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
- 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)
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

• 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 (inherited 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)
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
• 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 ⇒ 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
BLER Curves
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
• Ns3 provides only SISO propagation model
• MIMO has been modeled as SINR gain over SISO according to
• 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 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
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)

<table>
<thead>
<tr>
<th>System Bandwidth</th>
<th>RBG Size (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{RB}^{DL} )</td>
<td></td>
</tr>
<tr>
<td>( \leq 10 )</td>
<td>1</td>
</tr>
<tr>
<td>11 – 26</td>
<td>2</td>
</tr>
<tr>
<td>27 – 63</td>
<td>3</td>
</tr>
<tr>
<td>64 – 110</td>
<td>4</td>
</tr>
</tbody>
</table>

- 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)
    \[
    \begin{align*}
    BER &= 0.00005 \\
    \Gamma &= \frac{-\ln(5 \times BER)}{1.5} \\
    \eta_i &= \log_2 \left( 1 + \frac{\gamma_i}{\Gamma} \right)
    \end{align*}
    \]
    \(\gamma_i\) 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
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)
- Maximum Throughput (MT)
- Throughput to Average (TTA)
- Blind Average Throughput (BET)
- Token Bank Fair Queue (TBFQ)
- Priority Set Scheduler (PSS)
- Channel and QoS Aware Scheduler (CQA)

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

LENAs project
GSoC 2012
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)
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

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

- $M_{i,k}(t)$: MCS usable by user on resource block
- $\tau$: TTI duration

- At RBG $k$ pick the user that maximize

$$\hat{i}_k(t) = \arg\max_{j=1,\ldots,N} \left( \frac{R_j(k, t)}{T_j(t)} \right)$$

- $T_j(t)$: past throughput perceived by the user $j$
- $T_j(t) = (1 - \frac{1}{\alpha})T_j(t - 1) + \frac{1}{\alpha}\hat{T}_j(t)$

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)**
  
  \[ R_i(k, t) = \frac{S(M_{i,k}(t), 1)}{\tau} \]
  \[ \hat{i}_k(t) = \arg\max_{j=1,\ldots,N} (R_j(k, t)) \]

- **Throughput to Average (TTA)**
  
  \[ \hat{i}_k(t) = \arg\max_{j=1,\ldots,N} \left( \frac{R_j(k, t)}{R_j(t)} \right) \]

- **Blind Average Throughput (BET)**
  
  \[ \hat{i}_k(t) = \arg\max_{j=1,\ldots,N} \left( \frac{1}{T_j(t)} \right) \]

- **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
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…)

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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:
    - HANOVER REQUEST
    - HANOVER REQUEST ACK
    - HANOVER PREPARATION FAILURE
    - SN STATUS STRANSFER
    - UE CONTEXT RELEASE
  - SON primitives:
    - LOAD INFORMATION
    - RESOURCE STATUS UPDATE
• 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 simulation program
  – Using GtkConfigStore
Simulation Output

• 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

LTE+EPC with real RRC

maxMemory [MB] vs HeNBs

- 1 UEs/HeNB
- 3 UEs/HeNB
- 6 UEs/HeNB
- 10 UEs/HeNB
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 platforms
    • LENA dev code tested daily on ubuntu
Documentation

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

• LENA web page
Reference papers


- B. Herman, N. Baldo, M. Miozzo, M. Requena, J. Ferragut, *Extensions to LTE Mobility Functions for ns-3*, WNS3 2014