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Workshop on ns-3

2022 Workshop on ns-3

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

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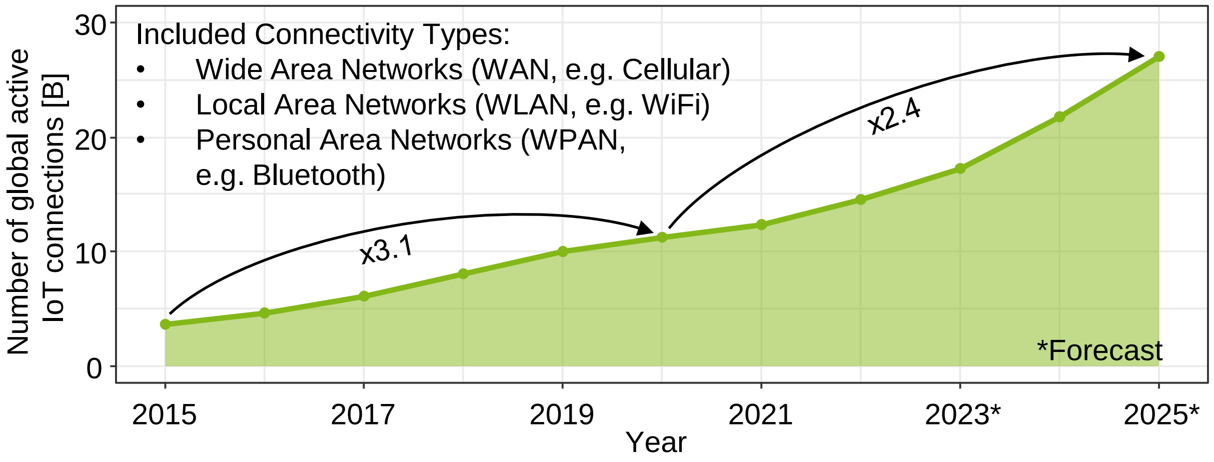
LPWAN Challenges in the Context of the IoT

- 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]

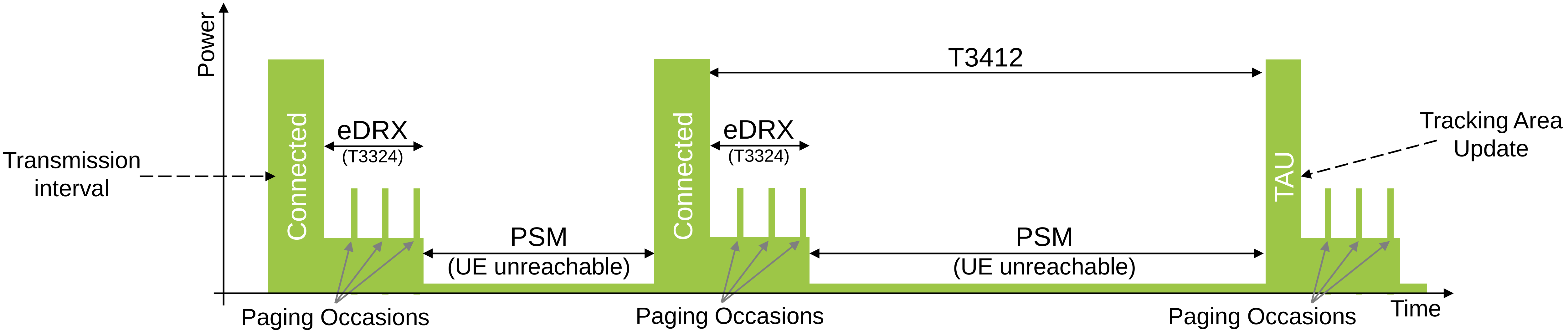
[1]



[1] Global IoT market forecast (in billion connected IoT devices). [Online]. Available: https://iot-analytics.com/wp/wp-content/uploads/2021/09/Global-IoT-market-forecast-in-billion-connected-iot-devices-min.png
[2] 3GPP TSG GERAN, “TR 45.820 v13.1.0: Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT) (release 13),” 3GPP Technical Report, Tech. Rep., 2015
[3] O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, and G. Wikström, Cellular Internet of Things: From Massive Deployments to Critical 5G Applications. Elsevier Science, 2020

Fundamentals of NB-IoT

Power Saving Techniques



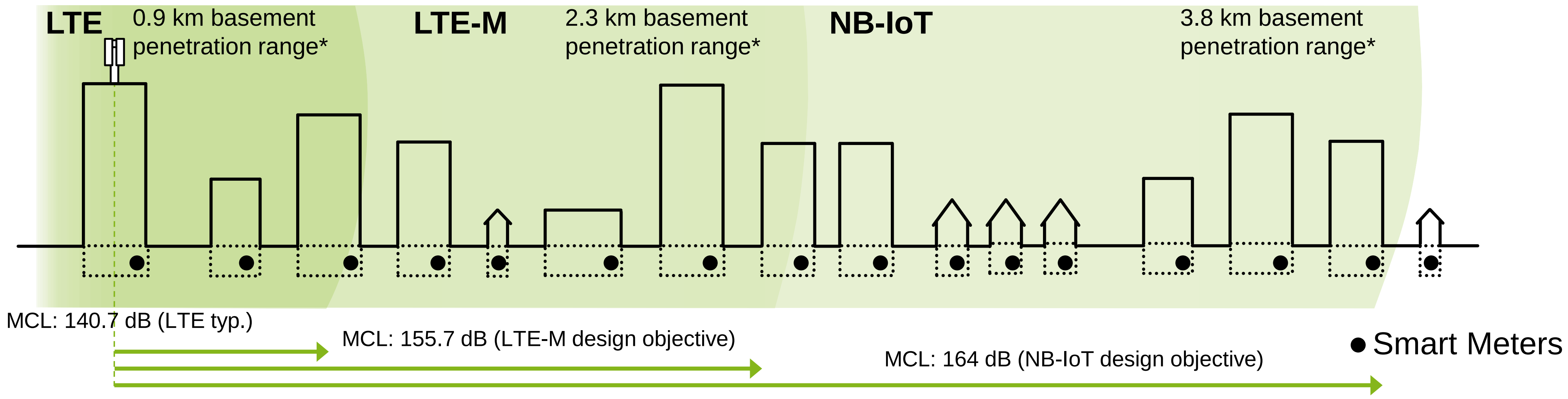
- Extended Discontinuous Reception (eDRX)
  - Devices remain longer in power saving state between Paging Occasions
- Power Saving Mode (PSM)
  - Devices don‘t monitor paging → unreachable
  - Lowest power consumption

UE: User Equipment

O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, and G. Wikström, Cellular Internet of Things: From Massive Deployments to Critical 5G Applications. Elsevier Science, 2020

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…

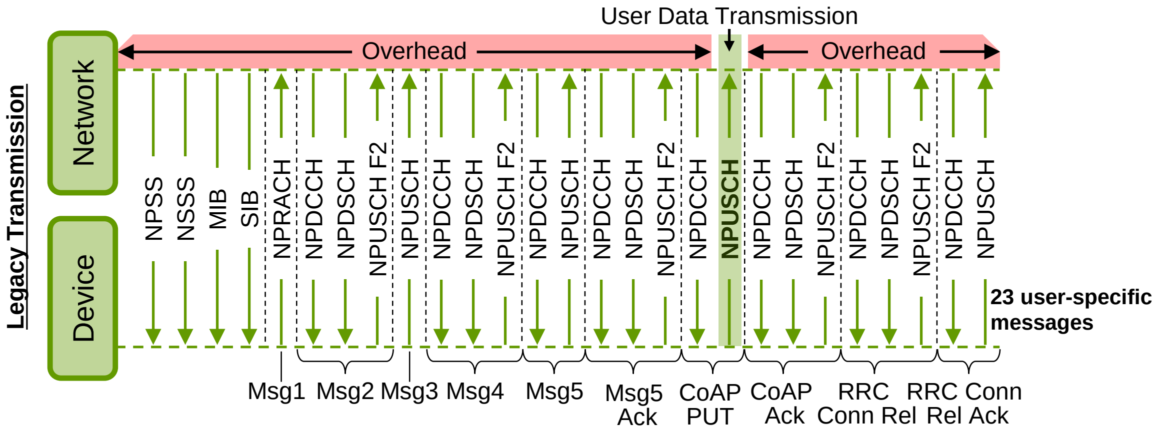
- Repeated transmission of data **increases time-on-air** drastically → decreased spectral efficiency affects cell capacity

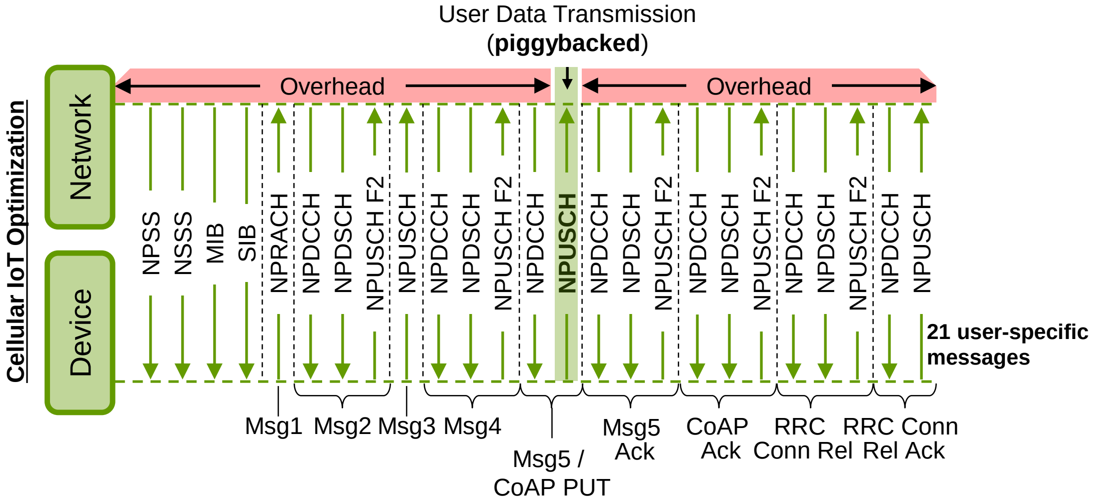
*) based on 800 MHz Okumura Hata channel models for urban environments + 15dB additional basement penetration loss

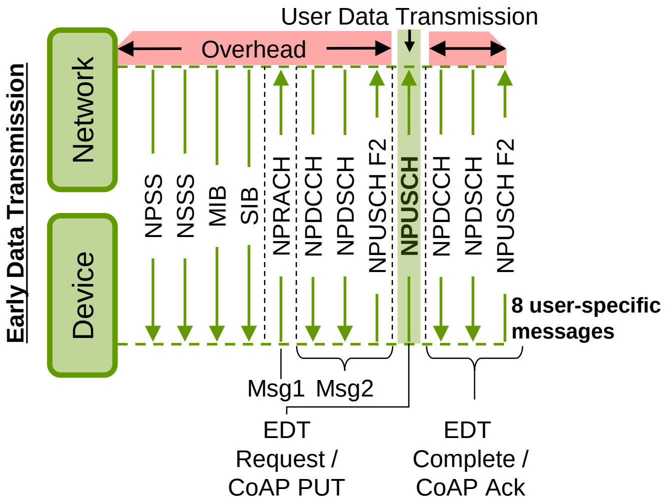
MCL: Maximum Coupling Loss

O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, and G. Wikström, Cellular Internet of Things: From Massive Deployments to Critical 5G Applications. Elsevier Science, 2020

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

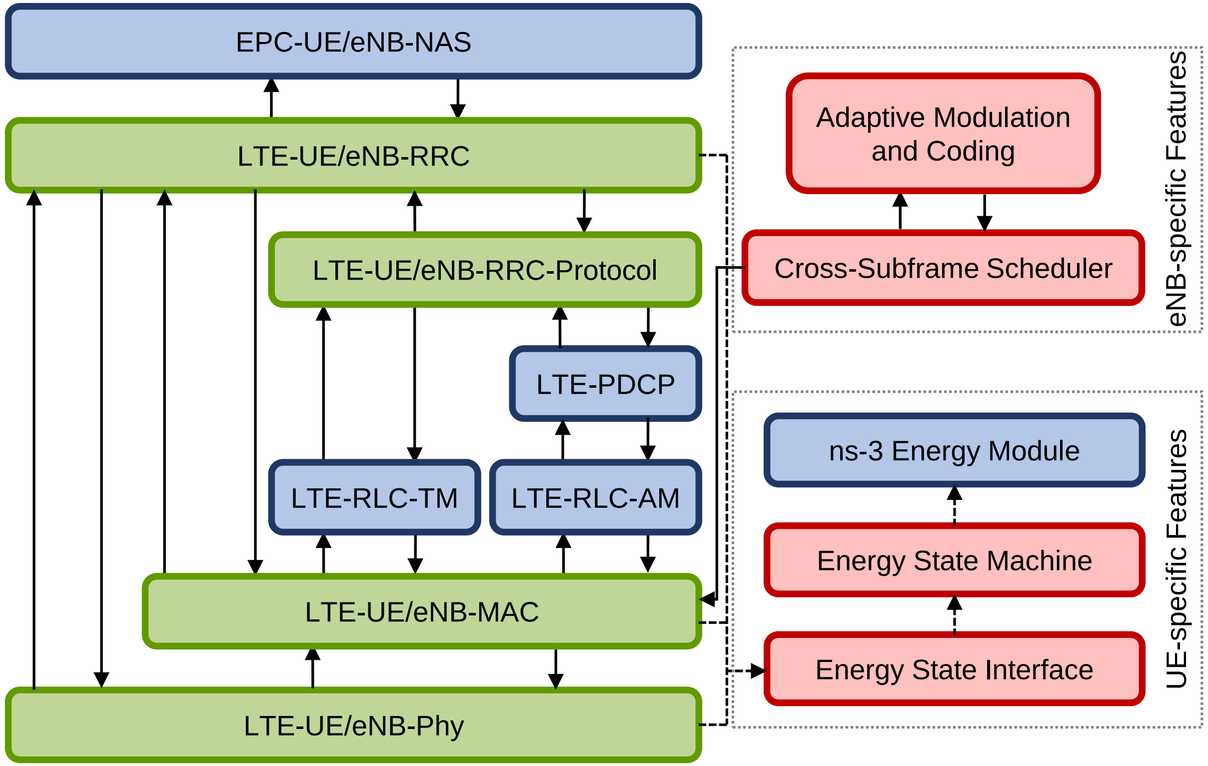
How will it perform in highly scaled networks?

RRC: Radio Resource Control CoAP: Constrained Application Protocol UE: User Equipment

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



LENA-NB Radio Protocol Stack for UE / eNB

Minor Changes | Major Changes | Newly Implemented

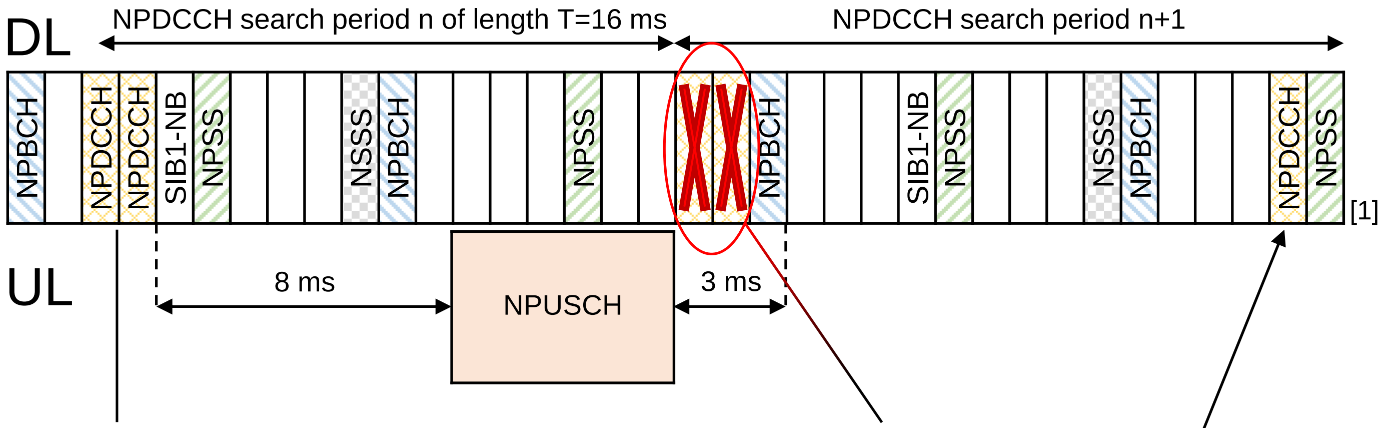
EPC: Evolved Packet Core
UE: User Equipment
eNB: Evolved Node B
RRC: Radio Resource Control
RLC-TM: Radio Link Control Protocol – Transparent Mode
RLC-TM: Radio Link Control Protocol – Acknowledged Mode
MAC: Medium Access Control
Phy: Physical Layer
PDCP: Packet Data Convergence Protocol

T. Gebauer and P. Jörke, "NS-3 LENA-NB," https://github.com/tudo-cni/ns3-lena-nb, 2021

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:

UL bandwidth [kHz]	Length of RU [ms]
3.75	32
15	8
45	4
90	2
180	1



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

UE can‘t monitor DCI on NPDCCH because it hasn‘t switched back to DL reception

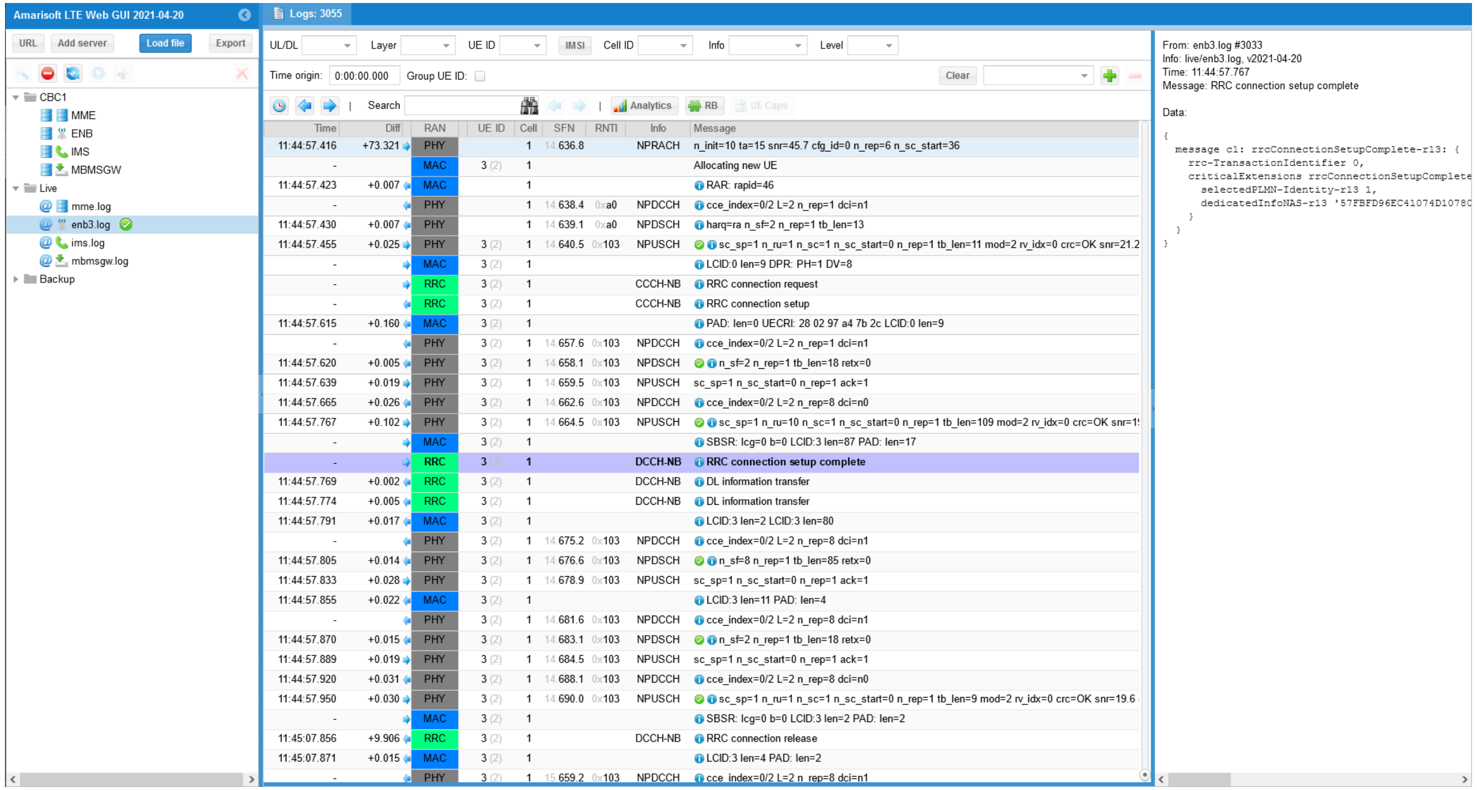
It needs to wait for the next NPDCCH search period

RU: Resource Unit
DCI: Downlink Control Information
MCS: Modulation and Coding Scheme
DL: Downlink
UL: Uplink
NPBCH: Narrowband Physical Broadcast Channel
NPDCCH: Narrowband Physical Downlink Control Channel
NPUSCH: Narrowband Physical Uplink Shared Channel
NPSS: Narrowband Primary Synchronzation Signal
NSSS: Narrowband Secondary Synchronization Signal
SIB1-NB: System Information Block 1 Narrowband

[1] O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, and G. Wikström, Cellular Internet of Things: From Massive Deployments to Critical 5G Applications. Elsevier Science, 2020

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

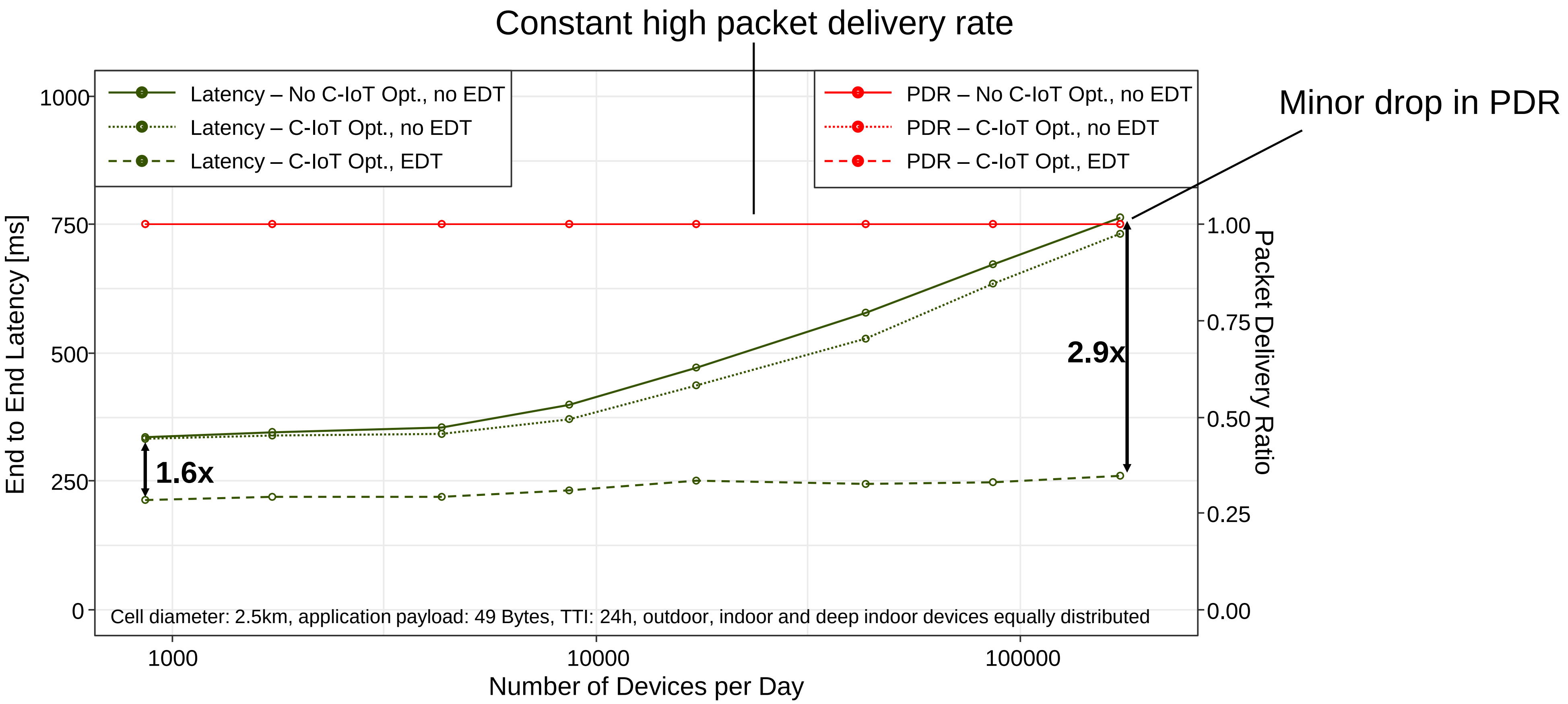
Simulation Parameters

- 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

Parameter	Value
Simulation Time	15 min
Cell diameter	2.5 km
Cell area	4.91km²
Channel Model	Winner+ (UmaNLOS)
Base station height	50 m
Device height	1.5 m
UDP data size (UL direction)	49 bytes
Transmission interval	24 hours

Evaluation and Results

Latency, PDR and Energy Consumption

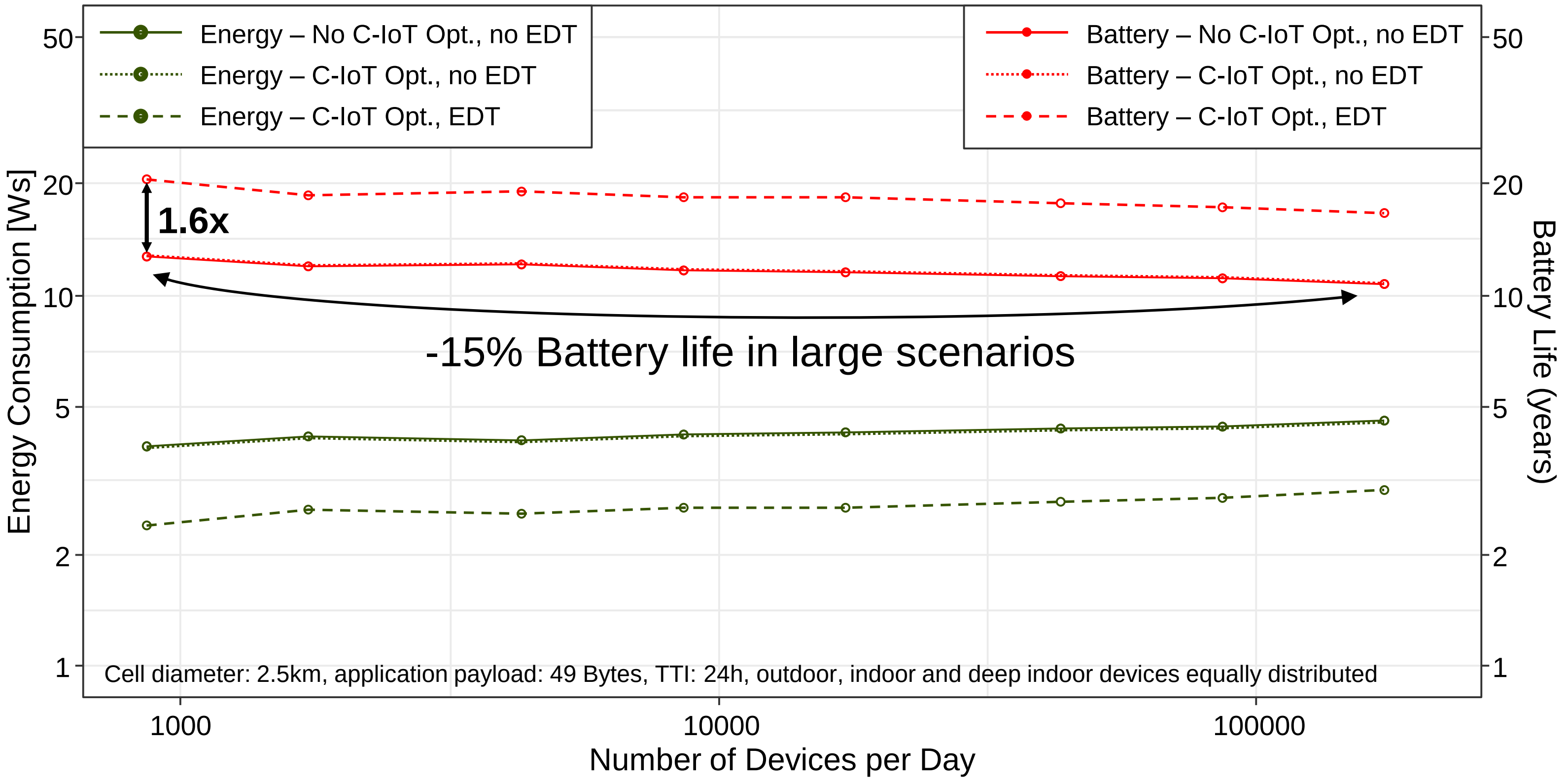


In large scenarios EDT provides 2.9x better latency than standard transmissions

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

Evaluation and Results

Latency, PDR and Energy Consumption



EDT provides 1.6x more battery life than standard transmission.

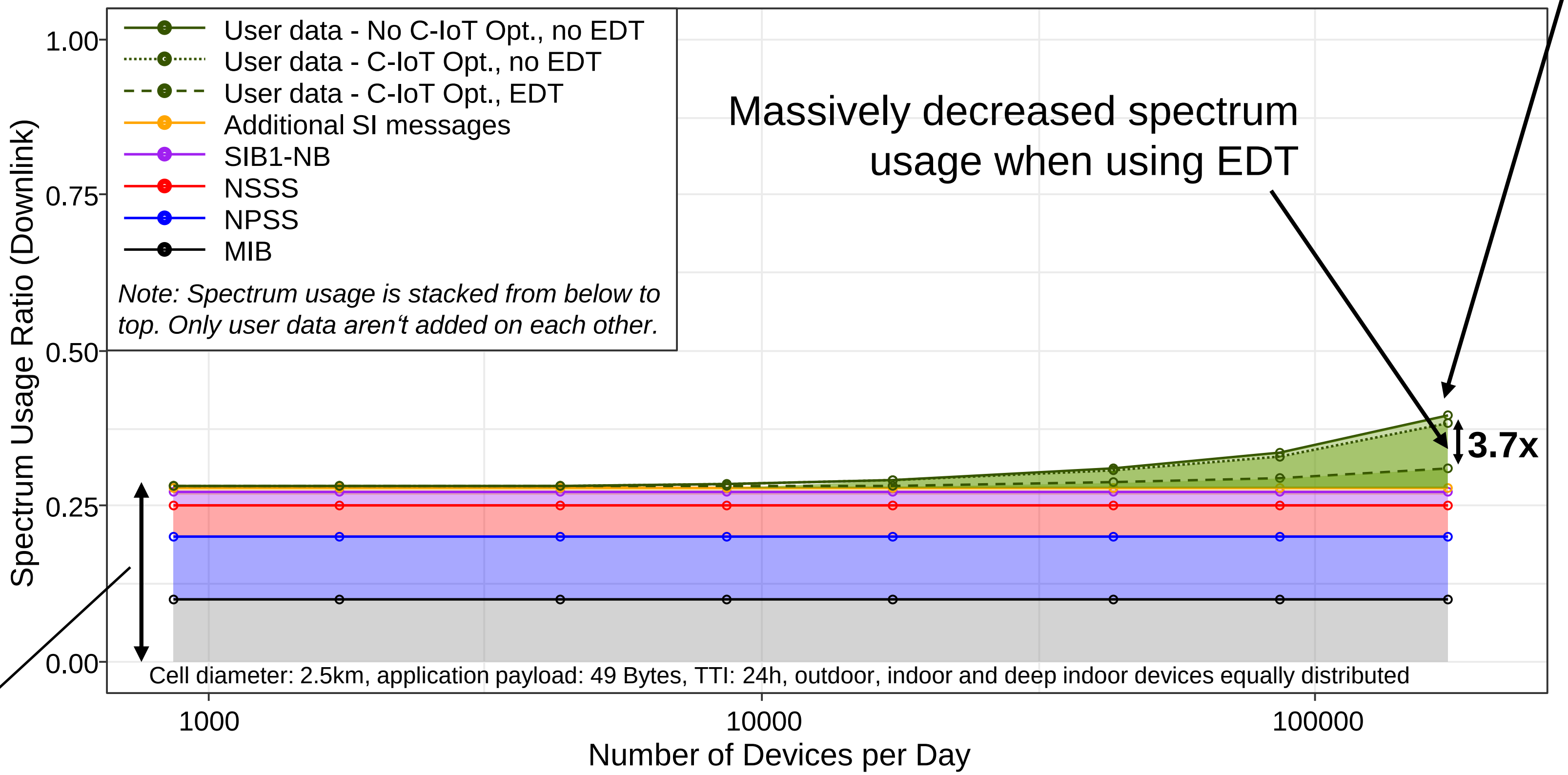
Yet, the impact of large-scaled scenarios on the energy performance is low, since devices are most of the time in idle.

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)

Network capacity still enables more devices to join



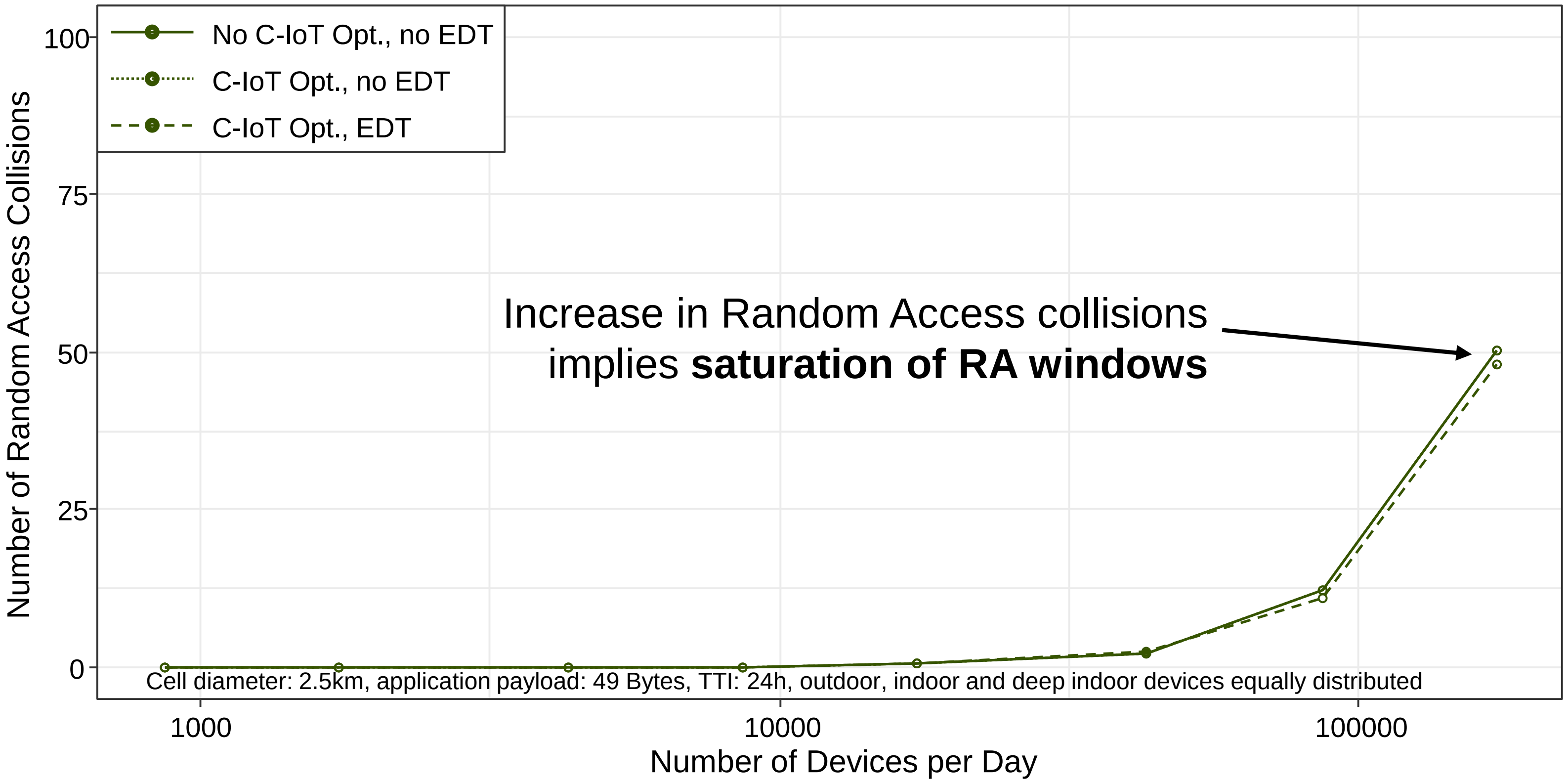
Broadcasts occupy 30% of DL spectrum without any user data

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



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

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!