Exploiting NB-IoT Network Performance and Capacity for Smart-Metering Use-Cases

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***Abstract*—The requirements introduced in directive 2019/944 of the European Parliament for the smart metering scenarios, which differ from the ones defined in ITU-R M.2410, accelerated the integration of cellular technologies for the Internet of Things (IoT). Requiring a permanent connection to the cellular network (radio resource control in a connected state) and more synchronous-oriented data transmissions led to selecting the Narrowband IoT (NB-IoT) technology as the main enabler for the secured data transmissions. This paper focuses on the features introduced by 3GPP in Release 13, i.e., user plane and control plane optimization, and Release 15 early data transmissions (EDT) for the smart metering scenarios. Our simulation results confirm that EDT is a powerful feature for decreasing transmission delay and improving spectrum efficiency with reduced overheads. Our results show that the transmission delay is reduced by over 50 %. Notably, the data indicates EDT significantly improves latency for smaller messages (for Release 13, less than 97 B in uplink and 57 B in downlink). Finally, the results confirm that an NB-IoT network (3GPP Release. 13; NB1) can manage 1000 smart meters per single base station communicating in a 15 minutes window.**

***Index Terms*—NB-IoT, Smart metering, Network performance, Network capacity, NS-3, LENA-NB**

I. INTRODUCTION

The European Parliament directive 2019/944 firmly defines that intelligent electricity meters are going to be rolled out across the European Union member states starting in 2024 [1], [2]. Once approved, this regulation put pressure on the electricity distributors and the telecommunication operators who are supposed to enable data transmissions via the new generation of wireless communication technologies. The use-case of smart metering, i.e., remote reading, monitoring, and management of the electricity meters, exceeds the requirements initially targeted to the Internet of Things (IoT) and Industry 4.0. As the smart metering scenario falls into the critical infrastructure, it must provide permanent (not only on-demand) connectivity to the electricity meters. On top of this, there are strict rules related to the maximum time the smart meters have to be accessible, e.g., in a blackout situation, all the electricity meters are supposed to be back online within 15 minutes [3].

The cellular technologies introduced by the 3rd Generation Partnership Project (3GPP), i.e., Narrowband-IoT (NB-IoT) and LTE Cat-M, are specifically designed to enable the massive Machine-Type Communication (mMTC). Nevertheless, the initial idea of asynchronous data transmissions is converted to more difficult synchronous scenarios in smart metering. Such applications require smart meters to have permanently established connectivity with the cellular network operating in a Radio Resource Control (RRC) connected state and polling smart meters over regular time intervals [4], [5]. This behavior eventually results in batch arrivals over the radio access part of the network, drastically increasing the latency at the air interface and not complying the mMTC requirements of 5G-IoT defined in ITU-R M.2410, i.e., 10^6 EDs/km^2 with the data transmission intensity of one packet per two hours with no more than 10 % losses [6], [7].

Considering the completely new set of requirements for the smart metering use-cases over the cellular IoT (CIoT) technologies, the telecommunication operators already started the performance evaluation of the CIoT technologies in question [8]. Nevertheless, the lack of fully functional smart meters equipped with the CIoT modules, as well as the level of integration of the CIoT technologies from the operators' side, limits the number of finished proof-of-concept trials, which results in the need to obtain the initial data from the simulations, i.e., create digital twins of the expected scenarios.

This paper focuses on the performance evaluation of the scenario with hundreds of smart meters (up to 1000) connected simultaneously to the NB-IoT network and communicating with the remote server (the head-end system). The simulations are conducted using the Network Simulator 3 (NS-3) with the LENA-NB module implementing features introduced in 3GPP Release 13 up to Release 15, i.e., user plane optimization, control plane optimization, and Early Data Transmissions (EDT). Aiming to cover the most important outputs for the real deployment of smart meters, we created two simulation scenarios differing in radio conditions, i.e., different Enhanced Coverage Level (ECL) classes.

The key outputs of our work can be summarized as follows:

- EDT decreases transmission delay and improves spectrum efficiency with reduced overheads. Our results indicate that the transmission delay is reduced by over 50 %, even with the message size exceeding the single packet payload in the downlink direction.

- NB-IoT network (defined by 3GPP Release 13) can manage 1000 UEs per single cell (base station) communicating in a 15 m window, even with basic UP optimization. Moreover, there is a sufficient buffer to serve thousands of devices distributed in 90 to 10 % for ECL0 and ECL1, respectively.
- Results show the importance of proper network settings, as even transmitting a perfectly suitable message of 64 B with EDT can introduce double the Random Access Procedure (RAP) collisions.

The rest of the paper is organized as follows. The description of the NB-IoT technology and its features is given in Section II. Then, we provide an in-detail description of the simulation scenario in Section III. Next, the simulation results are presented in Section IV together with the thorough discussion. Finally, we conclude the paper in the Section V.

II. Background and Rationale

The massive increase in mMTC over the course of the last decade resulted in the advent of new communication technologies collectively referred to as Low-Power Wide-Area Networks (LPWAN)s. These technologies, designed explicitly for infrequent transmission of small data blocks over large distances with minimum power consumption, allowed us to realize the vision of ubiquitous connectivity for wireless sensors. One of these technologies is NB-IoT, first introduced in 3GPP Release 13) in 2016 [9], [10].

NB-IoT is specifically designed to fulfill the LPWAN requirements of extended coverage up to 164 dB (+20 dB over legacy Long-Term Evolution (LTE) systems), prolonged battery life of more than ten years, and communication delay under 10 s. Because the significant part of the NB-IoT builds upon LTE numerology, it can be deployed in the same band as legacy LTE, occupying a 180 kHz spectrum chunk (matching one Physical Resource Block (PRB)) in in-band mode. It can also be deployed in the LTE guard band or a standalone channel of a global system for mobile communication (GSM) [10], [11].

The main goal of LPWAN, i.e., extended coverage, is achieved mainly through repetitions and utilization of low-rate Modulation Coding Schemes (MCS). Notably, the Narrowband Physical Random Access Channel (NPRACH) utilizing single-tone transmission with frequency hopping and 3.75 kHz subcarrier spacing can benefit from up to 128 repetitions. Furthermore, formats 0 and 1 using 66.67 μs and 266.7 μs cyclic prefixes allow up to 10 km and 40 km cell radius, respectively. Similarly, the uplink transmissions backed up by a Narrowband Physical Uplink Shared Channel (NPUSCH) may use up to 128 repetitions. NPUSCH can utilize 3.75 or 15 kHz spacing with $\pi/2$-BPSK or $\pi/4$-QPSK modulated signal to reduce Peak-to-Average Power Ratio (PAPR) in single-tone mode. Otherwise, 15 kHz spacing with QPSK modulation in multi-tone mode is used. The NPUSCH further allows up to 1000 bits Transport Block (TB) in Release 13 and up to 2536 bits in Release 14. Moreover, NPUSCH utilizes a Demodulation Reference Signal (DMRS) dedicated to channel estimation in the frequency domain [9], [10], [12].

Unlike the uplink consisting of NPRACH and NPUSCH, the downlink frame structure consists of up to eight distinct signals/channels and relies on 15 kHz spacing with QPSK modulation with a maximum TB of 680 bits (up to 2535 bites in Release 14). The Narrowband Reference Signal (NRS) is used to estimate download channel conditions needed for signal strength and quality measurements. Further, Narrowband Primary Synchronization Signal (NPSS) and Narrowband Secondary Synchronization Signal (NSSS) are designated to synchronize User Equipment (UE) with NB-IoT cell. Notably, they allow UE to detect the physical cell identity (PCI) by utilizing a synchronization algorithm during initial acquisition without the knowledge of deployment mode based on an 80 ms repetition interval in specific subframes [12]–[14].

Then, every 10 ms, the Master Information Block (MIB) is transmitted via the Narrowband Physical Broadcast Channel (NPBCH). On the other hand, the System Information Block (SIB) and UL grant and DL scheduling information are conveyed via a Narrowband Physical Download Control Channel (NPDCCH) with a basic Transmission Time Interval (TTI) of 1 ms. Finally, the actual unicast data from eNB to UE are transmitted via a Narrowband Physical Downlink Shared Channel (NPDSCH). The packets from the upper layer are segmented into one or more TBs and sent one by one [12], [13], [14], [9].

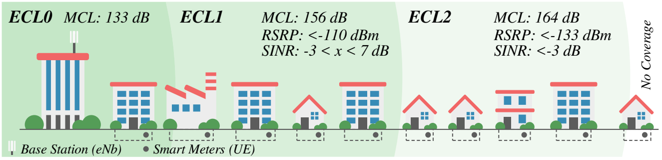

Fig. 1: Coverage enhancement levels.

A. Coverage Enhancement Levels

As mentioned in the previous section, the main idea behind extended coverage lies in repetitions. However, the prolonged range is redeemed by increased latency, which can easily overcome the limit of 10 s when the message is larger than the actual TB size. To tackle this issue, NB-IoT introduces three ECL classes in which the TB sizes and maximum number of repetitions for each channel are defined. As depicted in Fig. 1, each ECL has a threshold value where the system passes to the appropriate ECL. The Reference Signal Received Power (RSRP) and Signal-to-Noise Plus Interference (SINR) values determine the threshold levels. However, due to the impracticability of SINR estimation in simulations, only RSRP values are used. It must be noted that the ECL values are not fixed but can be changed based on network operator requirements [9].

B. Data Transport in Cellular IoT

With the ultimate goal of serving thousands of UEs with a single eNB, CIoT requires minimizing the signal overheads, especially in the Radio Access Network (RAN). To this aim, Release 13 introduced CIoT Evolved Packet System (EPS) optimization in both the Control Plane (CP) and User Plane (UP). Moreover, in Release 15, the Early Data Transmission (EDT) mechanism representing a significant improvement in spectrum utilization was introduced [14], [15].

1) User Plane Optimization: The NB-IoT technology introduced a new Radio Resource Control (RRC) resume procedure preceded by an initial RRC connection configuring the radio bearers and the Access Stratum (AS) security context. Then, the UP enables suspending the RRC connection, which the newly introduced *RRC Resume Procedure* can later resume [14], [15].

As depicted in Fig. 2, UE in the *RRC Idle* state stores the context at the UE, eNB, and Mobility Management Entity (MME) and uses it to resume the connection when there is new traffic. To resume the context, UE must provide a Resume ID used by eNB to access the stored UE data. It allows UE to avoid the AS security setup and RRC reconfiguration with each data transmission. Since optimization utilizes the user plane, subsequent communication can be realized via data paths. Thus, it can be used for short and long data transactions [15], [14].

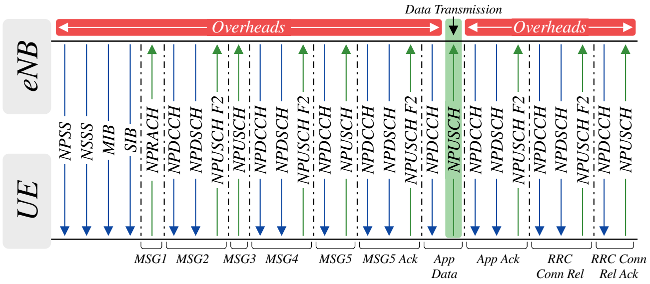

Fig. 2: NB-IoT: User Plane Optimization.

2) Control Plane Optimization: In this optimization, UE utilizes the CP to forward data packets encapsulated in Non-Access Stratum (NAS) signaling messages to the MME. Thanks to this optimization, UE avoids the AS security setup and UP bearer establishment; see Fig. 3. Thus, it is more suitable for short data transfers [14], [15].

The uplink data from UE in the NAS signaling can include a Release Assistance Information (RAI), which allows UE to notify the MME that (i) no further data transmissions are expected, (ii) single downlink data transmission succeeding this message is expected. In these cases, MME can immediately call the release procedure, reducing the period of UE waiting for possible data transmission [14], [15].

3) Early Data Transmission: With the advent of NB-IoT Release 15, the UE in idle mode can transmit messages during the MSG3 called *RRC Early Data Request* in early data transmission (EDT). In case of successful uplink transmission, the RAP can be exited by the *RRC Early Data Complete* message. Notably, this message alone may contain downlink data, such as application acknowledgment. As a result, UE does not have transit to a connected state unless MME or eNB decides otherwise. The EDT is allowed by using a pre-configured set of NPRACH resources, and the overhead reduction of EDT can be seen in Fig. 4 [12], [14], [15].

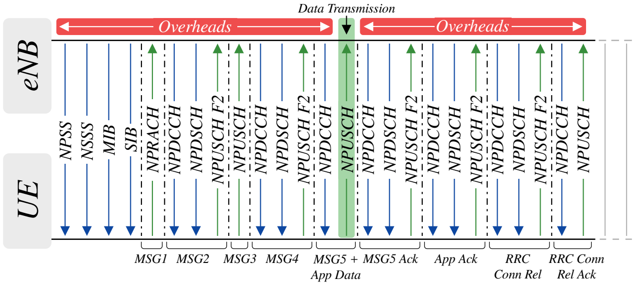

Fig. 3: NB-IoT: Control Plane Optimization.

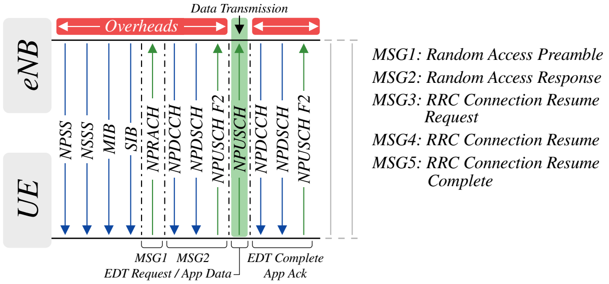

Fig. 4: NB-IoT: Early Data Transmission.

C. Data Transmission Mechanisms

The eNB indicates downlink data transmission to UE through the Downlink Control Indicator (DCI) message in NPDCCH. However, the NB-IoT UEs are designed with reduced computational capability; the time offset of at least 4 ms is used between the end of NPDCCH and the beginning of NPDSCH. Once the data contained in NPDSCH is received, 4 ms of decoding is expected in good radio conditions with MCS 10 and TB of 680 bits. After at least 12 ms, a Hybrid Automatic Repeat Request (HARQ) message with acknowledgment of transmission is conveyed via NPUSCH. If more data needs to be sent, UE has to wait 3 ms before listening for NPDCCH. The whole process combining DCI and NPDCCH is depicted in Fig. 5. Thus, the expected throughput in downlink can then be derived as follows:

$$\begin{aligned}T &= TB_{Max}/(\mathrm{NPDCCH}+\mathrm{NPDSCH}+\mathrm{NPUSCH}+Off)\\ &= 680/(1+4+2+(4+12+3)) = 26.15\ kbps,\end{aligned} \tag{1}$$

which is, however, valid only for NB-IoT in Release 13 as the newer releases brought the possibility to utilize larger TB and two HARQ processes improving maximum throughput up to 127 kb/s [13], [16].

In the uplink direction, when the UE receives signaling about the scheduled grant via DCI in NPDCCH, it takes at least 8 ms before the device sends uplink data via NPUSCH.

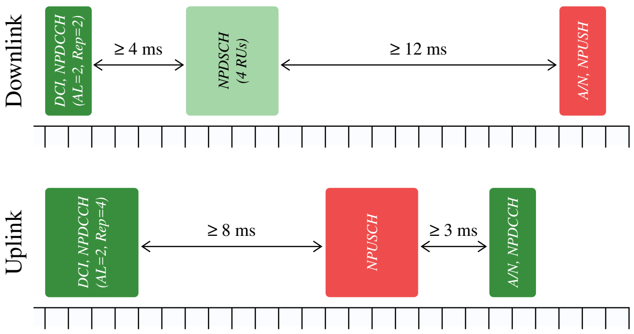

Fig. 5: NB-IoT: Transmission Timing.

If we consider good radio conditions with a maximum MCS 12, TB of 1000 bits, and all 12 tones, it takes 4 ms to send data through NPUSCH. In the case of single-tone transmission, it takes at least 48 ms. Then, it takes at least another 3 ms to receive an acknowledgment from eNB via NPDCCH and possibly the following grant. Based on these values, the maximum throughput (for both single and multi-tone) can be calculated as:

$$\begin{aligned} T &= TB_{Max}/(\mathrm{NPDCCH}+\mathrm{NPUSCH}+Off) \\ T_{Multi} &= 1000/(1+4+(8+3)) = 62.5\ kbps. \\ T_{Single} &= 1000/(1+48+(8+3)) = 16.7\ kbps. \end{aligned} \tag{2}$$

Similarly to downlink, these values are valid for the first NB-IoT release. The newer versions allow for throughput up to 159 kb/s due to larger TBs and two HARQ [13], [14], [16].

III. SIMULATION SCENARIO

With the ultimate goal of evaluating NB-IoT performance in scenarios with hundreds of devices simultaneously communicating with the remote server, we leaned toward the simulation tools. For this purpose, we selected the discrete-event network simulator NS-3, which provides an extensive toolset for evaluating wireless cellular technologies. Concretely, we chose the LENA-NB module developed at the Technical University Dortmund. Unlike the other available frameworks, LENA-NB provides a full-stack implementation of NB-IoT protocol, including power states and even the newest NB-IoT features, such as EDT [17].

To thoroughly evaluate NB-IoT performance, we created two simulation scenarios in which a single eNB serves from 50 to 1000 devices. All devices are uniformly distributed over a circular area with a diameter of 3 km, with the base station placed in the center so the communication distance is not longer than 1.5 km. Such a setup represents a typical suburban or rural area with comparable eNB density. In the first scenario, all UEs share the exact height of 1 m above ground level, allowing them to operate in nearly perfect conditions. Thus, all UEs are expected to use ECL0 with maximum MCS, resulting in the best data rates. The second scenario focuses on a more realistic deployment where 20 % of deployed UEs lie 1.5 m underground, representing a deep-indoor condition. It can be expected that most of these devices will fall into the ECL1, characterized by a lower MCS and increased repetitions.

In the remainder, both scenarios are identical. More precisely, the simulation time ranges from 15 to 30 minutes according to the number of devices. The simulation times are selected as a minimum value when all UEs are connected to the network and transmit a single message size of 64 B. To minimize overheads from the transmission on higher layers, we selected User Datagram Protocol (UDP) as it provides connectionless communication. Notably, the EDT communication determines the message size of 64 B, which can transmit only a limited amount of data with reduced signaling. We compare the EDT performance with the remaining UP and CP optimizations.

A. Simulator Parameters

For the most realistic parameters, we used the settings from the LENA-NB framework derived from the real NB-IoT network in Germany combined with our findings from the Vodafone network available in the Czech Republic. The complete list of parameters for all three ECLs can be found in Table I.

TABLE I: Simulator radio resource configuration [17].

	Parameter	**ECL0**	**ECL1**	**ECL2**
	RSRP Threshold [dBm]	-	-110	-133
NPRACH	*Periodicity [ms]*	320	640	2560
	Subcarriers Offset	36	24	12
	Subcarriers Number	12	12	12
	MSG3 Range Start	2/3	2/3	2/3
	Max Preamble Attempts	10	10	10
	Repetitions Per Pream. Att.	1	8	32
NPDCCH	*Repetitions Number*	8	64	512
	Start Subframe	2	1.5	4
	Starting Subframe Offset	0	0	0

IV. RESULTS AND DISCUSSION

Based on previously described simulation scenarios, we obtained two sets of results from purely ECL0 and 90 % vs. 10 % combination of ECL0 and ECL1. Notably, both scenarios cover transmission delay, RAP delay, and the number of collisions.

A. Transmission Delay

Considering the transmission delay, one can see that EDT provides at least a 50 % reduction compared to both UP and CP optimizations, as depicted in Fig. 6 and Fig. 7. The figure's bar height represents the average value, whereas the top and bottom edge of the error line stand for the 85th and 15th percentile, respectively. It must also be noted that the influence of CP optimization improves the transmission delay only marginally by approximately 10 to 20 ms. However, it is the expected outcome as the only difference in those two optimizations is that CP data are transmitted in MSG 5, i.e., in *RRC Connection Resume Complete*. Whereas for UP, data is transmitted after acknowledgment of this message.

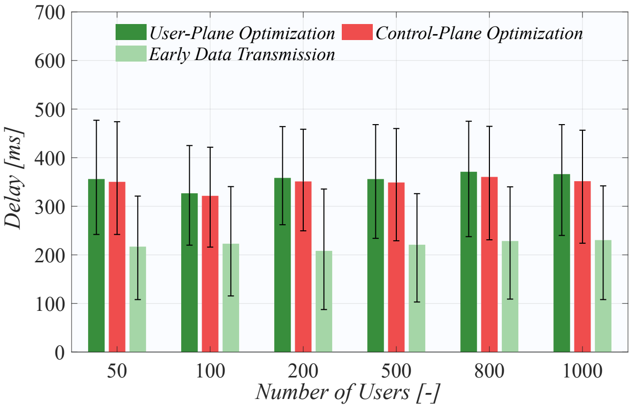

Fig. 6: Transmission delay in first scenario.

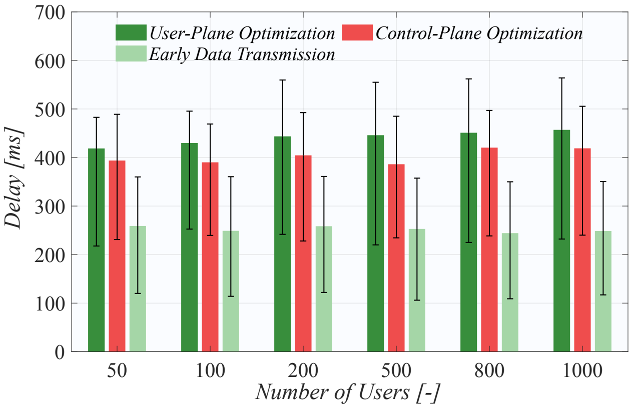

Fig. 7: Transmission delay in second scenario.

It is also clear that the transmission delay is nearly constant for the first scenario, even with an increasing number of UEs. On the other hand, in the second scenario, there is more than a 60 ms increase in delay values. Further, the linear dependency of transmission delay with an increasing number of users can be seen for UP and CP optimizations. However, in the case of EDT, the situation is identical to the first scenario. The primary outcome that can be drawn from this is that even a tiny number (approx. 10 %) of ECL1 UEs can visibly influence the network performance. Thus, it is essential to reflect this fact when network capacity planning and evaluation are conducted.

B. Random Access Delay

The following essential parameter influencing the resulting transmission delay is the duration of the random access procedure. In the case of EDT, it represents nearly the whole delay in the radio access network, as depicted in Fig. 8 and Fig. 9.

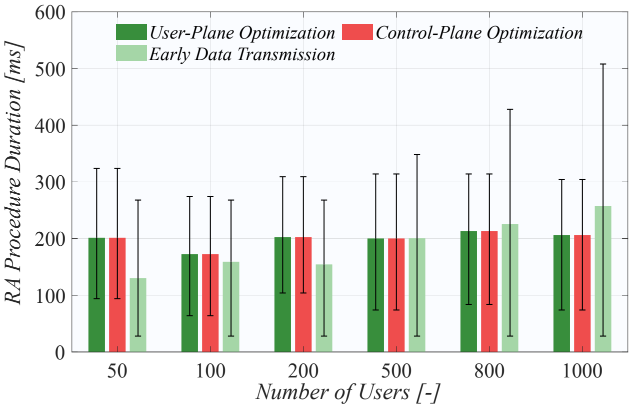

Fig. 8: Random access delay in first scenario.

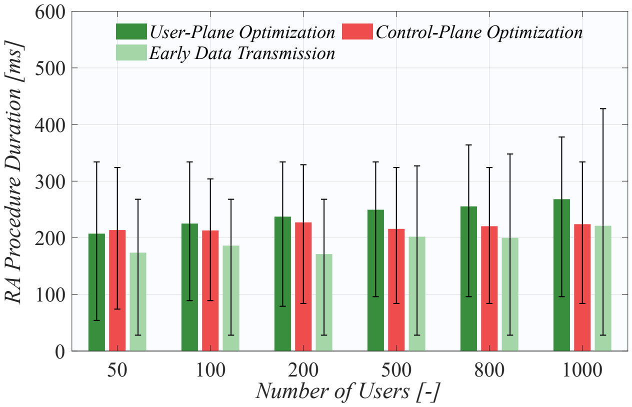

Fig. 9: Random access delay in second scenario.

If we compare the results of transmission delay with the average random access procedure, it is clear that the results for EDT deny the reduced delay values. However, such behavior is not seen for UP and CP optimizations. Similar behavior can be seen in both ECL0 and combined scenarios. As the primary mechanism of the random access procedure is the same for all three approaches (EDT may utilize a reserved pool in NPRACH), there is no reason for such a behavior. Thus, the only logical explanation for this increase in RAP delay is the high number of collisions on the Medium Access Control (MAC) layer. Although it sounds counter-intuitive for EDT, the later results verified this premise.

C. Number of Collisions

Surprisingly, the simulation results for the number of RAP collisions verified the premise proposed in the previous section, as depicted in Fig. 10 and Fig. 11. For better clarity, the y-axis of both figures is in logarithmic scale.

The subsequent exciting finding is that the collisions are more frequent in the pure ECL0 scenario. This claim is valid even for UP and CP optimizations, which is probably caused by shorter inter-repetition delays in NPRACH. Since devices report their current/expected ECL, the scheduler may shuffle with these values based on the actual network conditions.

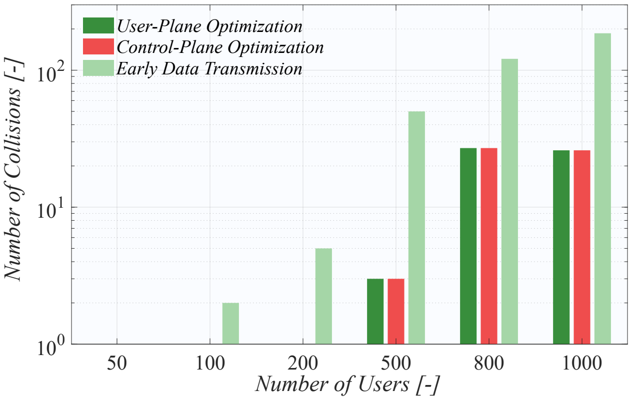

Fig. 10: Collisions in first scenario.

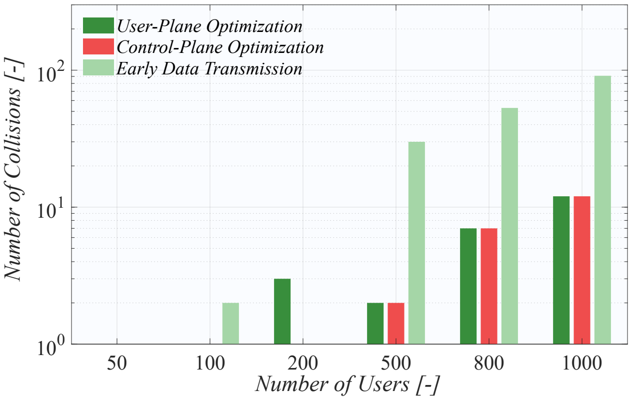

Fig. 11: Collisions in second scenario.

To analyze the number of collisions more thoroughly, we further depicted the number of random access procedures and collisions over time in Fig. 12. For this purpose, we utilized results for the combined scenario with 1000 users. To our surprise, the results for the number of EDT RAPs indicated double the number of actual UEs. This finding logically explains increased collisions leading to prolonged RAP times. However, it raises the question of why there are two times the amount of RAPs than needed.

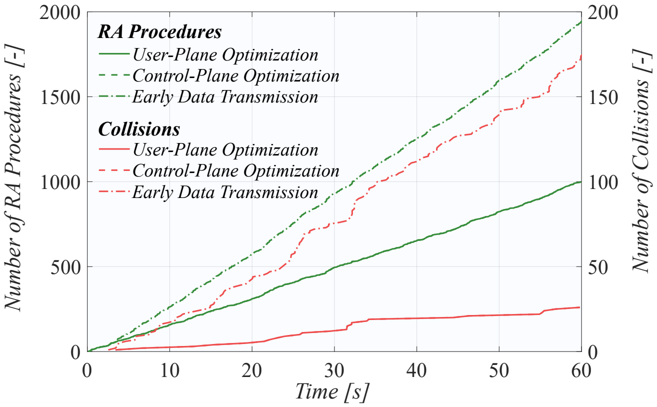

Fig. 12: Number of RAPs and collisions over time.

Thus, we conducted a subsequent analysis of MAC layer logs and found that after the successful uplink transmission in the uplink direction, each UE undergoes a second RAP after around 30 ms. Notably, this RAP is not followed by an uplink message transmission. Therefore, there was no reason for such a behavior until we analyzed the downlink transmission. The message in EDT can occupy the whole TB, which is 1000 bits (NPUSCH) for uplink and only 680 bits (NPDSCH) for downlink direction in Release 13. The reason for additional RAP is apparent if we consider our UDP payload of 64 B, which is echoed back to the UE from the remote server. Combining 64 B of user payload with 8 B UDP header and at least 20 B from the IP header, we overcome the maximum TB size with 57 B of user payload. For our 64 B message, a TB larger than 736 bits is needed.

By extending the maximum TB to the Release 14 value of 2536 bits, the additional RAP is no longer present. Still, we are presenting the results from the default setup of the LENA-NB modules to show that even the wrong configuration of the network may have fatal consequences for its performance. It is also crucial for real-world deployments as the network operators tend to “cherry-pick” the part of newer NB-IoT releases based on the potential benefits in contrast with deployment costs.

V. CONCLUSION

Motivated by the massively deployed smart-metering devices requiring permanent connectivity in a harsh deep-indoor environment, in this paper, we conducted a set of simulations evaluating the performance of a single NB-IoT cell with hundreds of devices. To this aim, we assessed the performance of all NB-IoT optimization mechanisms, allowing the technology to achieve high network capacity.

From this perspective, the EDT is a vital tool for decreasing transmission delay and improving spectrum efficiency with reduced overheads. Our results show that the transmission delay is reduced by over 50 %, even with our unfortunate selection of message size. Thus, it must be noted that EDT significantly improves latency for smaller messages (for Release 13, less than 97 B in uplink and 57 B in downlink). In the case of larger messages, the payload may be segmented, or a standard RRC procedure is initiated, which leads to reduced spectral efficiency. On the contrary, when the predefined TBS for EDT is overestimated, much padding data is transmitted.

It must be noted that an NB-IoT network can easily handle 1000 UEs per single cell communicating in a 15 m window, even with basic UP optimization. Moreover, there is a sufficient buffer to serve thousands of devices distributed in 90 to 10 % for ECL0 and ECL1, respectively.

Finally, the simulation results show the importance of proper network settings, as even transmitting a perfectly suitable message of 64 B with EDT can introduce double the RAP collisions. This document thus can serve network operators as a blueprint for achieving the highest network capacity and spectrum efficiency.

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