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

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ABSTRACT

With the growing Internet of Things, more small devices require internet connections. To address the scaling number of Internet of Things devices, Narrowband Internet of Things is enhanced with new features for more efficient transmission of small data. With Early Data Transmission, a promising feature has been introduced in 3GPP Release 15, which aims to reduce the overall overhead of NB-IoT data transmissions by transmitting data without an active Radio Resource Control connection. To evaluate the impact of Early Data Transmission on the efficiency and scalability from a user and network provider perspective, we have implemented NB-IoT in ns-3, called LENA-NB. It features performance improvements such as Cellular-IoT C-Plane Optimization, Early Data Transmission, RRC Resume procedure, as well as a new cross-subframe scheduler, adaptive modulation and coding, and a detailed energy state machine. Using LENA-NB, a performance comparison of different NB-IoT transmission modes is performed, which results in a clear recommendation to use Early Data transmission per default, since it improves latency, battery lifetime, and spectral efficiency, especially in scenarios with a large number of devices.

CCS CONCEPTS

• **Networks** → **Link-layer protocols**; **Network simulations**; Network reliability.

KEYWORDS

Internet of Things, simulation, NB-IoT, Early Data Transmission, LENA-NB, ns-3, implementation, performance evaluation

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1 INTRODUCTION

The growing number of worldwide Internet of Things (IoT) devices challenges communication networks. From Personal Area Networks (PAN), such as Bluetooth, to Wide Area Networks (WAN) like Long Term Evolution (LTE), forecasts expect billions of IoT devices to require internet access in the next few years (Figure 1). The use cases are diverse: Waste bins that alarm the waste collection when they need to be emptied, environmental sensors that transmit air quality reports frequently, parking sensors that help to navigate to free parking lots. Since most IoT applications only transmit a small amount of data, many devices are battery-powered for a more flexible and cost-effective installation, which requires communication networks to be energy efficient. In some use cases even battery-less, self-powered devices using energy harvesting techniques are developed [18].

Taking the new challenges of an energy and spectrum efficient transmission of small data packets into account, 5th mobile radio generation (5G) addresses the new IoT requirements and aims to enable a very high subscriber density. For this purpose, the ITU-R defines correlating requirements for massive IoT applications in the context of massive Machine Type Communication (mMTC) [16]. With Narrowband Internet of Things (NB-IoT), a promising technology has been derived from LTE, designed for small and efficient data transmissions. With a typical bandwidth of 180 kHz, the goal of providing cell access to 1.000.000 devices per km^2 is very challenging. Besides enabling communication for a massive number of devices, NB-IoT is also designed to enable a long battery lifetime, deep indoor penetration for flexible device placement as well as a latency not exceeding 10 s.

Unlike common Low Power Wide Area Network (LPWAN) solutions like LoRaWAN, NB-IoT transmissions are centrally coordinated and scheduled for minimizing the risk of transmission collisions and thus optimizing the cell capacity. Scheduling produces a large control overhead for each transmission, which is contra-productive in terms of efficient transmissions. Therefore, NB-IoT has been optimized, using features such as Radio Resource

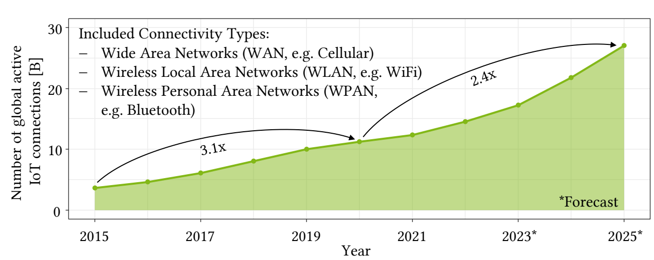

Figure 1: Forecast of IoT Growth for Different Connectivity Types [15]

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Control (RRC) Connection Resume procedure and Cellular Internet of Things Optimization (C-IoT-Opt) transmission mode. With every release, new features are added for more efficient transmission. With 3rd Generation Partnership Project (3GPP) Rel. 15, a new transmission mode called Early Data Transmission (EDT) has been introduced, which promises a huge step forward in minimizing the overhead of small data transmissions. All these features aim for reduced overhead, resulting in better energy and spectral efficiency in highly-scaled networks.

This work focuses on the implementation of a full NB-IoT protocol stack for realistic simulations, including an NB-IoT-specific scheduler, a new power consumption model, and features such as EDT and C-IoT-Opt. Therefore, this paper is organized as follows: Section 2 briefly outlines previous works on EDT, NB-IoT scalability evaluations, and simulation tools, while Section 3 gives a short overview of techniques for reduced signaling overhead and more efficient transmission in NB-IoT. Section 4 introduces a novel, detailed ns-3 LENA-NB extension for NB-IoT, which is used in this work. It is followed by an analysis of the NB-IoT performance in high-scaled networks in Section 5 and finally, the results are concluded in Section 6.

2 RELATED WORK

Since ns-3 has a good reputation in the research community, multiple projects and publications have started the integration of NB-IoT in the ns-3 LENA framework. However, they only focus on specific aspects of NB-IoT but have not been maintained over a long time and might not receive any additional functionalities in the future. The implementation in [22], with no commit since 2017, only includes the periodical transmission of Master Information Block Narrowband (MIB-NB) and System Information Block 1 - Narrowband (SIB1-NB). Accordingly, no connection or data transmission of NB-IoT User Equipment (UE)s can be simulated using the current implementation state. In [10] the authors analyzed the performance of NB-IoT and enhanced Machine Type Communication (eMTC) in smart city applications, especially in the context of battery life and power-saving features. Although the authors state their intention to release the source code as an open-source project, they do not provide any source code as part of this publication. Another analysis of NB-IoTs power-saving features is performed by the authors of [26]. As part of this work, an open-source project was published at [14]. In addition to a basic RRC layer state machine and paging, the project further implements a repetition-based transmission and the differentiation between physical NB-IoT channels. Still, it does not consider Narrowband Physical Downlink Control Channel (NPDCCH) search spaces and Hybrid Automatic Repeat Request (HARQ) resources for the communications and reduces the Modulation and Coding Scheme (MCS) to Quadrature Phase Shift Keying (QPSK), which results in incorrect Transport Block Size (TBS). According to these simplifications, this implementation is lacking a critical portion of NB-IoTs latency overhead.

3 FUNDAMENTALS OF NB-IOT

The growing number of IoT devices with low requirements on data rate but high requirements on efficiency and communication range has led to the development of Cellular IoT communication solutions, which has been introduced in 2016 as NB-IoT and eMTC. While eMTC is designed to operate in existing LTE networks by using legacy LTE signaling, NB-IoT is more flexible. Three operation modes allow NB-IoT an independent network operation in existing LTE networks, in guard bands, and standalone. With only 180 kHz bandwidth it can easily operate in-band using a single Resource Block (RB) in existing LTE networks or can be deployed in unused guard bands between LTE cells. The third operation mode is standalone, independent of any network. This flexibility makes it easily deployable, which is why NB-IoT networks can already be found in many countries around the world [13].

3.1 Coverage Enhancement

To take IoT-specific requirements on the networks into account, NB-IoT has been designed to extend the network coverage to a Maximum Coupling Loss (MCL) of 164 dB. Figure 2 gives an overview of typical communication ranges of different technologies.

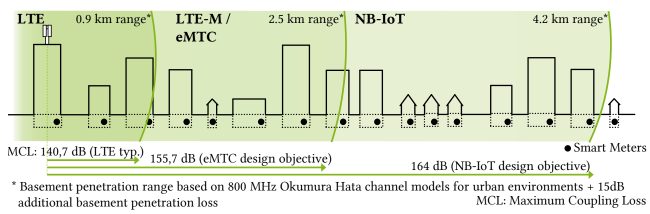


Figure 2: Maximum Coupling Loss of NB-IoT Compared to Other Cellular Networks [2][3]

While LTE is typically limited to an MCL of 140.7 dB [2], NB-IoT is designed to extend the MCL to 164 dB, based on the proposed objectives in [3]. Using an empirical channel model for urban environments with additional 15 dB basement penetration loss [21], the communication range of basement-installed NB-IoT devices can be extended from approx. 1 km to over 4 km compared to LTE devices. To achieve this, NB-IoT uses up to 2048 repetitions of a single transmission, as well as a small bandwidth of only 180 kHz in Downlink (DL) direction and down to 3.75 kHz in Uplink (UL) direction.

3.2 Battery Lifetime Extension

IoT devices are often known to be battery-powered, which makes energy-efficient communication mandatory. With NB-IoT, new power-saving techniques are introduced (ref. Figure 3).

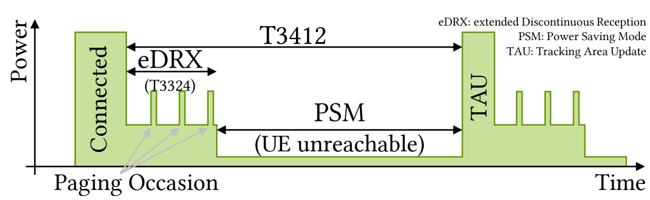


Figure 3: NB-IoT Transmission Cycle Including New Power Saving Techniques eDRX and PSM

3.2.1 extended Discontinuous Reception (eDRX). With Discontinuous Reception (DRX), devices don't need to consistently monitor the DL for upcoming transmissions but use paging occasions, in which they listen to upcoming transmissions. This way, the device can use a low power mode between these paging occasions and save energy. NB-IoT supports a new mode called eDRX, which can be configured with a DRX cycle just below 3 h [4], enabling devices with low requirements on latency even more energy efficiency.

3.2.2 Power Saving Mode (PSM). In addition to eDRX, an ultra-low-power mode has been introduced, called PSM, which is defined in [1]. After a timer defined by T3324 expires, the UE can switch into PSM, in which it shuts off most of its hardware for a typical power consumption of only 13 μW [23]. It remains unreachable for the network until mobile-originated data is available or the timer T3412 expires and triggers a Tracking Area Update (TAU). The device can remain over a year in PSM.

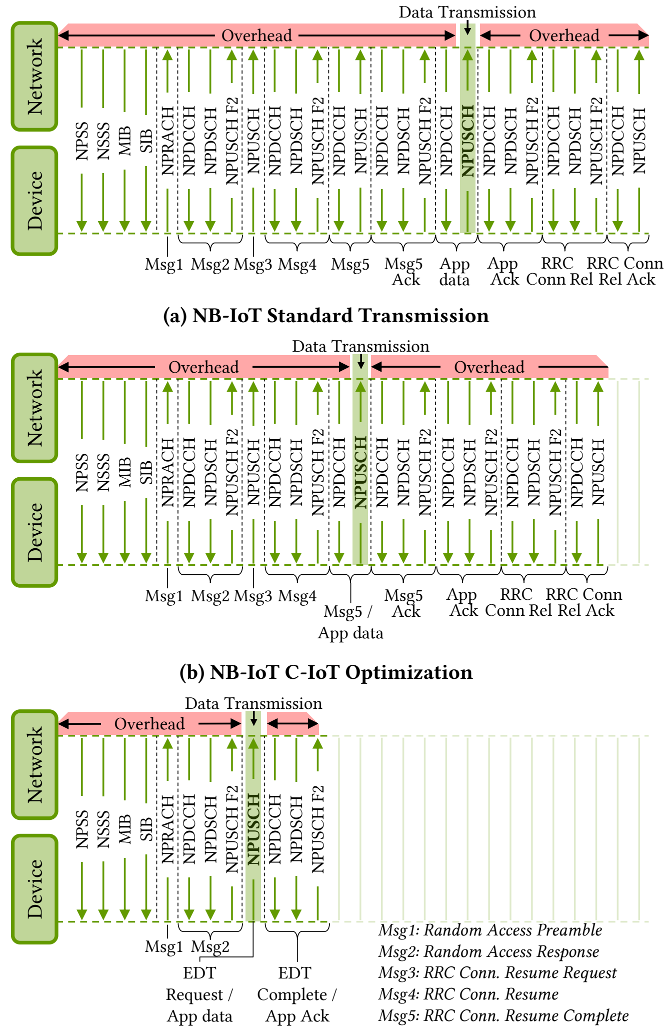
3.3 Scalability Optimization

Besides energy efficiency, spectral efficiency is addressed as well in NB-IoT. Since most devices only transmit several Bytes of data per message, the ratio of signaling overhead to application data is very high usually. Therefore, NB-IoT provides new techniques for more efficient transmission of small data. Since spectral efficiency optimizations reduce overhead, it has a positive impact on energy consumption and eventually battery lifetime.

3.3.1 RRC Resume Procedure. NB-IoT doesn't provide an Uplink Control Channel, which means for indication of new uplink data an RRC Resume procedure needs to be performed. Since the UE has been connected before, its AS context has been stored after the connection has been suspended. With the new RRC Resume procedure, this context is restored. Before the user data is transmitted, the connection setup is now limited to 5 messages, which are defined in [5]. The message sequence chart of this new procedure is shown in Figure 4a.

3.3.2 C-IoT-Opt. Besides a relaxed RRC Resume procedure, with Control Plane (C-Plane) C-IoT-Opt an additional small data optimization is introduced with NB-IoT. Usually user data is transmitted after the RRC connection is (re-)established. With C-IoT-Opt, data exchange between the UE and the evolved Node B (eNB) is already possible on RRC level. In DL direction, application data may be piggybacked in the Msg4 as a dedicatedInfoNAS Information Element (IE). In UL direction, application data may be piggybacked in the Msg5, again as a dedicatedInfoNAS IE [24] (ref. Figure 4b).

3.3.3 EDT. With EDT, introduced in 3GPP Release 15, an idle mode UE is able to already transmit data in Msg3, which is called RRCEarlyDataRequest in EDT [8]. When the UL data is successfully transmitted, the Random Access (RA) procedure is terminated by a RRCEarlyDataComplete message, which itself can also transport downlink data, like an application acknowledgement. The UE does not transition to connected mode unless the Mobility Management Entity (MME) or eNB decides to move the UE to connected mode. The EDT is granted by using a pre-configured set of Narrowband Physical Random Access Channel (NPRACH) resources for its preamble transmission [12][7]. The impact of EDT can be seen



(a) NB-IoT Standard Transmission

(b) NB-IoT C-IoT Optimization

(c) NB-IoT EDT

Figure 4: Control Message Overhead for Different Types of NB-IoT Data Transmissions

in Figure 4c. Compared to the NB-IoT standard transmission in Figure 4a and the C-IoT-Opt transmission in 4b, EDT is much more lightweight, which will increase spectral and energy efficiency.

4 IMPLEMENTATION OF LENA-NB

In 2016, NB-IoT has been introduced in 3GPP Release 13. Since its release, several scientific works have addressed the performance of NB-IoT UEs, but only a few have taken into account the interaction of multiple UEs. With EDT, a promising feature for better energy and spectral efficiency has been introduced in 3GPP Rel. 15. To perform a comparison of these different transmission modes, a powerful simulation framework is required. While related works can't provide detailed models of the NB-IoT cellular radio access technology, we have implemented NB-IoT, including the transmission modes C-IoT-Opt and EDT, using the LENA framework of ns-3

[9] as a base, which is known for its good reputation in the research community. This section will give an overview of the NB-IoT implementation of LENA-NB. The source code of LENA-NB is provided in [11] and will be extended by additional features in the future.

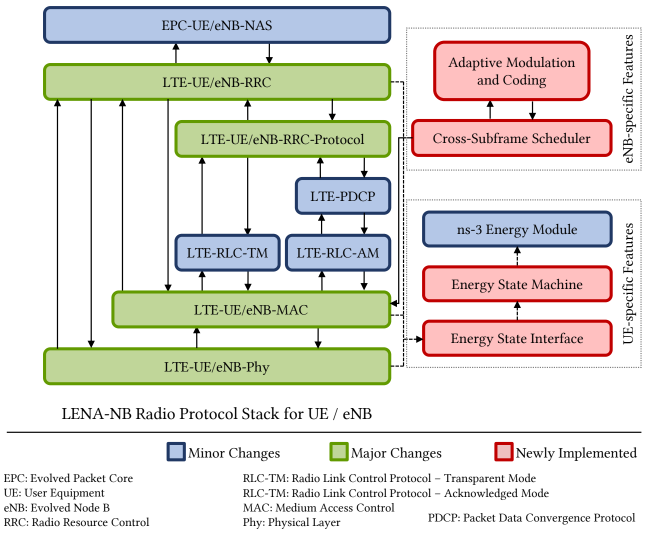


Figure 5: Overview over the Different Modifications Made in LENA-NB Compared to LENA

Figure 5 gives an overview of the changes made in the LENA protocol stack. Although NB-IoT is derived from LTE, major changes have been implemented in the radio interface. Unlike eMTC, which uses existing LTE signaling and channels, NB-IoT is designed for a narrowband operation, in co-existence with other Radio Access Network (RAN)s, or standalone, and therefore requires individual signaling. Additionally, the new features for efficient communication need to be taken into account.

4.1 Connection Resume Procedure

Since the Connection Resume procedure is a main component of NB-IoT, this procedure was implemented close to the already implemented RRC Connection Setup procedure. The UE needs a resume ID transmitted in the previous RrcConnectionRelease-NB message to initiate the Connection Resume procedure, but currently, LENA has not entirely implemented the connection release. Therefore the first step was to implement the RRC Release procedure. Using a newly implemented data inactivity timer, the UeManager keeps track of the last transmission. When the timer expires, the UeManager starts the RRC Connection Release procedure, in which UE-specific entities are saved and mapped to a resume ID, but the Cell-Radio Network Temporary Identifier (C-RNTI) must be released. Next, the LteEnbRrc cancels all pending events of the UE and removes the remaining information. When the UE receives the RrcConnectionRelease-NB message, it saves the received resume ID, notifies the upper layer about the released connection, and switches from the CONNECTED state to the IDLE state (or power-saving).

When a suspended device later wants to reconnect to the cell, it issues an RA. If the RA succeeds, the LteUeRrc then evaluates if it has a saved resume ID. In the case of a saved resume ID, it applies the newly received C-RNTI to its Signalling Radio Bearer (SRB)s and Data Radio Bearer (DRB)s. It then issues the transmission of the RrcConnection-ResumeRequest-NB message containing the resume ID using the SRB0. On reception, the LteEnbRrc layer first checks its suspend table for the received resume ID. If the ID is found, the LteEnbRrc layer resumes the UeManager and further advises every layer to resume the associated components and update their C-RNTI to the current one. Additionally, it has to delete the UeManager created by the RA procedure. Next, the UeManager transmits the RrcConnectionResume-NB message, if the RRC resume procedure is permitted. Otherwise, it sends an RrcConnectionSetup or RrcConnectionReject, and the UE reacts accordingly. The LteUeRrc further responds with the RrcConnectionResumeComplete-NB message and thereby completes the resume procedure.

4.2 Cellular IoT Optimization

The next implemented NB-IoT improvement in LENA-NB is C-IoT-Opt. As discussed in Section 3.3.2, it allows user data to be transmitted in the RRC Resume procedure. While this allows lower complexity and lower device costs, the implementation focuses on piggybacking user data to the RRC messages. To implement C-IoT-Opt, mainly the LteUeRrc, and the LteEnbRrc are modified. First, the LteUeRrc evaluates if it can use C-IoT-Opt and if the additional data would fit into the Msg5. Usually, the transmission over the control plane would still differ from the data plane, but the main focus of this implementation is the reduced signaling overhead on the air interface.

When Msg3 is passed to the LteRlcTm, the LteUeRrc also notifies the LteUeMac about the payload size of the upcoming Msg5. The LteUeMac then updates the Data Volume and Power Headroom Report (DPR) of Msg3 to advise the LteEnbMac to grant a larger uplink opportunity. When sending Msg5, the upper-layer packet, saved in the dedicatedInfoNas field of the Msg5 struct, is appended to the ns-3 packet by the LteUeRrcProtocol. It is not parsed as an ASN.1 octet string due to the high complexity of parsing an octet string of unknown size in a statically typed programming language like C++. On the LteEnbRrcProtocol, a trick can be used. Due to LENAs implementation and by sticking to its guiding principle in LENA-NB, every layer of the LteEnb protocol stack removes its related headers. Accordingly, when the ns-3 packet reaches the LteEnbRrc layer, every NB-IoT header is removed, allowing the LteEnbRrc to pass the packet to its upper layers the same way as if it received it over a DRB. To not modify the following Evolved Packet System (EPS) stack, the LteEnbRrc layer adds a temporary EPS Byte-Tag to the packet, pretending it is a packet received over a DRB. The packet is then forwarded to the EPS.

4.3 Early Data Transmission

As a promising candidate for a significant performance improvement, EDT was also implemented into LENA-NB. Due to EDT using its own NPRACH resources, first, the System Information Block 2 - Narrowband (SIB2-NB) in LteEnbRrc was extended by parameters like the EDT TBS, and the specific NPRACH resources. After examining if EDT qualifies for transmitting the size of the available user data, the LteUeRrc stores the data and instructs the LteUeMac to start an EDT RA. When the LteEnbMac detects an EDT preamble, it triggers a normal Random Access Response (RAR) but increases its TBS to the one advertised in the SIB2-NB. If the LteUeMac receives an uplink grant with a TBS greater than 88 bit of a standard Msg3, it assumes that the EDT is granted, and notifies higher layers. Otherwise, if the LteEnbMac only grants a TBS of 88 bit, the LteUeMac assumes that it should use the legacy RRC Connection Resume procedure instead. On the notification that the EDT was granted, the LteUeRrc prepares an EarlyDataRequest struct (again implemented conform to its ASN.1 definition), fills in the necessary information, and appends the data packet again as the dedicatedInfoNas element. Then the LteUeRrcProtocol converts the struct to an EarlyDataRequest-NB message and transmits it using the SRB0.

On the LteEnbRrc, the reception procedure proceeds equivalent to the C-IoT-Opt procedure. Further, it was assumed that the LteEnbRrc awaits a potential downlink message for the UE, which is then appended to the EarlyDataComplete-NB message. For this implementation, it was assumed that the received data wouldn't exceed the downlink TBS. After the UE receives the EarlyDataComplete-NB, the connection is terminated and the UE switches back in IDLE mode.

4.4 Further NB-IoT Specific Modifications of LENA

Besides implementing the new transmission modes of NB-IoT, several additional modifications were made for NB-IoT compliance. The most relevant are listed below.

4.4.1 Cross-Subframe Scheduling. To allow low-complexity devices, NB-IoT uses cross-subframe scheduling. Since the UEs are designed for half-duplex operation and thus are not able to simultaneously transmit and receive data, time gaps are used between UL and DL transmissions for changing the transceiver frequency. Additionally, since Downlink Control Information (DCI) and the scheduled data transmission do not occur in the same subframe, NB-IoT UEs benefit from relaxed processing time requirements [17].

In DL and UL direction, repetitions are used for more robust communication. The long timespan of a single transmission needs to be taken into account by the scheduler, as well as the different lengths of an UL Ressource Unit (RU), depending on the scheduled bandwidth. Figure 6 gives an overview of a typical scheduling example, which demonstrates timings between UL and DL transmissions.

Since available LTE schedulers do not provide support cross-subframe scheduling, a new scheduler has been implemented in LENA-NB.

4.4.2 Adaptive Modulation and Coding. Currently, LENA-NB does not provide an NB-IoT specific error model. Instead, a lookup table was generated using MATLAB NB-IoT Block Error Rate (BLER) simulations [19][20]. Depending on the TBS size and channel conditions, UL and DL configurations, which meet the BLER requirements, are derived from this table and used in the simulations. Although it is planned in the future to implement an NB-IoT-specific error model, using a lookup table instead of a detailed error model had a great impact on the simulation performance of large-scale scenarios, which are discussed later.

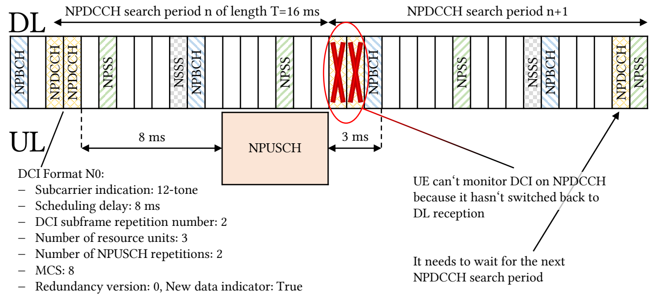


Figure 6: Example of an UL Data Transmission With Cross-Subframe Scheduling [17]

4.4.3 Energy State Machine. The RRC level was enhanced to support the new power-saving techniques eDRX and PSM. The UE can now additionally switch into three new IDLE states EARLY_DATA_-TRANSMISSION, SUSPEND_EDRX, SUSPEND_PSM, and the CONNECTION_RESUME state.

Using the ns-3 energy module, an NB-IoT energy state machine has been implemented. For a detailed energy consumption analysis, the UE uses this state machine to keep track of the following energy states: Sending NPRACH, Receiving NPDCCH, Receiving NPDSCH, Sending NPUSCH, Sending NPUSCH F2, as well as eDRX and PSM. Taking real network power consumption of a Quectel BG95 NB-IoT/eMTC module [23] into account, a corresponding discharge of the device's battery is simulated.

5 EVALUATION

For realistic simulations and a good transferability to the real world, we extracted NB-IoT Radio Resource Configurations from public NB-IoT networks in Germany, using an Ettus USRP B210 with srsRAN [25] and used the parameters in our simulation (Table 1).

5.1 Validation of LENA-NB

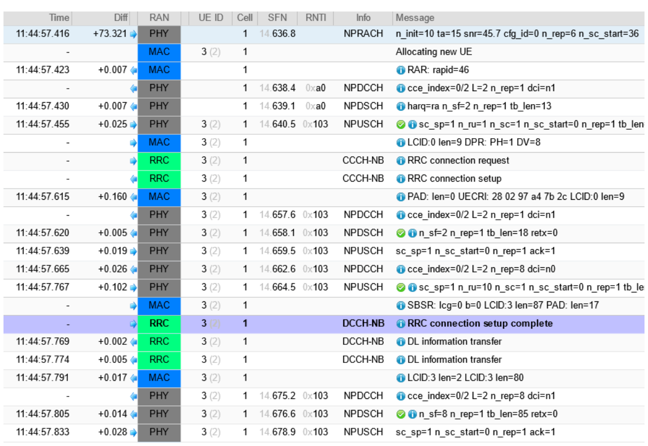
Compared to other IoT networks such as LoRaWAN, NB-IoT uses a rather complex data transfer procedure, including RA, RRC procedures, and different shared channels. Therefore, the message sequence and allocation of a growing number of Transport Block (TB)s for an increasing data size is examined in the following.

5.1.1 Message Sequence Validation. To validate the implemented message sequence of a Mobile Originated (MO) user data transfer with the RRC Resume procedure, we set up an NB-IoT network using an Amarisoft Callbox Classic. Along with the identical parametrization used in the simulations, data transmissions are logged on different layers and compared to the transmissions logged in the LENA-NB simulation framework. Figure 7 shows the Amarisoft log of an uplink transmission. The results have validated the implemented RRC Resume message sequence in LENA-NB, since both message traces are identical.

5.1.2 Segmentation of User Data. As defined in 3GPP Release 13, NB-IoT supports TB sizes of 1000 bits in UL direction and 680 bits in DL direction [6]. When the data exceeds the available TBS, the data is segmented and transmitted in multiple TBs. To ensure the data segmentation and the scheduling of multiple TBs based on the

Table 1: Release 13 NB-IoT Radio Resource Configuration Derived from Public NB-IoT Network

Parameter	CE0	CE1	CE2
rsrp-Thresholds-PrachInfoList-r13	-	-116 dBm	-128 dBm
nprach-Periodicity-r13	ms320	ms640	ms2560
nprach-StartTime-r13	ms256	ms256	ms256
nprach-SubcarrierOffset-r13	n36	n24	n12
nprach-NumSubcarriers-r13	n12	n12	n12
nprach-SubcarrierMSG3-RangeStart-r13	twoThird	twoThird	twoThird
maxNumPreamble-AttemptCE-r13	n10	n10	n10
numRepetitionsPer-PreambleAttempt-r13	n1	n8	n32
npdcch-NumRepetitions-RA-r13	r8	r64	r512
npdcch-StartSF-CSS-RA-r13	v2	v1dot5	v4
npdcch-Offset-RA-r13	zero	zero	zero



Time	Diff	RAN	UE ID	Cell	SFN	RNTI	Info	Message
11:44:57.416	+73.321	PHY		1	14.636.8		NPRACH	n_init=10 ta=15 snr=45.7 cfg_id=0 n_rep=6 n_sc_start=36
-		MAC	3 (2)	1				Allocating new UE
11:44:57.423	+0.007	MAC		1				RAR: rapid=46
-		PHY		1	14.638.4	0xa0	NPDCCH	cce_index=0/2 L=2 n_rep=1 dci=n1
11:44:57.430	+0.007	PHY		1	14.639.1	0xa0	NPDSCH	harq=ra n_sf=2 n_rep=1 tb_len=13
11:44:57.455	+0.025	PHY	3 (2)	1	14.640.5	0x103	NPUSCH	sc_sp=1 n_ru=1 n_sc=1 n_sc_start=0 n_rep=1 tb_len
-		MAC	3 (2)	1				LCID:0 len=9 DPR: PH=1 DV=8
-		RRC	3 (2)	1			CCCH-NB	RRC connection request
-		RRC	3 (2)	1			CCCH-NB	RRC connection setup
11:44:57.615	+0.160	MAC	3 (2)	1				PAD: len=0 UECRI: 28 02 97 a4 7b 2c LCID:0 len=9
-		PHY	3 (2)	1	14.657.6	0x103	NPDCCH	cce_index=0/2 L=2 n_rep=1 dci=n1
11:44:57.620	+0.005	PHY	3 (2)	1	14.658.1	0x103	NPDSCH	n_sf=2 n_rep=1 tb_len=18 retx=0
11:44:57.639	+0.019	PHY	3 (2)	1	14.659.5	0x103	NPUSCH	sc_sp=1 n_sc_start=0 n_rep=1 ack=1
11:44:57.665	+0.026	PHY	3 (2)	1	14.662.6	0x103	NPDCCH	cce_index=0/2 L=2 n_rep=8 dci=n0
11:44:57.767	+0.102	PHY	3 (2)	1	14.664.5	0x103	NPUSCH	sc_sp=1 n_ru=10 n_sc=1 n_sc_start=0 n_rep=1 tb_le
-		MAC	3 (2)	1				SBSR: lcg=0 b=0 LCID:3 len=87 PAD: len=17
-		RRC	3 (2)	1			DCCH-NB	**RRC connection setup complete**
11:44:57.769	+0.002	RRC	3 (2)	1			DCCH-NB	DL information transfer
11:44:57.774	+0.005	RRC	3 (2)	1			DCCH-NB	DL information transfer
11:44:57.791	+0.017	MAC	3 (2)	1				LCID:3 len=2 LCID:3 len=80
-		PHY	3 (2)	1	14.675.2	0x103	NPDCCH	cce_index=0/2 L=2 n_rep=8 dci=n1
11:44:57.805	+0.014	PHY	3 (2)	1	14.676.6	0x103	NPDSCH	n_sf=8 n_rep=1 tb_len=85 retx=0
11:44:57.833	+0.028	PHY	3 (2)	1	14.678.9	0x103	NPUSCH	sc_sp=1 n_sc_start=0 n_rep=1 ack=1

Figure 7: Amarisoft Message Sequence Chart of an Acknowledged Uplink Data Transmission

buffer status, a small-scale analysis with increasing message sizes was performed (cf. Figure 8).

For this analysis, the parameters Transport Block Size Index (TBSI), number of repetitions, as well as number of subframes in DL direction and number of resource units in UL direction was set to the parameters for a Coupling Loss (CL) of 154 dB, given in [17]. For UL TB sizes up to 125 Bytes, data can be carried in a single TB. Since C-IoT-Opt carries its data in Msg5, less TBS is available for user data and thus C-IoT-Opt adds an additional TB to its user data transmission just below a payload of 125 Bytes. For EDT, the procedure is only granted to a maximum size of 1000 bits, or 125 Bytes. If the data exceeds this limit, EDT falls back to C-IoT-Opt, which can be seen in Figure 8. Finally, the stepwise increase of

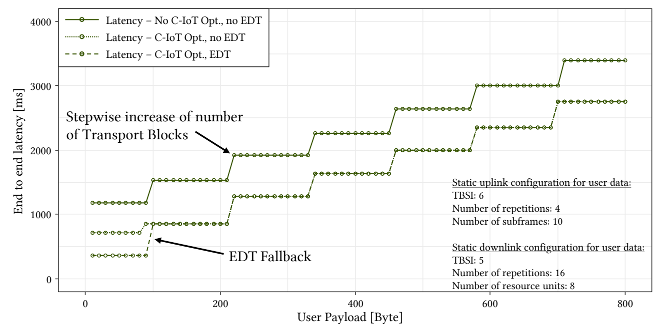


Figure 8: Latency Results for a Single Device with Increasing Message Size

the number of transport blocks is presented through the stepwise increase in latency. All results meet the expected behavior of the different transmission modes.

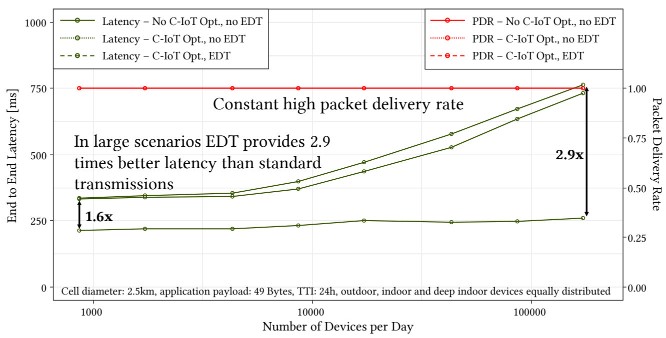
5.2 Scalability Results

As stated in Section 4, the motivation for the implementation of LENA-NB was to allow performance comparisons of different transmission modes of NB-IoT in large scenarios. This section gives an overview of the first results derived from scenarios with over 100.000 transmitting devices per day in LENA-NB. In each scenario UEs are distributed on a disc with a cell area of 4.91 km^2, or a radius of 2.5 km, which is the average cell size in the city of Dortmund, Germany, and derived from the Dortmund mobile radio register [27].

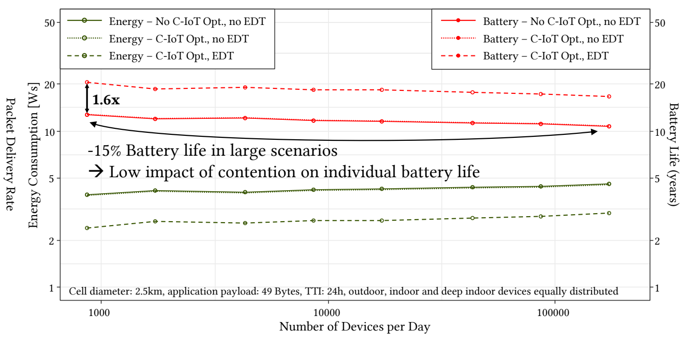
The devices are distributed equally over three different coverage conditions: 1/3 of all devices are considered to be placed outdoors (height 1.5 m), while 1/3 are indoor and 1/3 are deep indoor (basement) devices. In respect of indoor and deep indoor placement, the device's path loss, calculated using the Winner+ UMaNLOS channel model, is supplemented with additional building entry losses (15.4 dB for indoor and 20.9 dB for deep indoor), which are derived from [21].

For all scenarios, 15 minutes of simulation time are simulated, but only the intermediate 5 minutes are evaluated in the following. The first 5 minutes produce no significant results since devices at the beginning are scheduled in an empty cell and experience very good transmission conditions. After 5 minutes, new devices will find ongoing transmissions of previous devices, which enables a more realistic situation and produces significant results. Since devices that have started transmissions within the intermediate 5 minutes of the simulation may not complete their transmissions in this intermediate time slot, additional 5 minutes are simulated with more new transmissions to keep the channels busy and let the intermediate devices complete their transmissions.

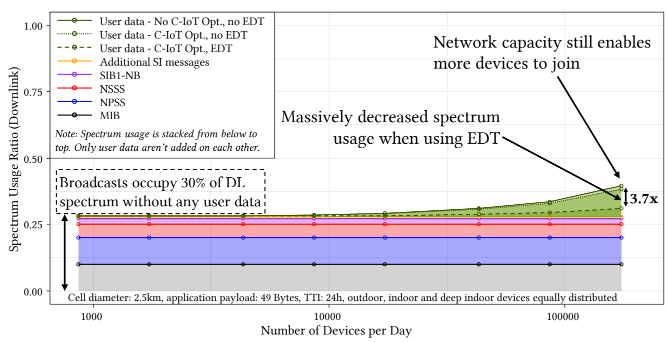
In our simulations scenarios with different number of devices are simulated, ranging from 9 to 1.800 devices per cell within the 15 minutes simulation time, which result in a total of 864 devices per cell daily in small scenarios to 172.800 devices per cell in the largest scenario. With randomly distributed transmission start times, each scenario size and configuration is simulated with up to 15 different seeds. Due to the high number of devices and associated events, the



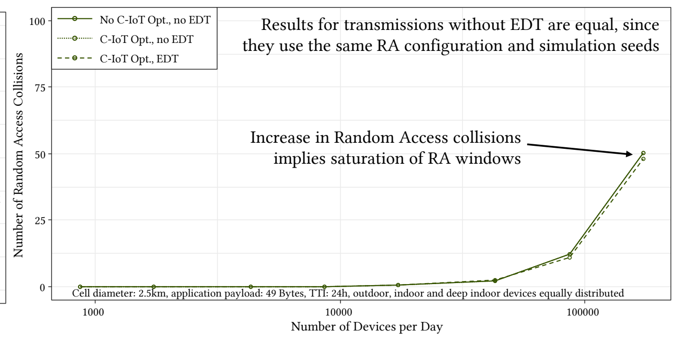
(a) Latency and Packet Delivery Rate



(b) Energy Usage and Battery Life



(c) Downlink Spectrum Usage



(d) Random Access Collisions

Figure 9: Scalability performance of NB-IoT Transmissions

largest simulation with 1.800 devices per cell ran for approx. 116 minutes per seed on an Intel Core i5-6500 CPU with 24 GB RAM along with the optimized build profile.

5.2.1 Latency, Packet Delivery Rate and Energy. Figure 9a shows the results for the average end to end latency and Packet Delivery Rate (PDR) results using the NB-IoT Radio Resource configuration given in Table 1. For configurations without EDT, an increasing latency can be noted starting at approx. 9.000 devices per cell. Since all devices use the same shared channels, one device needs to wait for other devices to pause or finish their transmissions, before it can be scheduled. While C-IoT-Opt can only slightly lower the average latency, EDT outperforms all other configurations with an up to 2.9 times lower latency.

The impact of EDT on the user performance is also noticeable in the battery life (cf. Figure 9b). When comparing the battery life of small and large scenarios, the impact of high-scaled networks is limited. While the drastically increased latency in large scenarios mostly depends on long scheduling pauses, the device can remain in a low power idle state and thus save energy, which only decreases the battery lifetime by 15% in large scenarios. When EDT is used, the battery life is extended by a factor of 1.6. This has a great impact on most IoT business models, since IoT devices may only need maintenance every e.g. 16 years instead of every 10 years.

5.2.2 Spectrum Usage. Since most IoT use cases are tolerant to increased latency, the increased battery life is a more important factor when evaluating the impact of EDT on the user performance. Besides application-specific metrics like latency and battery life, spectral efficiency needs to be considered as well, since an increased spectral efficiency results in a more scalable network.

Figure 9c shows the DL spectrum usage. Without any user data, DL broadcasts like Master Information Block (MIB), Narrowband Primary Synchronisation Channel (NPSS), Narrowband Secondary Synchronisation Channel (NSSS), SIB1-NB and additional System Information (SI) messages already occupy 30% of the downlink spectrum, leaving only 70% for user-specific DL transmissions. As expected, with an increasing number of devices the spectrum usage ratio increases. Since EDT reduces the overhead of small data transmissions (cf. Section 3.3.3), the spectrum usage is reduced as well compared to non-EDT scenarios. A decreased spectrum usage by a factor of 3.7 will results in an 3.7 fold increased cell capacity. Therefore, the usage of EDT is highly recommended.

Though, the cell capacity is not only limited by the DL spectrum, but also by the UL spectrum. Although the UL does not carry any broadcasts, the available spectrum is reduced by the configurable RA windows. These RA windows preoccupy UL spectrum, whether the windows are used for RA or not. Therefore, a tradeoff between a sufficient interval RA windows and spectrum for application data has to be made. With the configuration in our simulations (cf. Table 1), the RA windows are well-configured, since only a few RA collisions occur in the largest scenario (cf. Figure 9d). Since the RA procedure supports retransmissions when a collision occurs, the PDR in Figure 9a is still at 100%. Still, when the number of devices per day is further increased, RA collisions will increase as well and prevent devices to perform cell access. In this case, the RRC configuration has to be optimized.

All in all, the simulation results show good scalability results in a cell with an area of 4.91 km^2 for all NB-IoT standard, C-IoT Opt, and EDT scenarios. When the results of all different NB-IoT transmission modes are compared, EDT clearly outperforms C-IoT-Opt and standard transmission without EDT and C-IoT-Opt in terms of latency, energy efficiency, and especially spectral efficiency. Therefore, EDT is highly recommended from an application and network operator perspective.

6 CONCLUSION

With NB-IoT, a promising solution of cellular IoT networks has been introduced to face the challenges of small IoT devices. Introduced in 3GPP Release 13, it is still an object of improvement and is optimized with new features such as Early Data Transmission, which drastically reduces the signaling overhead of small data transmissions. In this work, we have introduced the implementation of NB-IoT into ns-3, based on the existing implementation of LTE. In addition to standard transmission capabilities, optimized NB-IoT features such as Cellular-IoT C-Plane Optimization, Early Data Transmission as well as an improved Connection Resume procedure are integrated into the new LENA-NB framework. For realistic modeling of NB-IoT, a new scheduler for cross-subframe-scheduling, a lightweight adaptive modulation and coding feature as well as an extended energy state machine has been implemented. LENA-NB then was used for a performance comparison of the different NB-IoT transmission modes, standard, Cellular-IoT C-Plane Optimization, and Early Data Transmission, in large-scale scenarios. The simulation results show a good scalability for all NB-IoT standards, C-IoT Opt, and EDT scenarios. All in all, the results have shown that Early Data transmission is highly recommended to be used per default, since it provides 2.9 times less latency as well as 3.7 times less spectral usage in the largest scenarios. When it comes to energy efficiency, EDT can increase the individual battery life by a factor of 1.6. In future work, additional features will be integrated into LENA-NB, including an advanced scheduler for multi-tone uplink transmissions, support for non-anchor carriers, and wake-up signals. Additionally, the scalability boundaries of the different NB-IoT transmission modes are evaluated in scenarios with 1.000.000 devices and more.

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