From LENA to LENA-NB: Implementation and Performance Evaluation of NB-IoT and Early Data Transmission in ns-3

Pascal Jörke, Tim Gebauer and Christian Wietfeld

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Faculty of Electrical Engineering and Information Technology
Communication Networks Institute
Prof. Dr.-Ing. Christian Wietfeld
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LPWAN Challenges in the Context of the IoT

- LPWAN requires:
  - Energy efficiency for long battery life
  - Robust signals for deep indoor penetration
  - High scalability for a massive number of devices
- Billions of IoT devices predicted for the future → Upcoming networks are designed for massive scalability
- Design goals NB-IoT:
  - 3GPP Rel. 13: 60,000 devices / km² [2]
  - 3GPP Rel. 15: **1,000,000 devices / km²** [3]

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Fundamentals of NB-IoT

Power Saving Techniques

- Extended Discontinuous Reception (eDRX)
  - Devices remain longer in power saving state between Paging Occasions
- Power Saving Mode (PSM)
  - Devices don't monitor paging → unreachable
  - Lowest power consumption

Fundamentals of NB-IoT

Coverage Enhancement

- NB-IoT includes up to **2048 repetitions** for deep indoor coverage
- Repetitions increase energy per bit → reduced bit error rate but…
- Repeated transmission of data increases **time-on-air** drastically → decreased spectral efficiency affects cell capacity

*) based on 800 MHz Okumura Hata channel models for urban environments + 15dB additional basement penetration loss
MCL: Maximum Coupling Loss

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Fundamentals of NB-IoT

Small Data Transmission

Early data transmission (EDT) introduced in NB-IoT Rel. 15

- EDT enables data transmission in Msg3 (UL) and Msg4 (DL)
- UE won't use RRC Reestablishment procedure, but switches directly back to Power Saving Mode (PSM) after EDT Complete
- Energy and spectral efficient for single data transmissions

How will it perform in highly scaled networks?
Simulation Framework

**Introducing ns-3 LENA-NB**

- Based on ns-3 LTE framework LENA
- MAC/PHY changes: **NB-IoT RA procedure** including different CE levels
- RRC changes: New **RRC Resume** procedure
- Energy model
  - Energy state machine includes **eDRX** and **PSM**
- **Cross-Subframe Scheduler**
  - Due to low-cost devices, **transmission gaps** introduced in between DL and UL in NB-IoT
  - **Repetitions** occupy up to 2048 consecutive subframe with additional transmission gaps

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Simulation Framework

Scheduling in NB-IoT

- **Cross-Subframe-Scheduling:** *Different subframes* for DCI and scheduled data
- **Repetitions:** up to 2048 rep. of a *single transmission* with additional transmission gaps for serving other devices during a gap
- **Variable length of RUs:**

<table>
<thead>
<tr>
<th>UL bandwidth [kHz]</th>
<th>Length of RU [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75</td>
<td>32</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>45</td>
<td>4</td>
</tr>
<tr>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>180</td>
<td>1</td>
</tr>
</tbody>
</table>

**DCI Format N0:**
- Subcarrier indication: 12-tone
- Scheduling delay: 8 ms
- DCI subframe repetition number: 2
- Number of resource units: 3
- Number of NPUSCH repetitions: 2
- MCS: 8
- Redundancy version: 0, New data indicator: True

Validation of LENA-NB implementation

Message Sequence Validation

- **Hardware setup:**
  - Amarisoft Callbox Classic (NB-IoT eNodeB and EPC)
  - Quectel BG96 (UE)

- **Mobile Originated (MO) user data transmission**

- **RRC Resume procedure and C-IoT Optimization for reduced overhead**

- **Both Amarisoft and ns-3 message traces are identical**
Evaluation and Results

Simulation Parameters

- Simulation time:
  - 15 minutes in total
  - 5 minutes pre-run (devices are scheduled in empty cell and experience best spectral conditions)
  - Intermediate 5 minutes are used for performance evaluation
  - Last 5 minutes to keep channel busy and letting intermediate devices complete their transmissions

- Cell diameter based on **average cell size** in Dortmund, Germany
- Devices are **distributed equally** outdoors, indoors and deep indoors (basements)
- Payload at UDP layer
  - 32 Bytes 5G mMTC payload + 4 Bytes CoAP header + 13 Bytes DTLS header

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>15 min</td>
</tr>
<tr>
<td>Cell diameter</td>
<td>2.5 km</td>
</tr>
<tr>
<td>Cell area</td>
<td>4.91 km²</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Winner+ (UmaNLOS)</td>
</tr>
<tr>
<td>Base station height</td>
<td>50 m</td>
</tr>
<tr>
<td>Device height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>UDP data size (UL direction)</td>
<td>49 bytes</td>
</tr>
<tr>
<td>Transmission interval</td>
<td>24 hours</td>
</tr>
</tbody>
</table>
Evaluation and Results

Latency, PDR and Energy Consumption

Constant high packet delivery rate

In large scenarios EDT provides 2.9x better latency than standard transmissions

Cell diameter: 2.5km, application payload: 49 Bytes, TTI: 24h, outdoor, indoor and deep indoor devices equally distributed

Pascal Jörke

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Evaluation and Results

Latency, PDR and Energy Consumption

-15% Battery life in large scenarios

EDT provides 1.6x more battery life than standard transmission.

Yet, the impact of large-scaled scenarios on the energy performance is low, since devices are most of the time in idle.

Cell diameter: 2.5km, application payload: 49 Bytes, TTI: 24h, outdoor, indoor and deep indoor devices equally distributed
Evaluation and Results
Spectrum Usage Ratio (Downlink)

- User data - No C-IoT Opt., no EDT
- User data - C-IoT Opt., no EDT
- User data - C-IoT Opt., EDT
- Additional SI messages
- SIB1-NB
- NSSS
- NPSS
- MIB

Note: Spectrum usage is stacked from below to top. Only user data aren't added on each other.

Network capacity still enables more devices to join
Massively decreased spectrum usage when using EDT

Broadcasts occupy 30% of DL spectrum without any user data

Cell diameter: 2.5km, application payload: 49 Bytes, TTI: 24h, outdoor, indoor and deep indoor devices equally distributed
Evaluation and Results

Random Access Collisions

Results for transmissions without EDT are mostly equal, since they use the same RA configuration and simulation seeds.

Increase in Random Access collisions implies saturation of RA windows.
Conclusion and Outlook

- Billions of IoT devices predicted for the future → Upcoming networks are designed for massive scalability
- Early Data Transmission drastically decreases signalling overhead in NB-IoT networks
- Implementation ns-3 LENA for performance comparison between NB-IoT transmission modes

- Performance comparison:
  - EDT provides 2.9x lower E2E latency for approx. 173,000 devices and 1.6x longer battery life in general than NB-IoT legacy transmission
  - EDT uses 3.7x less DL spectrum but is limited by the current RA window configuration

- Further optimizations on the Radio Resource Configuration required for an optimized RA window / user data ratio in UL direction

EDT is highly recommended as a default transmission mode for small data transmissions

- Next steps in LENA-NB: Performance Optimizations (shorter computing time for large-scaled scenarios, additional NB-IoT features)
Thank you for your attention!