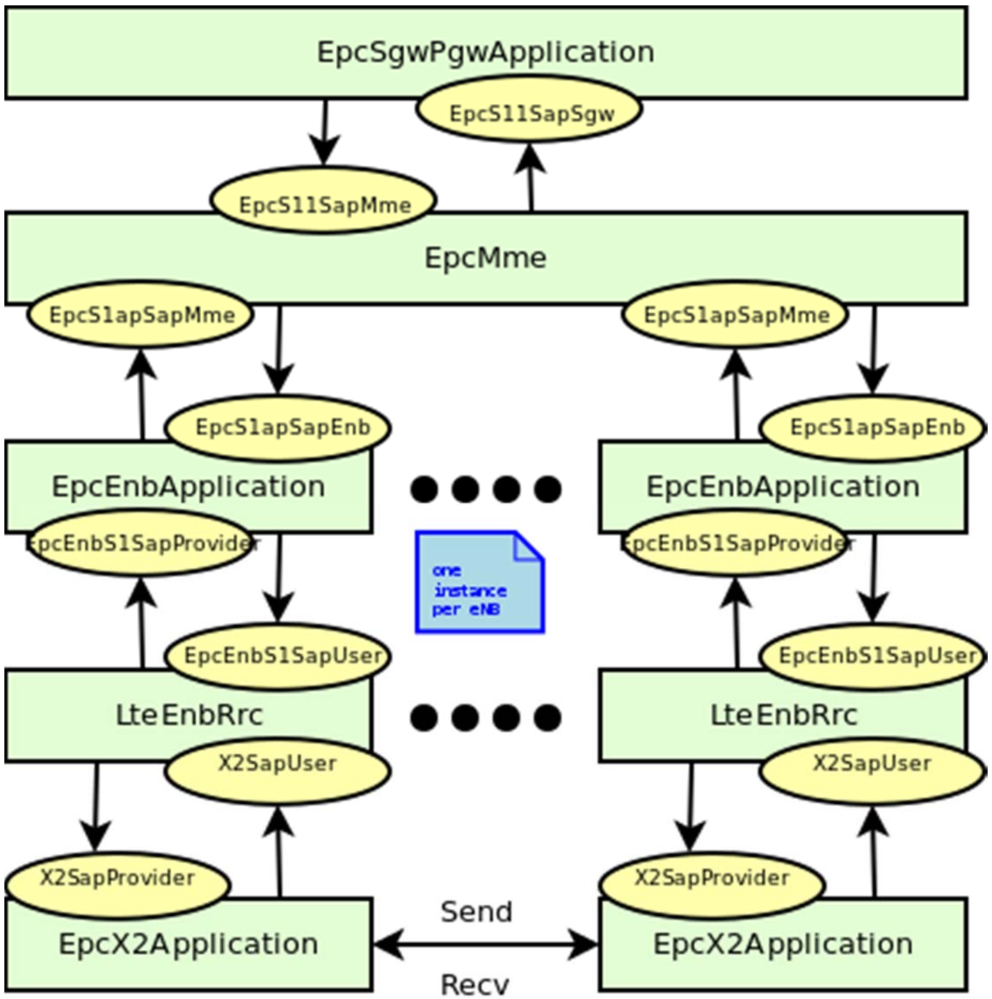
LTE Ctrl Plane protocol stack: UE

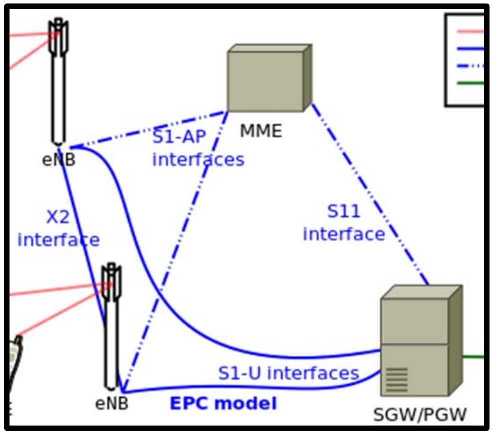


LTE Ctrl Plane protocol stack: eNB

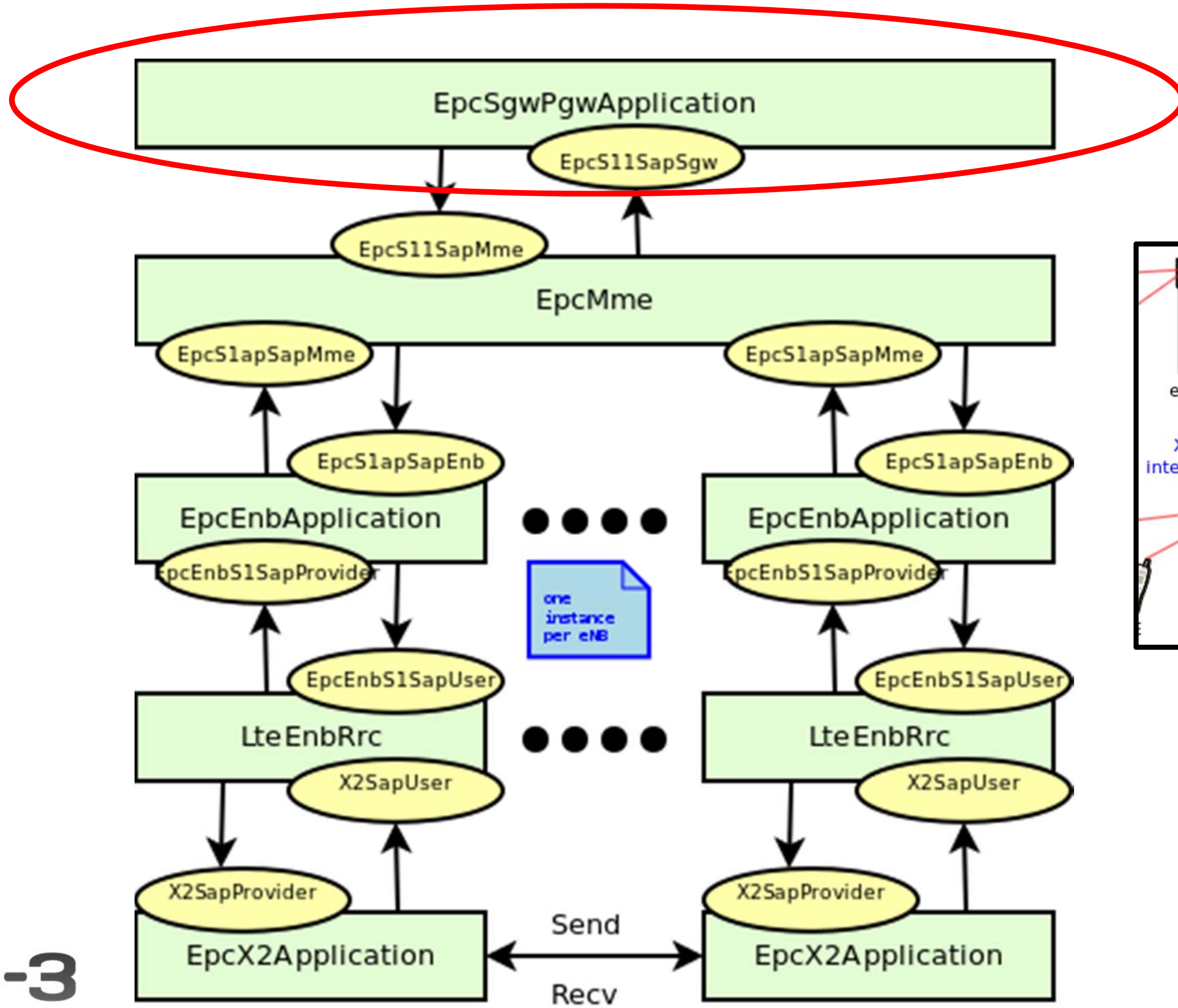


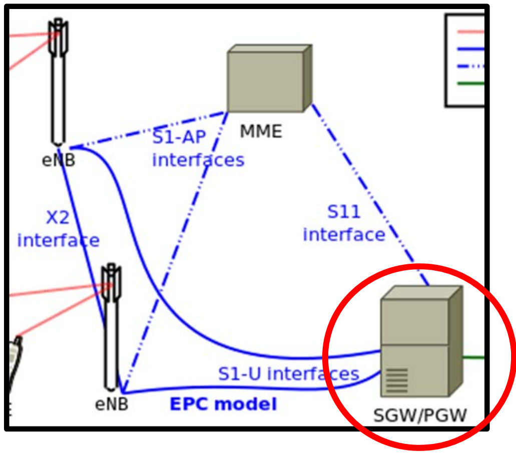
EPC Control Plane Architecture



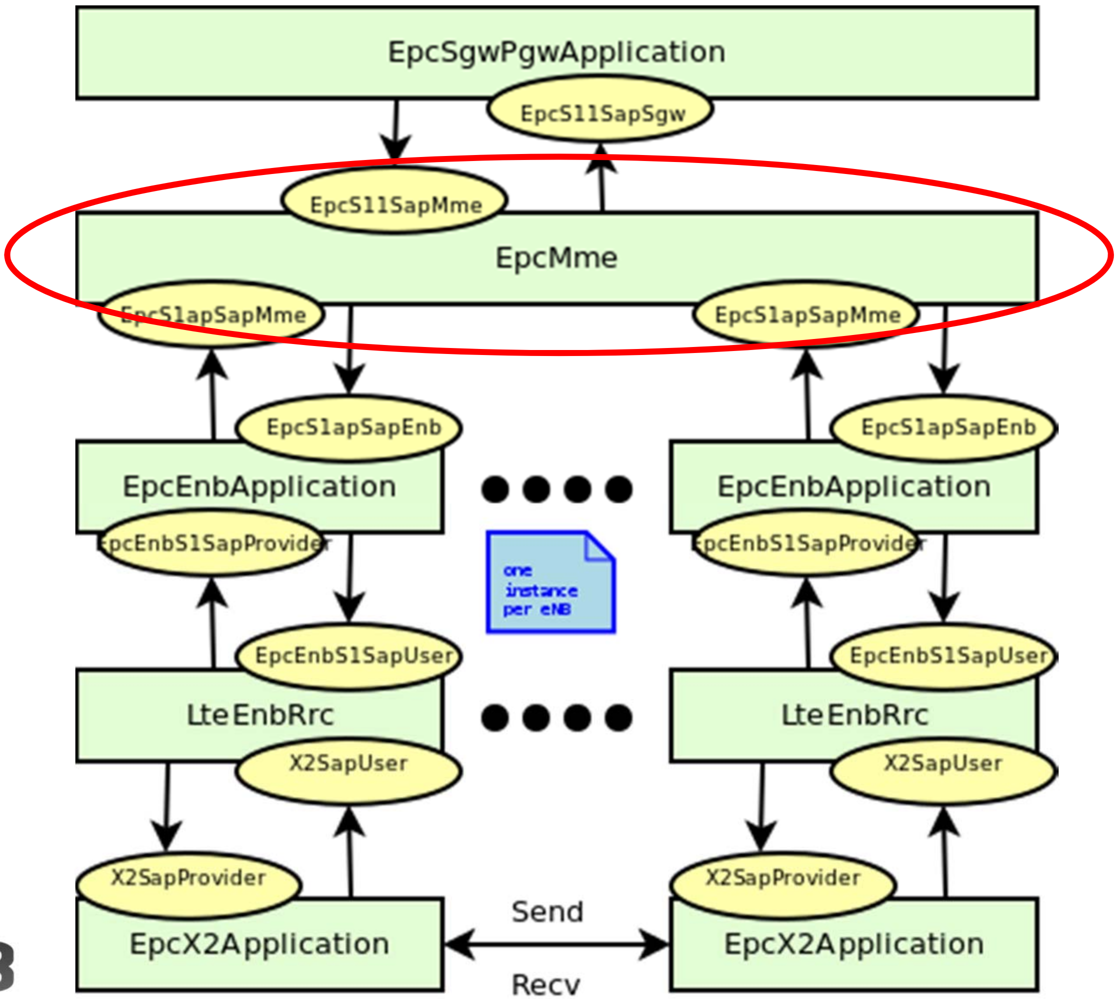


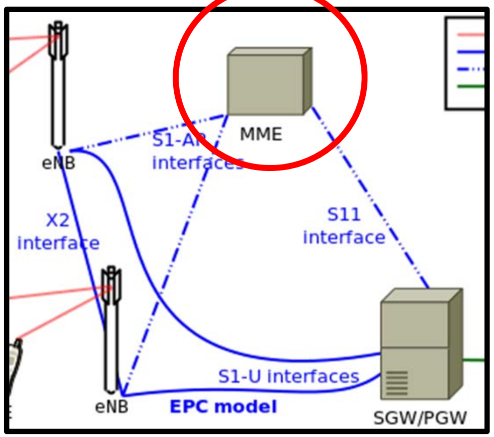
EPC Control Plane Architecture



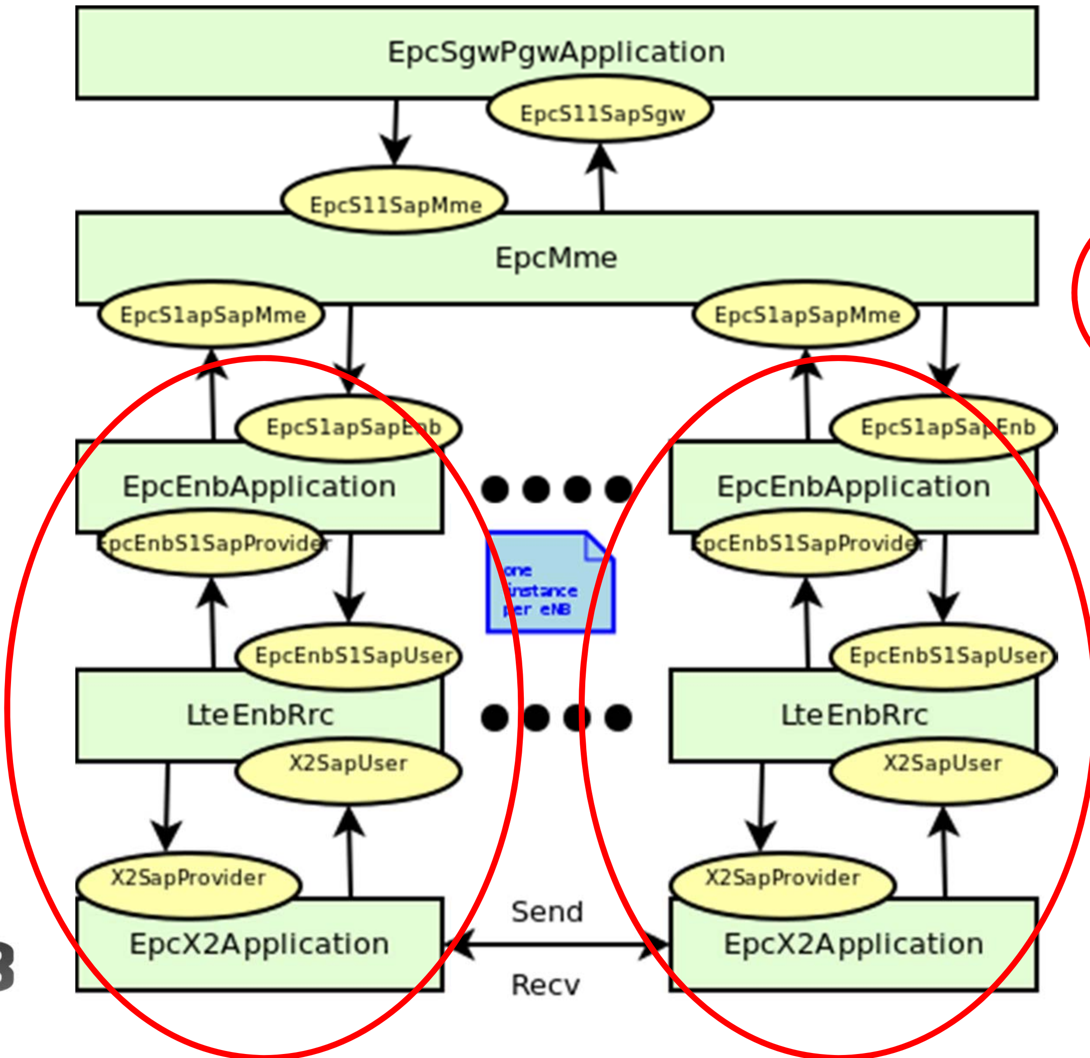


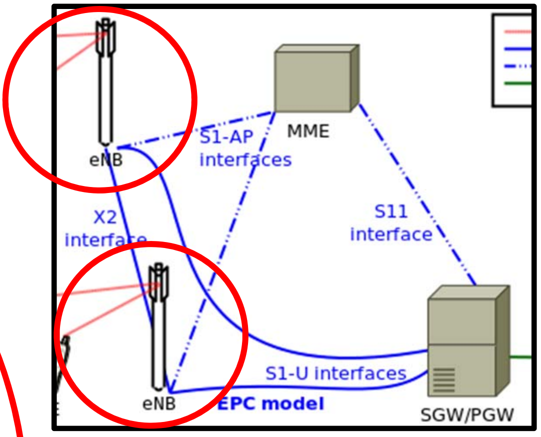
EPC Control Plane Architecture





EPC Control Plane Architecture





Radio Propagation Models

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

Outdoor Radio Propagation models

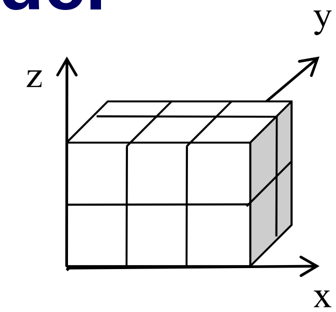
- Okumura Hata: open area pathloss for distances > 1 Km and frequencies ranging from 150 MHz to 2.0 GHz

- Kun empirical model for 2.6 GHz
  - Sun Kun, Wang Ping, Li Yingze "Path Loss Models for Suburban Scenario at 2.3GHz, 2.6GHz and 3.5GHz", 8th International Symposium on Antennas, Propagation and EM Theory (ISAPE), 2008.

- ITU-R P1411 Line-of-Sight (LoS) short range outdoor communication in the frequency range 300 MHz to 100 GHz
  - Used for short communication link (< 200 m.)

- ITU-R P1411 Non-Line-of-Sight (NLoS) short range outdoor communication over rooftops in the frequency range 300 MHz to 100 GHz.
  - Used for communication link < 1 km

Buildings model & Indoor Radio Propagation model



- Buildings defined as ns3 Box classes with
  - xMin, xMax, yMin, yMax, zMin, zMax (inherithed by Box)
  - Number of floors
  - Number of room in x-axis and y-axis (grid topology)

- Buildings model that allows to “install” building information to mobility model of a node:
  - the ns3 Box class containing the building
  - Position in terms of floors
  - Position in the grid of rooms
  - Node condition: indoor vs. outdoor

- ITU-R P1238 implements building-dependent indoor propagation loss model as function of the type of building (i.e., residential, office and commercial)

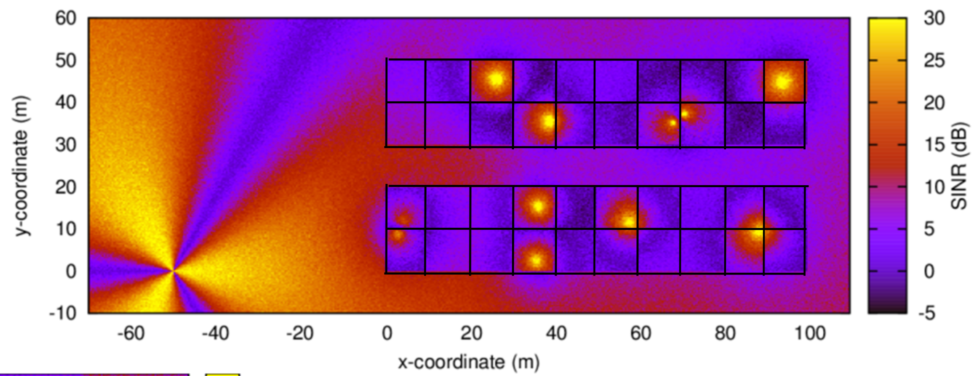
Hybrid Propagation Loss Model

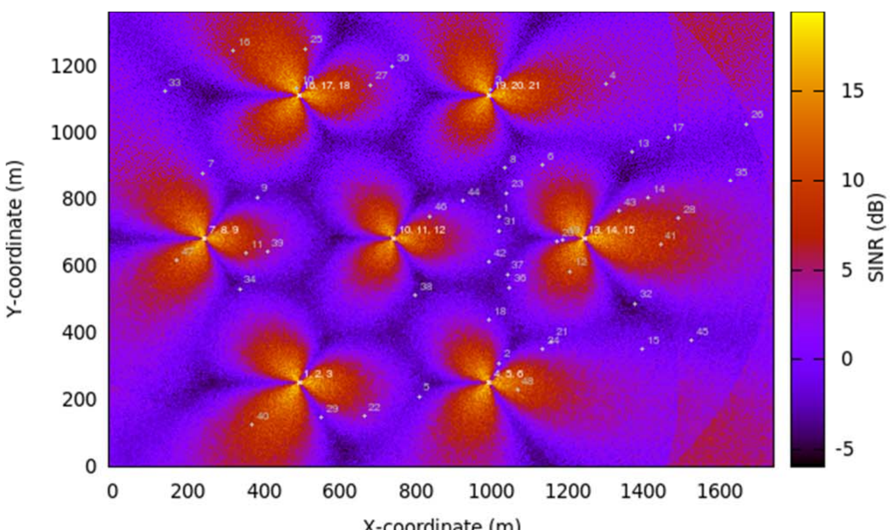
- External wall losses for penetration loss through walls for indoor to outdoor communications and vice-versa (from COST231)
  - Wood ~ 4 dB
  - Concrete with windows (not metallized) ~ 7 dB
  - Concrete without windows ~ 15 dB (spans between 10 and 20)
  - Stone blocks ~ 12 dB
- Internal wall losses evaluated assuming that each single internal wall has a constant penetration (5 dB) and evaluating the number of walls
- Log-normal shadowing standard deviation as function of the connection characteristics
  - Outdoor $\sigma_O = 7$
  - Indoor $\sigma_I = 10$
  - External walls penetration $\sigma_E = 5$
- Height gain model when transmitting device is on a floor above the ground (2 dB)

- Pathloss logic chooses correct model depending on nodes positions

Antenna models

- Isotropic [default one]
- Sectorial (cosine & parabolic shape)

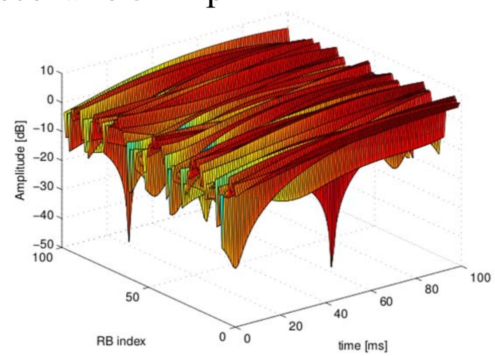




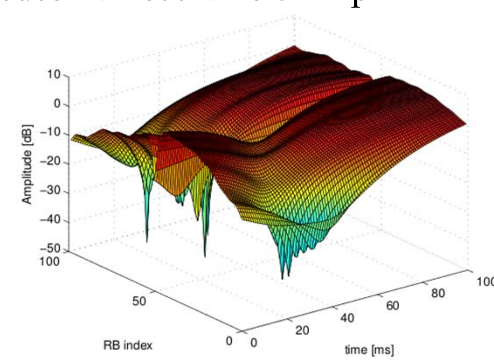
Fading model

- Fast fading model based on pre calculated traces for maintaining a low computational complexity
  - Matlab script provided in the code using `rayleighchan` function
- 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

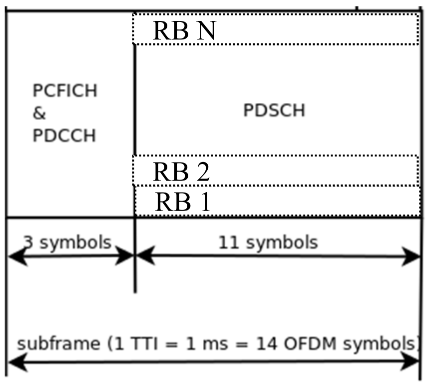


Pedestrian scenario 3 kmph

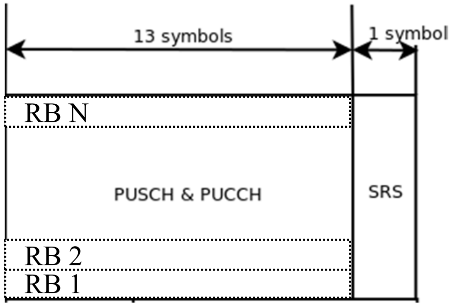


PHY model

- Only FDD is modeled
- Freq domain granularity: RB
- Time domain granularity: 1 TTI (1 ms)
- The subframe is divided in frequency into DL & UL



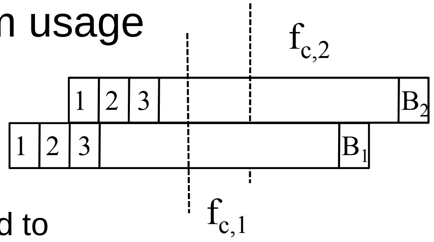
- DL part is made of
  - control(RS, PCFICH, PDCCH)
  - data (PDSCH)



- UL part is made of
  - control and data (PUSCH)
  - SRS

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

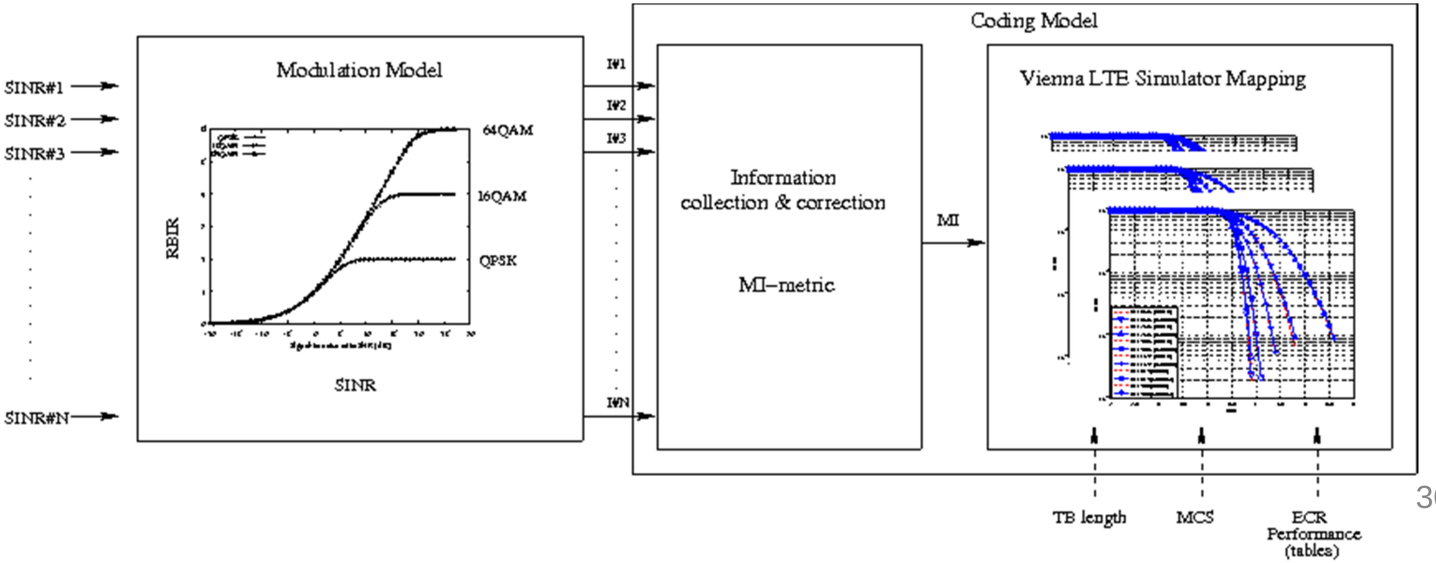


- Gaussian Interference model
  - powers of interfering signals (in linear units) are summed up together to determine the overall interference power per RB basis

- 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, PDCCH)
- In UL evaluated according to the SINR of
  - SRS signal periodically sent by the UEs.
  - PUSCH with the actual transmitted data.
- 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.
  - ALL_UL_CQI for storing all the CQIs received.

PHY Data error model

- Signal processing not modeled accurately $\Rightarrow$ 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 probabilty per codeblock
  - Multiple codeblocks per Transport Block



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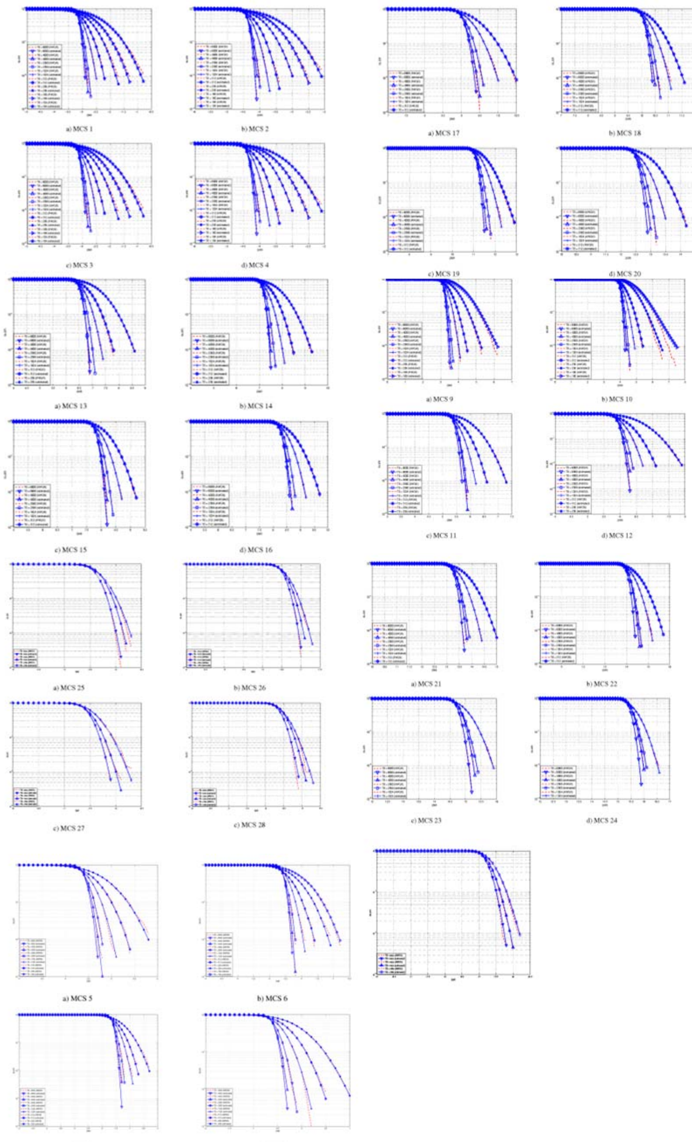
BLER Curves



MCS Index I_{MCS}	Modulation Order Q_m	TBS Index I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15
18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	2	reserved
30	4	
31	6	

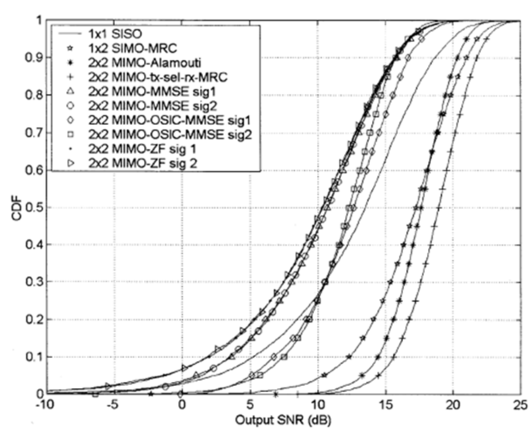
PHY DL Control error model

- Error model only for downlink, while uplink has an error-free channel
- Based on an evaluation study carried out in the RAN4 (R4-081920)
- Evaluated according to the equivalent SINR perceived in the whole bandwidth of PCFICH+PDCCH with MIESM model
- In case of error correspondent DCIs are discarded and data will not decoded

MIMO

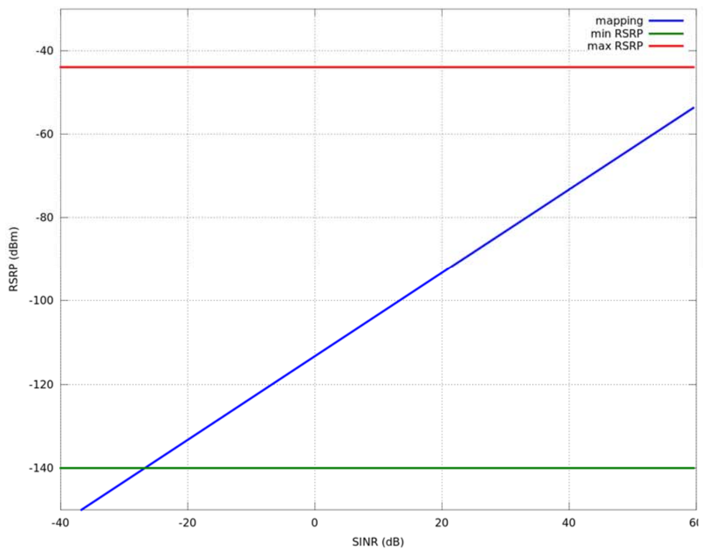
- Ns3 provides only SISO propagation model
- MIMO has been modeled as SINR gain over SISO according to
  - S. Catreux, L.J. Greenstein, V. Erceg, “Some results and insights on the performance gains of MIMO systems,” Selected Areas in Communications, IEEE Journal on , vol.21, no.5, pp. 839- 847, June 2003

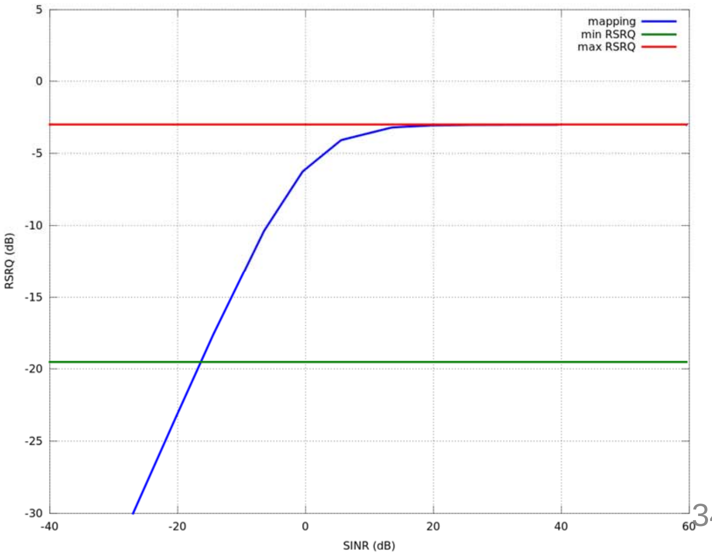
- Catreux et al. present the statistical gain of several MIMO solutions respect to the SISO one (in case of no correlation between the antennas as CDF)
- The SINR distribution can be approximated with a log-normal one with different mean and variance as function of the scheme considered (i.e., SISO, MIMO-Alamouti, MIMO-MMSE, MIMO-OSIC-MMSE and MIMO-ZF)
- Variances are not so different and they are approximatively equal to the one of the SISO mode already included in the shadowing component of the BuildingsPropagationLossModel
- MIMO can be modeled as different gains for different TX modes respect to the SISO



UE Measurements

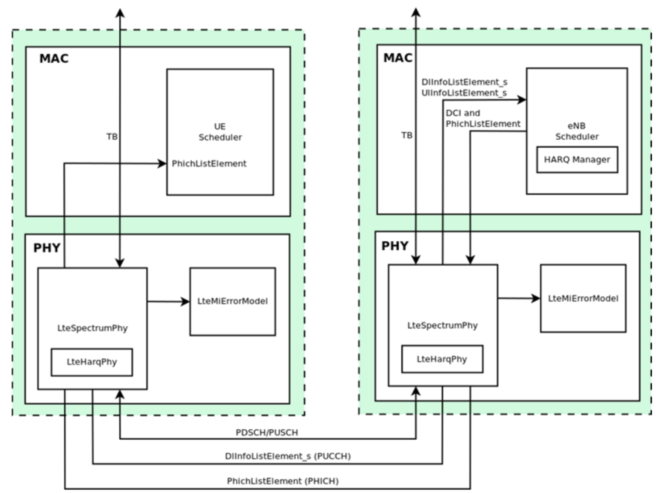
- UE has to report a set of measurements of the eNBs when it receives their physical cell identity (PCI)
  - **reference signal received power (RSRP)** ~ “average” power across the RBs
  - **reference signal received quality (RSRQ)** ~ “average” ratio between the power of the cell and the total power received across all the RBs
- Measurements are performed during the reception of the RS
- RSRP is reported by PHY layer in dBm while RSRQ in dB through the C-PHY SAP every 200 ms.
- Layer 1 filtering is performed by averaging the all the measurements collected during the last window slot.

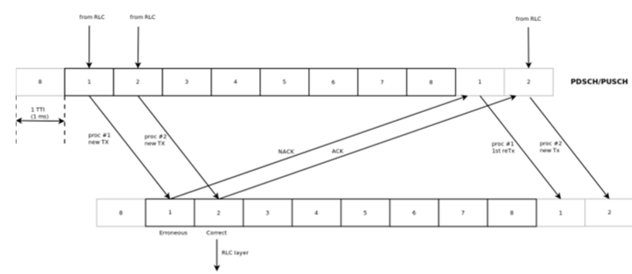




HARQ model

- 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
  - New rates due to the “soft combination” of the codeblocks
  - Extend the original ones with the ones of RVs with lower R_{eff} of each modulation order





$$R_{eff} = \frac{X}{\sum_{i=1}^{q} C_i}$$

X no. of info bits
C_i no. of coded bits

MAC & Scheduler model

- Resource allocation model:
  - allocation type 0
  - RBs grouped into RBGs
  - localized mapping approach (2 slots of the RBG to the same UE)

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
    - Consistent with requirements (scheduler neglects MAC OH)

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

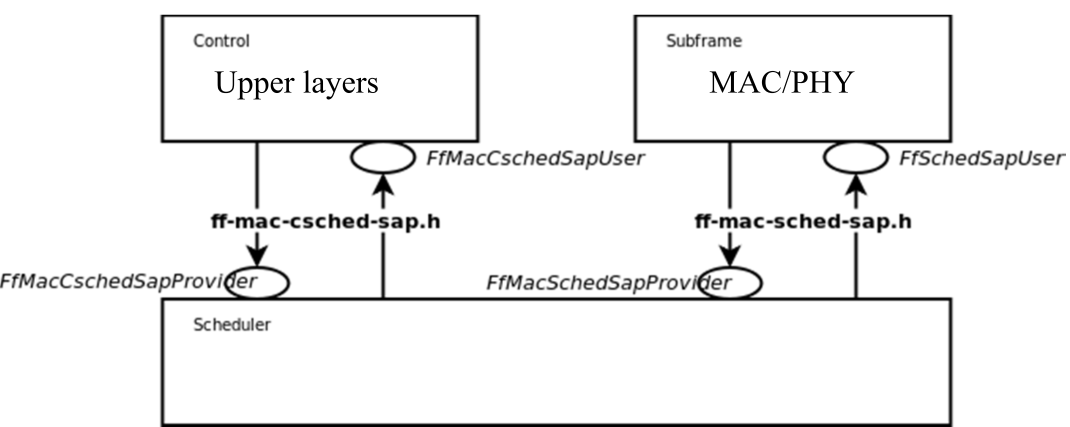
  - **Vienna** model: aim at max 10% BLER as defined in TS 36.213 based on error model curves

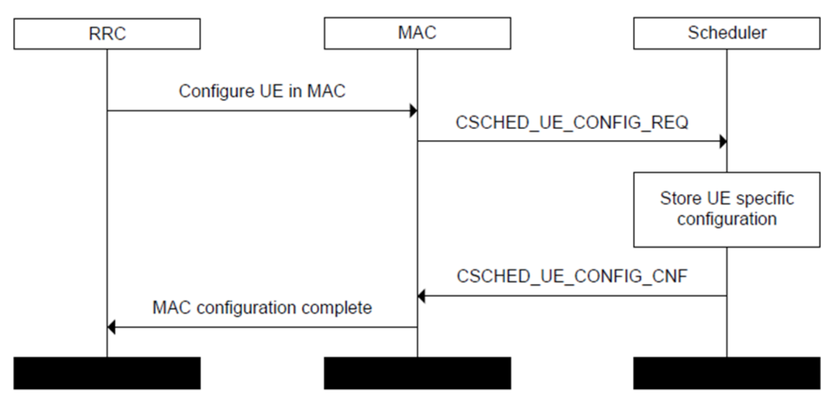
- Dynamic TX mode selection supported
  - Interface present in the scheduler interface
  - but no adaptive algorithm currently implemented

SCF-API MAC Scheduler Interface (1)

- Most of the primitives used in LENA are based on the scheduler APIs
  - Example: primitive CSCHED_CELL_CONFIG_REQ is translated to `CschedCellConfigReq` method with `struct CschedCellConfigReqParameters` parameters in the *ns-3* code
  - Control primitives has been implemented through Service Access Points (SAPs)

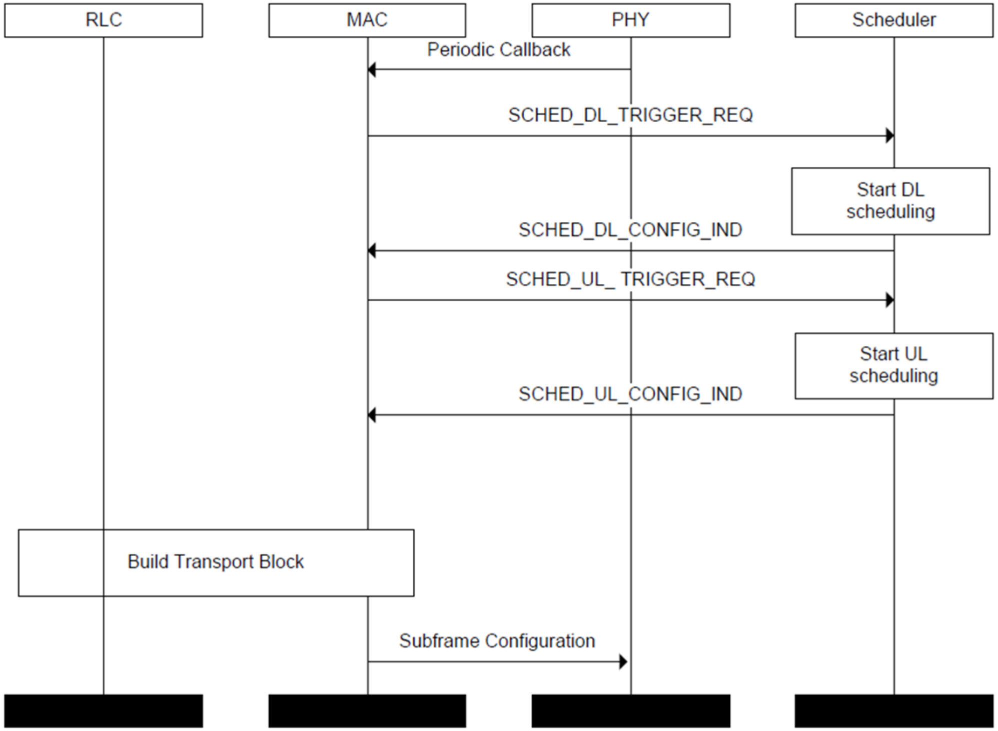
- Control APIs (configuration and update)
  - `CschedCellConfigReq`
  - `DoCschedUeConfigReq`
  - `DoCschedLcConfigReq`
  - `DoCschedLcReleaseReq`
  - `DoCschedUeReleaseReq`





SCF-API MAC Scheduler Interface (2)

- Scheduling primitives
  - `DoSchedDlRlcBufferReq`
  - `DoSchedDlTriggerReq` (containing info on HARQ)
  - `DoSchedDlRachInfoReq`
  - `DoSchedDlCqiInfoReq`
  - `DoSchedUlTriggerReq`
  - `DoSchedUlCqiInfoReq`



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

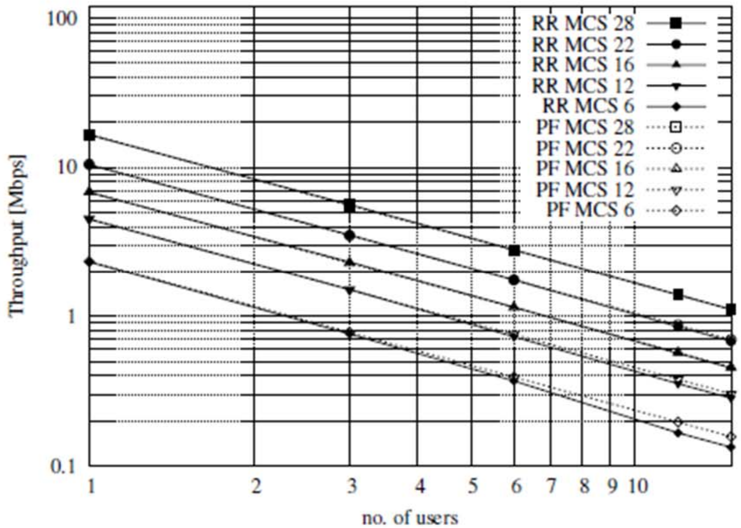
- Channel and QoS Aware Scheduler (CQA) NEW
  - B. Bojovic, N. Baldo, A new Channel and QoS Aware Scheduler to enhance the capacity of Voice over LTE systems , In Proceedings of 11th SSD, Feb 2014, Castelldefels (Spain)

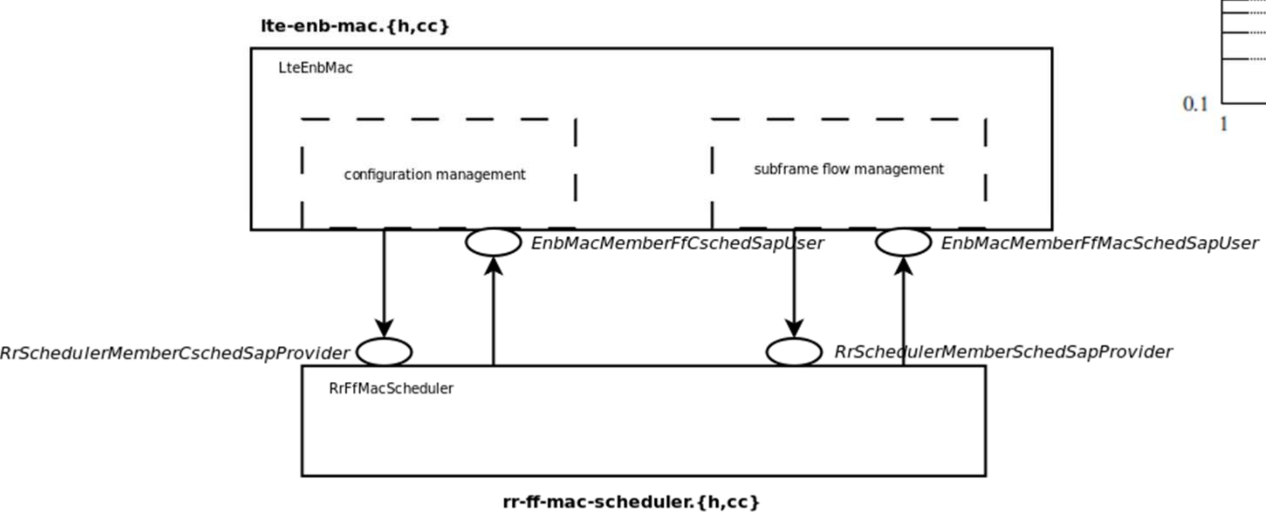
- All implementations based on the **FemtoForum API**
- The above algorithms are for downlink only
- For uplink, all current implementations use the same Round Robin algorithm
- Assumption: HARQ has always higher priority respect to new data

Round Robin

- Divide the available resources among the active UEs (i.e., the ones with at least one LC with buffer !=0)

- If no. of UEs > no. RBs
  - Circular buffer allocation





Proportional Fair

- Schedule a user when its instantaneous channel quality is high relative to its own average channel condition over time
- Defines per each UE *i* the *achievable rate* as

$$R_i(k,t) = \frac{S\left(M_{i,k}(t),1\right)}{\tau}$$

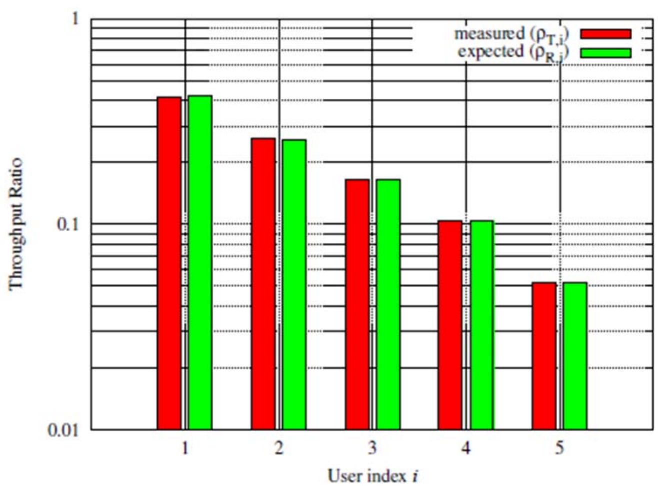
$M_{i,k}(t)$ MCS usable by user on resource block
τ TTI duration

- At RBG k pick the user that maximize

$$\widehat{i}_k(t) = \underset{j=1,\dots,N}{\operatorname{argmax}} \left(\frac{R_j(k,t)}{T_j(t)} \right)$$

$T_j(t)$ past throughput perceived by the user j

$$T_j(t) = (1 - \frac{1}{\alpha})T_j(t-1) + \frac{1}{\alpha}\widehat{T}_j(t)$$



achievable rate ratio $\rho_{R,i} = \frac{R_i}{\sum_{j=1}^{N} R_j}$

achievable throughput ratio $\rho_{T,i} = \frac{T_i}{\sum_{j=1}^{N} T_j}$

GSoC 2012 Schedulers

- Maximum Throughput (MT)

$$R_i(k,t) = \frac{S\left(M_{i,k}(t), 1\right)}{\tau} \qquad \widehat{i}_k(t) = \underset{j=1,\ldots,N}{\operatorname{argmax}} \left(R_j(k,t)\right)$$

$M_{i,k}(t)$ MCS usable by user on resource block
τ TTI duration

- Throughput to Average (TTA)

$$\widehat{i}_k(t) = \underset{j=1,\ldots,N}{\operatorname{argmax}} \left(\frac{R_j(k,t)}{R_j(t)}\right)$$

- Blind Average Throughput (BET)

$$\widehat{i}_k(t) = \underset{j=1,\ldots,N}{\operatorname{argmax}} \left(\frac{1}{T_j(t)}\right)$$

$T_j(t)$ past throughput perceived by the user j

- Token Bank Fair Queue (TBFQ)
  - leaky-bucket mechanism

- Priority Set Scheduler (PSS)
  - controls the fairness among UEs by a specified Target Bit Rate (TBR) defined with QCI bearer primitive

Random Access model

- Random Access preamble transmission
  - Ideal model: no propagation / error model
  - Collisions modeled with protocol interference model
  - No capture effect $\Rightarrow$ contention resolution not modeled
- Random Access Response (RAR)
  - ideal message, no error model
  - resource consumption can be modeled by scheduler
- message3
  - UL grant allocated by Scheduler
  - PDU with actual bytes, subject to error model
- Supported modes:
  - Contention based (for connection establishment)
  - Non-contention based (for handover)

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)

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
  - 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

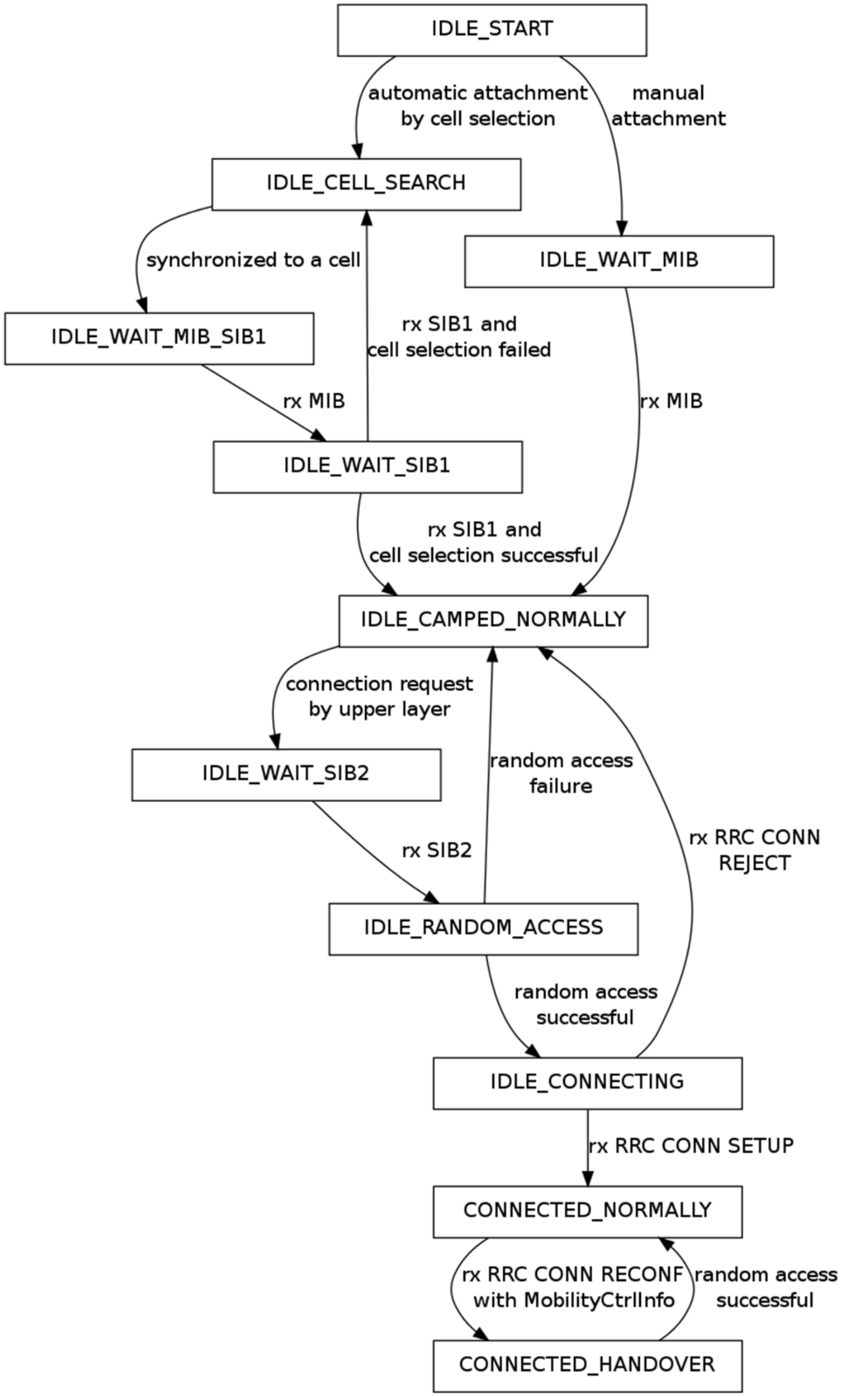
RRC Model features

- System Information (MIB, SIBs)
  - Generation at eNB
  - Reception and processing at UE
- Idle mode cell selection
- RRC Connection Establishment
- RRC Connection Reconfiguration, supporting:
  - SRB1 and DRB setup
  - SRS configuration index reconfiguration
  - PHY TX mode (MIMO) reconfiguration
  - Mobility Control Info (handover)
- 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

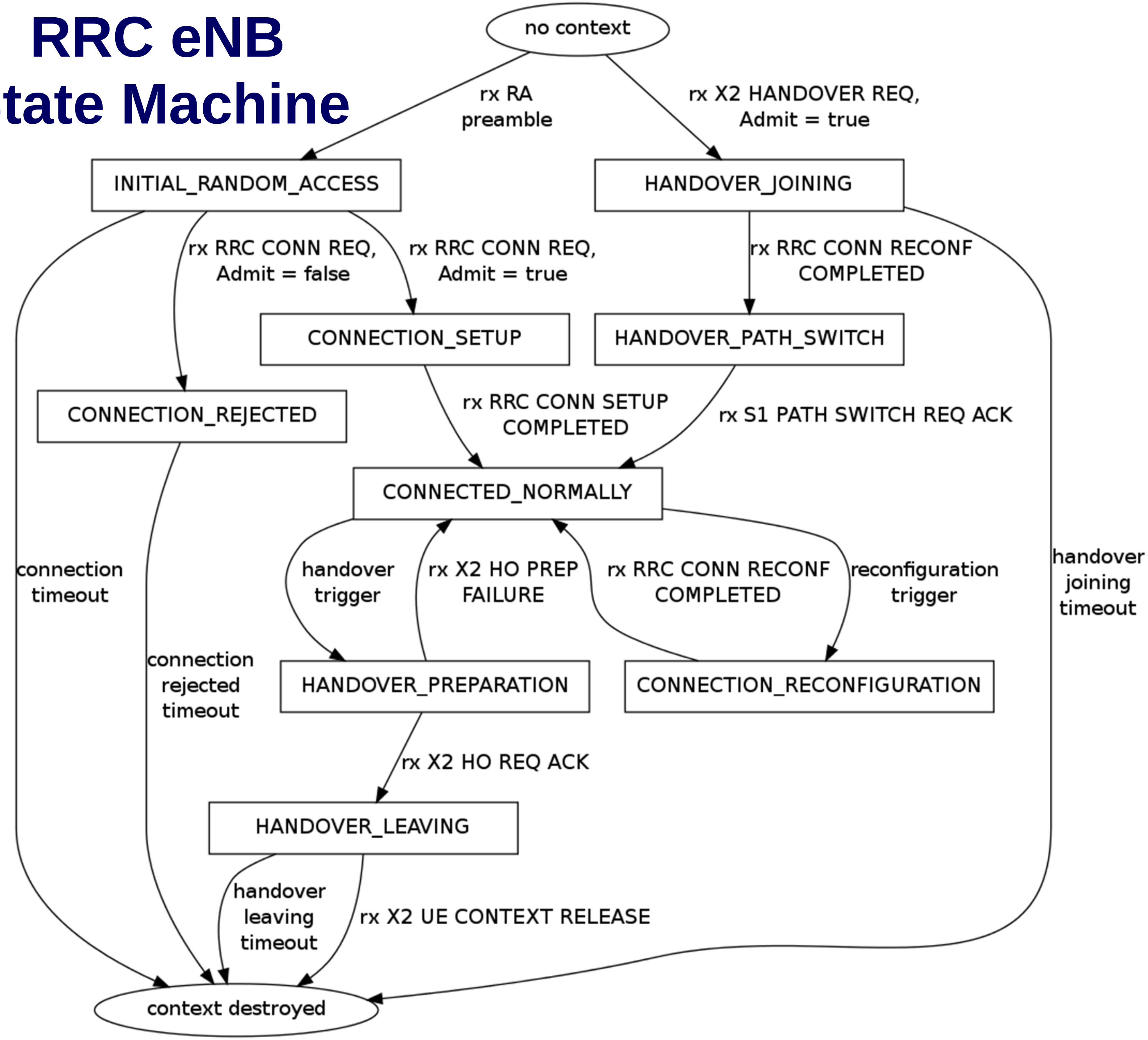
RRC Model architecture

- 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
    - with ASN.1 encoding

RRC UE state machine



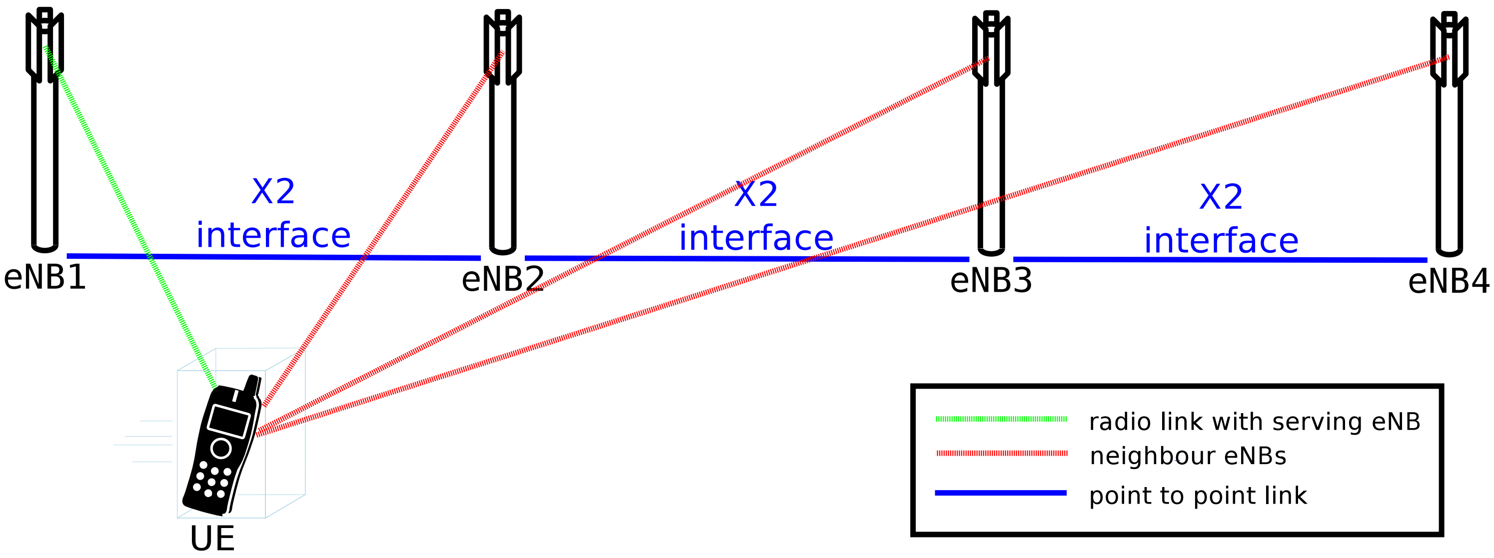
RRC eNB State Machine



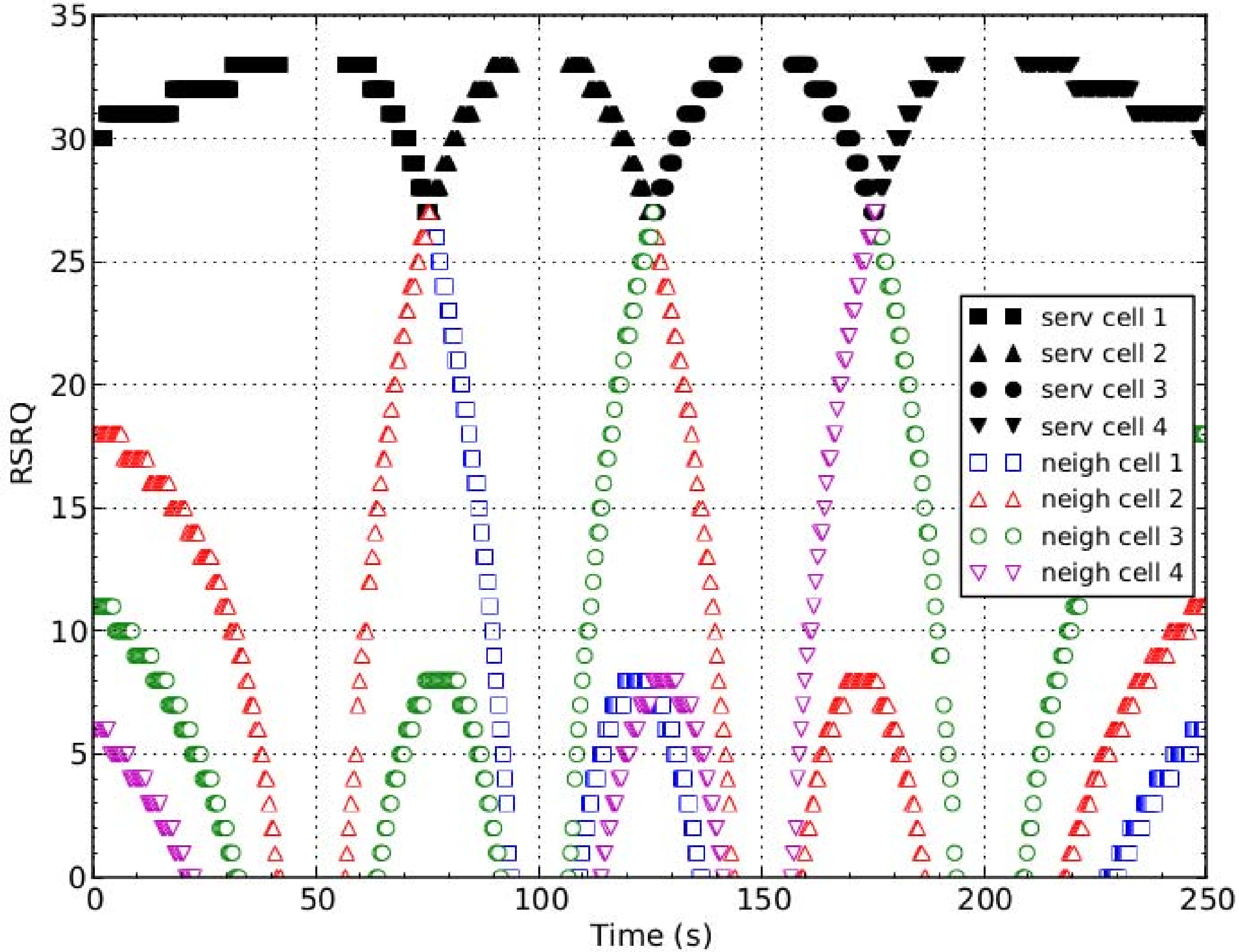
Handover Support

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

Handover example scenario



Handover behavior



NAS model

- Focus on NAS Active state
  - EMM Registered, ECM connected, RRC connected
- Logical interaction with MME
  - NAS PDUs not implemented
- Functionality
  - UE Attachment (transition to NAS Active state)
  - EPS Bearer activation
  - Multiplexing of data onto active EPS Bearers
    - Based on Traffic Flow Templates
    - Both UDP and TCP over IPv4 are supported
- Unsupported features
  - PLMN and CSG selection
  - Idle mode (tracking are update, paging…)

S1 interface model

- S1-U (user data plane)
  - Realistic model including GTP-U implementation
  - Data packets forwarded over GTP/UDP/IPv4
  - Communication over ns3::PointToPoint links
- S1-C (control plane)
  - abstract model, no PDUs exchanged
  - Supported S1-AP primitives:
    - INITIAL UE MESSAGE
    - INITIAL CONTEXT SETUP REQUEST
    - INITIAL CONTEXT SETUP RESPONSE
    - PATH SWITCH REQUEST
    - PATH SWITCH REQUEST ACKNOWLEDGE

X2 interface model

- X2-U (data plane)
  - GTP/UDP/IPv4 over ns3::PointToPoint (similar to S1-U)
- X2-C (control plane)
  - Messages as PDUs over ns3::PointToPoint links
  - Handover primitives:
    - HANDOVER REQUEST
    - HANDOVER REQUEST ACK
    - HANDOVER PREPARATION FAILURE
    - SN STATUS STRANSFER
    - UE CONTEXT RELEASE
  - SON primitives:
    - LOAD INFORMATION
    - RESOURCE STATUS UPDATE

S11 interface model

- abstract model
  - no GTP-C PDUs exchanged between MME and SGW
- Supported primitives:
  - CREATE SESSION REQUEST
  - CREATE SESSION RESPONSE
  - MODIFY BEARER REQUEST
  - MODIFY BEARER RESPONSE

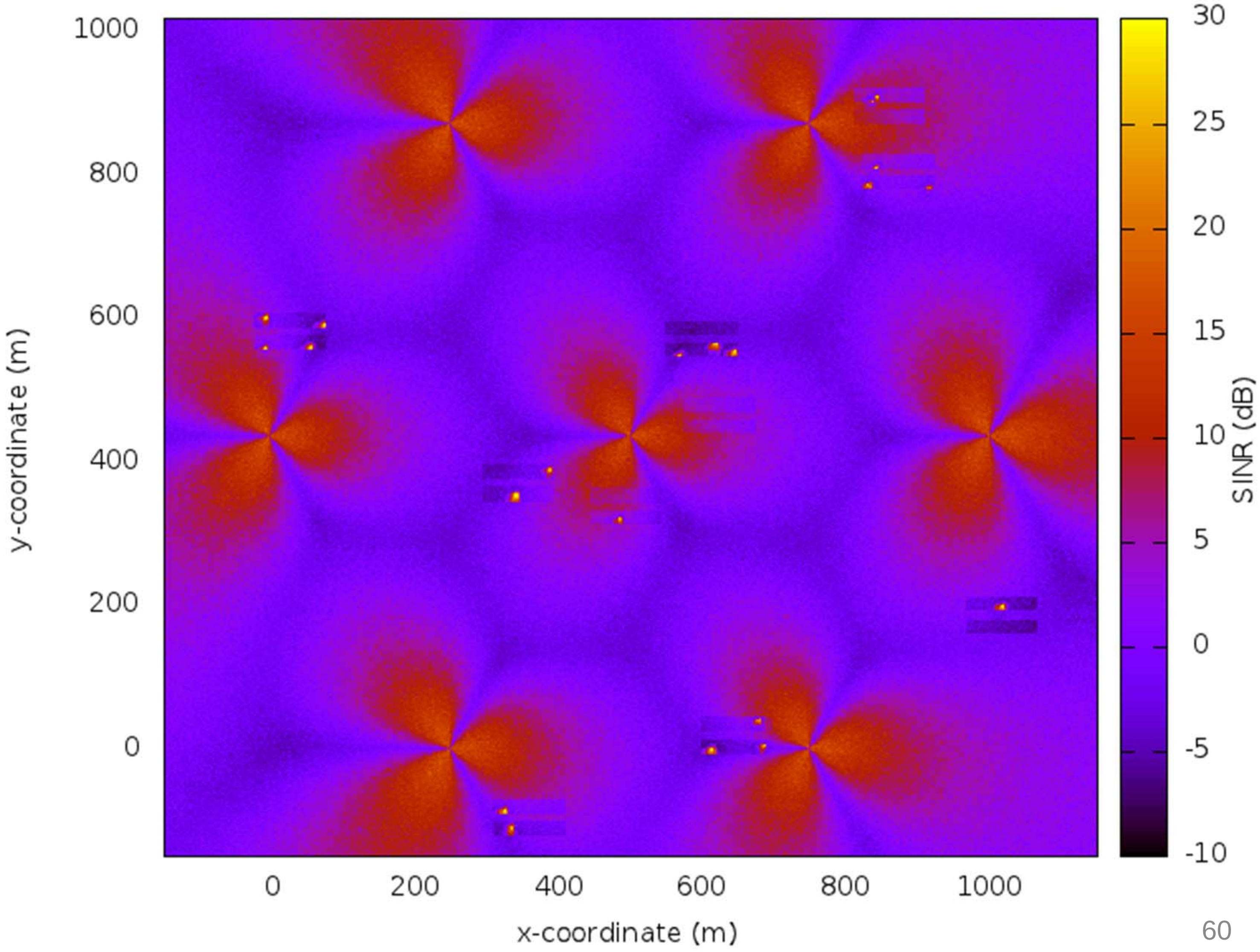
Simulation Configuration

- Done via ns-3 attribute system
- Several configurable attributes per LTE object
- Default attribute values can be configured:
  – Via input config file
  – Via command line
  – within simulation program
- Per-instance attribute values can be configured:
  – Within siulation program
  – Using GtkConfigStore

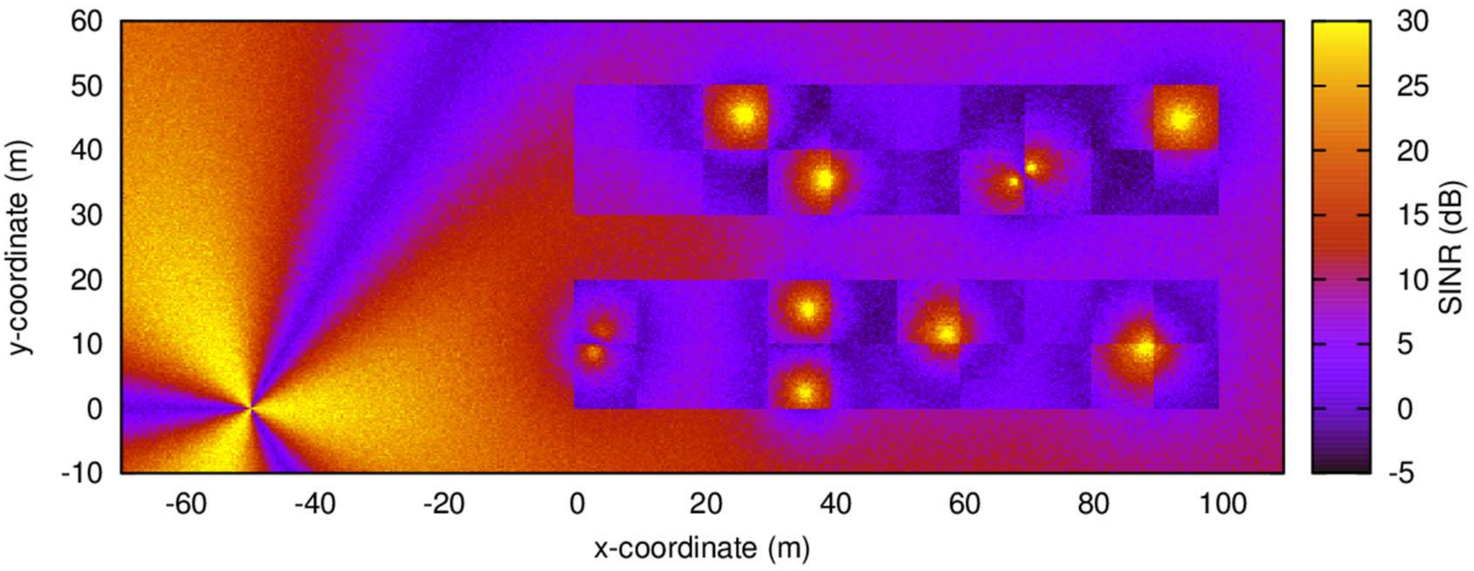
Simulation Ouput

- Lots of KPIs available at different levels:
  - Channel
    - SINR maps
    - pathloss matrices
  - 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
    - Can be obtained with usual ns-3 means
    - FlowMonitor, PCAP traces, get stats directly from app, etc.

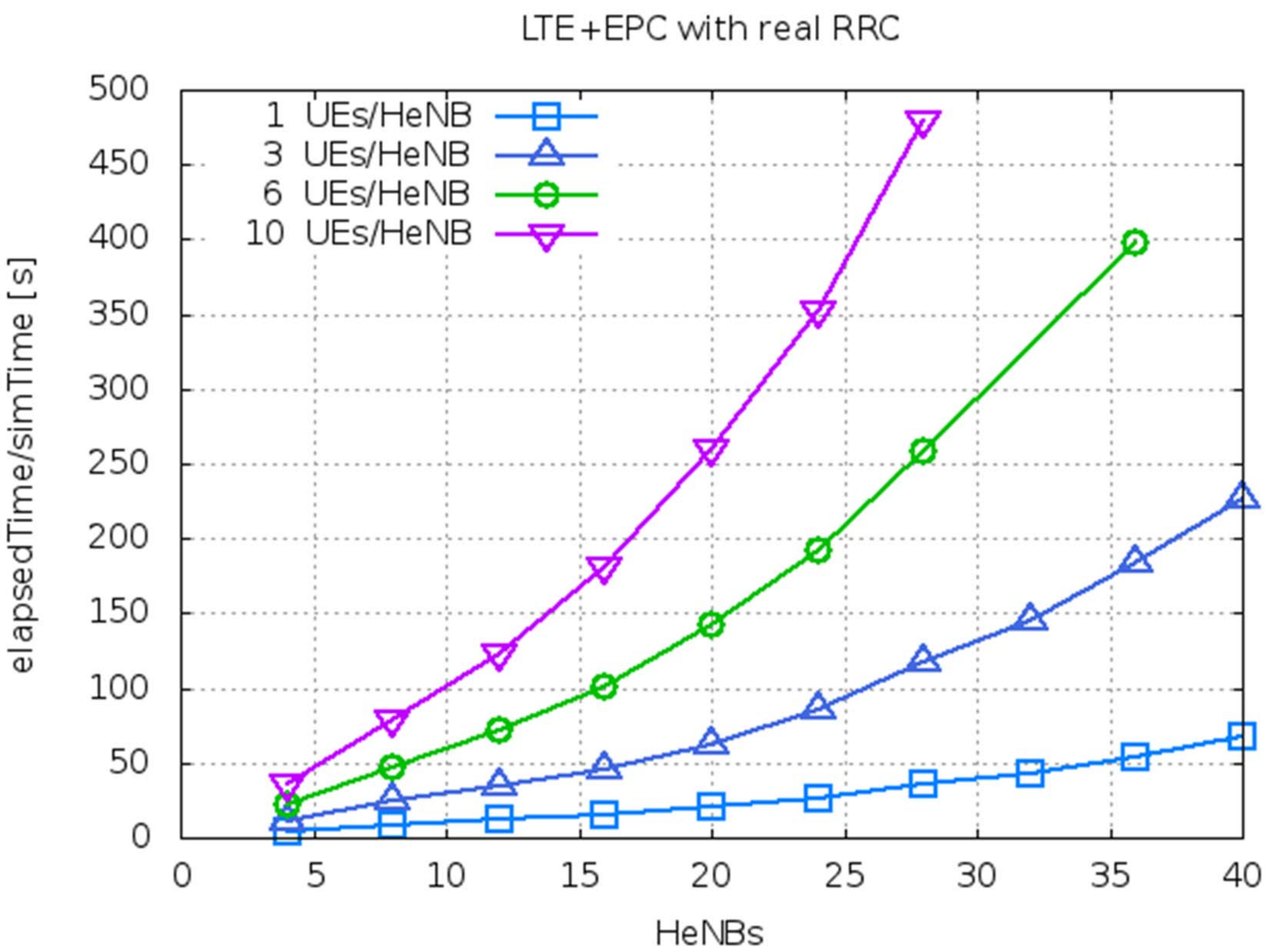
Example: 3GPP dual stripe scenario



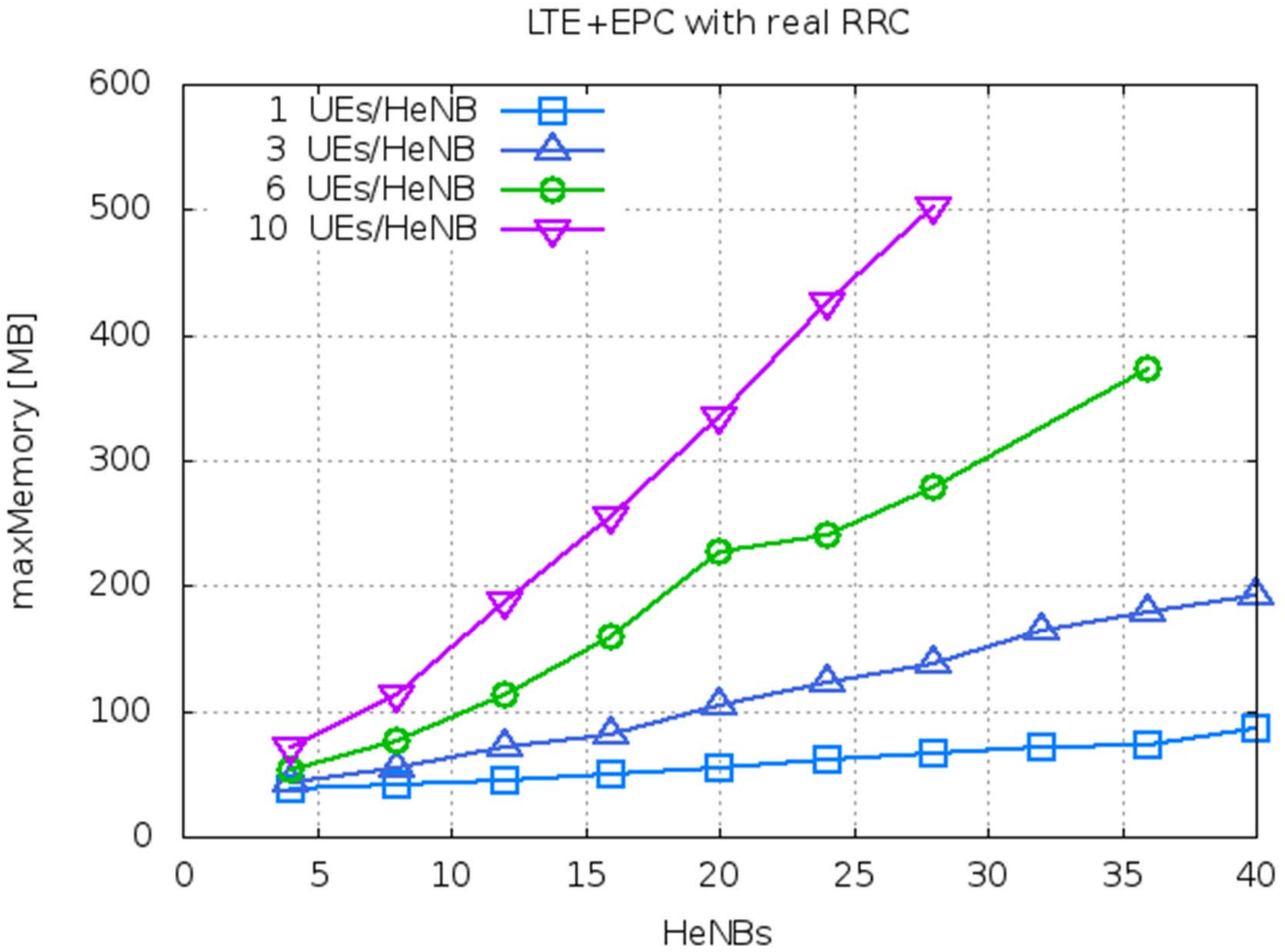
Example: 3GPP dual stripe scenario



Execution time performance



Memory consumption



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
  - Build tests
    - Provided by ns-3 project for stable LENA code
    - Verify correct build on all supported plaftorms
    - LENA dev code tested daily on ubuntu

Documentation

- LTE module documentation
  - Part of the ns-3 models library docs

- LENA web page
  - http://networks.cttc.es/mobile-networks/software-tools/lena/

Reference papers

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