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Performance Evaluation of Random Access for Small Data Transmissions in Highly Dense Public and Private NB-IoT Networks

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***Abstract*—With an increasing number of global Internet of Things devices, networks face the challenge of high scalability and support of massive numbers of small data transmissions. With Early Data Transmission for NB-IoT networks, which is called Small Data Transmission for 5G New Radio and Reduced Capabilities networks, standardization has introduced efficiency optimizations with reduced signaling overhead for better scalability of these networks. Though, previous work demonstrated that current NB-IoT configurations are not well-balanced when it comes to Random Access windows and additional uplink resources. In this work, we evaluated different sets of Random Access parameters derived from public NB-IoT networks and identified new optimal parameters for smart urban networks as well as for private high-density micro cells, based on a detailed analytic Random Access model. The identified optimal Random Access parametrization supports 30 million Random Access preamble transmissions per day when using 15 additional non-anchor carriers and 1% Block Error Rate, which is an improvement of 150% to 223% compared to current public networks. When it comes to private high-density micro cells, up to 1,200 Random Access preambles per second are supported, which is between 23 and 82 times more than with legacy configurations. The results demonstrate the importance of well-configured NB-IoT networks, especially for contention-based channels like Random Access. For further increasing numbers of Internet of Things devices in the future, networks must be adapted for better spectral efficiency and better support of small data transmissions, as shown in this work.**

***Index Terms*—Scalability, NB-IoT, Small Data Transmission, Random Access, Private Network**

I. INTRODUCTION

SINCE the first public cellular Internet of Things (IoT) networks were introduced in 2017, the global expansion of Cellular Internet of Things (C-IoT) solutions led to currently 170 mobile IoT networks using Narrowband Internet of Things (NB-IoT) and/or enhanced Machine Type Communication (eMTC) in 67 countries worldwide [1]. This large rollout addresses the challenge of the increasing number of IoT devices worldwide, which has been forecasted to be over 25 billion global active IoT connections in 2025 [2].

Besides Low Power Wide Area Network (LPWAN) requirements of energy efficiency and robust signals, massive scalability in IoT networks, especially in Smart Cities, becomes more important. To face this challenge, IoT networks must be optimized for the best spectral efficiency concerning its typical use cases. Besides capacity extension by using more carriers, existing configurations must be optimized for the best balance of control and user data.

Since public C-IoT networks can be used by a massive number of different subscribers, the growing number of participants, all sharing the same resources, will lead to decreasing performance such as longer latencies, increased energy consumption, and ultimately lower reliability due to network capacity limits. For reliable and scalable networking, private networks can be considered as an alternative, as already found in 5G New Radio (NR) campus networks. Using exclusive frequency spectrum, private C-IoT networks can be deployed for specific applications without having to share resources in public networks with unknown types and numbers of other applications.

Since C-IoT networks only require small bandwidths, but still aim for spectral and energy efficiency, typical private network frequencies like 3.6 GHz in the U.S., 2.37 GHz in Spain, or 3.7 GHz in Germany, do not meet LPWAN requirements as good as sub-1-GHz frequency bands. Lower frequencies result in less signal loss and therefore higher data rates when using small bandwidths. Due to this characteristic, an interest group called *450 MHz Alliance* has formed and forsters worldwide private cellular networks for utilities, public safety, transport, and rural connectivity. Depending on local regulations, frequency bands between 380 MHz and 512 MHz have been made available or will be available in the future for special applications [4]. In Germany for example, *450connect* holds the Long Term Evolution (LTE) frequency band 72 license (Uplink: 451-455.74 MHz, Downlink: 461-465.74 MHz)

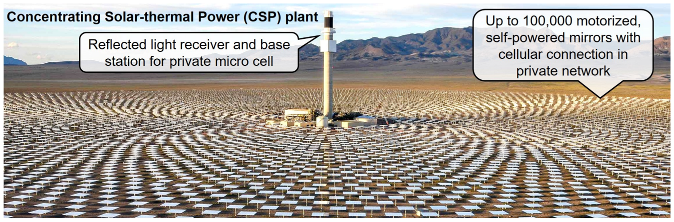


Fig. 1: Concentrating Solar-thermal Power plant as an example for highly dense private NB-IoT networks. Image based on [3]

and uses it with a focus on emergency voice communication, smart meters, smart grid, and communication of other critical infrastructures like Concentrating Solar-thermal Power plants (CSP)s (cf. Figure 1).

The aforementioned requirement of spectral efficiency is crucial for scalable networks. In previous work [5] we have identified the Random Access (RA) channel as the bottleneck of scalability in typical public NB-IoT networks since the RA channel is based on contention and usually used at the beginning of every IoT transmissions. This work will focus on comparing and optimizing the Narrowband Physical Random Access Channel (NPRACH) parameters for public NB-IoT networks and derive ideal RA parameters for small data transmissions in private high-density NB-IoT micro cells. Therefore, this work is organized as follows: Section II briefly outlines previous works on NB-IoT RA optimization, while Section III gives a short overview on NB-IoT basics and the RA procedure. Section IV introduces the analytical model, which is used in this work. It is followed by an overview of base parameters and scenarios and the analysis of the RA performance in high-scaled networks in Section V and finally, the results are concluded in Section VI.

II. RELATED WORK

Since the release of NB-IoT in 2016, multiple approaches to optimize the RA have been performed. In [6] a simulative and analytic approach are introduced. Though, the analytic model only uses stochastic estimations and is limited in its usage. In [7] the authors perform optimization of a novel, non-standardized RA procedure rather than optimizing the procedure as defined by standardization. Since the RA in NB-IoT uses three different Coverage Enhancement (CE) modes, which have a great impact on the overall performance of the RA procedure, its support in the RA model is very important. The authors in [8] include CE levels in their detailed model, but the overall documentation of this model is limited and thus not reproducible. In [9] all three CE levels are considered, but independently from each other without any cross-dependencies, which are important for the analysis. Since NB-IoT devices can fall back to a more robust CE level, when RA fails repeatedly, all three CE levels must be examined in combination, making the model in [9] unsuitable. Finally, the authors in [10] introduce a detailed analytical model of the NB-IoT RA procedure based on a slotted ALOHA approach, which is validated by simulation and well documented. The authors identify the impact of different RA parameters on the overall performance and provide extensive analysis to identify the limits of RA. While all authors have analyzed the scalability of NB-IoT RA, no comparison with parametrizations of real-world NB-IoT networks has been performed. Our work will take three parameter sets of live NB-IoT networks into account and will provide scalability results with realistic device distributions in Smart Urban environments as well as local high-density micro cell scenarios like solar thermal power plants.

III. FUNDAMENTALS OF NB-IOT

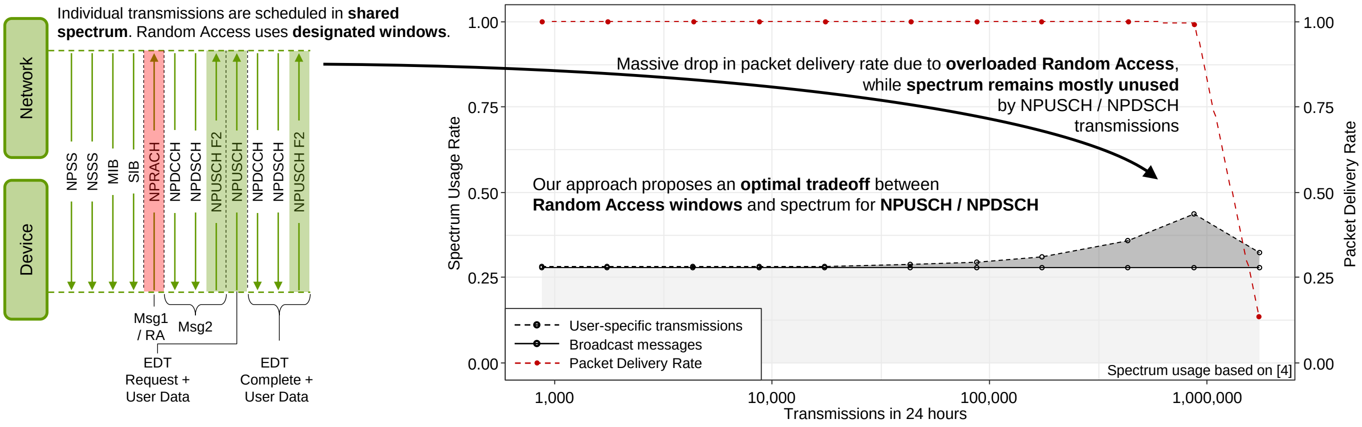
In 3rd Generation Partnership Project (3GPP) Release 13, NB-IoT has been introduced as a promising C-IoT solution. With every following release, additional features were introduced for better spectral and energy efficiency as well as optimized signal range. For better signal range, 3GPP Release 13 introduces repetitions. Message transmissions can be immediately repeated for up to 2048 times to ensure successful signal decoding at the receiver side. Since the RA is usually the first transmission in the event of mobile originated data transmissions, networks can define up to the sets of so-called CE modes for the User Equipment (UE), in which parameter sets for RA transmissions are defined. A major difference between these CE modes are the number of repetitions used for the specific RA. While CE mode 0, or short CE0, is used by UEs with good signal quality, CE1 and CE2 parameters include increasing numbers of RA repetitions for better signal ranges, but require more energy and spectrum.

For best energy efficiency, devices release their Radio Resource Control (RRC) connection after transmitting or receiving data and enter an extended Discontinuous Reception (eDRX) mode or Power Saving Mode (PSM), which shuts off most of the device for ultra-low power consumption [11]. Since the device is in RRC Idle mode, it needs to reconnect to the network using an RRC Resume procedure including a RA preamble in specific RA windows. To reduce the overall overhead in small data transmissions, NB-IoT introduced C-IoT Optimization in 3GPP Release 13, in which small user data can be piggybacked in control messages (e.g. Msg5 of the RA procedure, described in [12]), using the DedicatedInfoNAS information element as defined in [13].

Most LPWAN-related IoT use cases only transmit small data of 20 - 100 Bytes per transmission (cf. Table I) and can be easily piggybacked in control messages. Therefore, in 3GPP Release 15, a new transmission mode called Early Data Transmission (EDT) was introduced, in which user data can be added to an EDT Request message. After a response message, the connection is immediately terminated (Fig. 2, left), which enhances the spectral and energy efficiency of both the device and network. Since EDT has a great positive impact on the overall performance and can be used in most LPWAN-related IoT use cases, it is also specified for 5G NR networks and highly recommended for the new 5G Reduced Capability (RedCap) device category. Note that in 5G networks, this transmission mode is called Small Data Transmission (SDT) rather than EDT. More details on available NB-IoT transmission modes and scalability comparison can be found in [5].

A. Subcarriers

Since NB-IoT is derived from LTE, it uses Resource Blocks in the downlink direction as the smallest schedulable frequency and time unit for transmissions. In the uplink direction though, the NB-IoT bandwidth of just 180 kHz can be further divided into subcarriers. The number of available subcarriers depends on the subcarrier spacing. With 15 kHz subcarrier spacing 12



NPSS: Narrowband Primary Synchronization Signal
NSSS: Narrowband Secondary Synchronization Signal
MIB: Master Information Block
SIB: System Information Block
NPRACH: Narrowband Physical Random Access Channel
NPDCCH: Narrowband Physical Downlink Control Channel
NPUSCH F2: Narrowband Physical Uplink Shared Channel Format 2
NPDSCH: Narrowband Physical Downlink Shared Channel

Fig. 2: NB-IoT spectrum remains mostly unused while packet delivery rate drops due to imbalance between Random Access windows and NPUSCH spectrum

Application	Message interval	Message size
Consumer - wearables	10 per day	20 Bytes
Consumer - tracking	2 every hour	50 Bytes
Consumer - smart bicycles	8 every hour	50 Bytes
Assisted Living / Medical	8 per day	100 Bytes
Smoke detector	2 per day	20 Bytes
Agriculture - stock tracking	100 per day	50 Bytes
Industrial - asset tracking	100 per day	50 Bytes
Industrial - safety monitoring	2 per day	100 Bytes
Industrial - machinery control	100 per day	50 Bytes
Smart Grid	10 per day	20 Bytes
Tank monitoring	2 per day	100 Bytes
Max. EDT Transport Block Size	-	125 Bytes

TABLE I: References of LPWAN applications suitable for EDT [14]

subcarriers are available, which can be scheduled individually or collectively. The NPRACH uses 3.75 kHz subcarrier spacing, which results in 48 individual subcarriers [15]. These individual subcarriers enable multiple devices to transmit data at the same time, although the bandwidth is limited to 180 kHz per carrier.

B. Non-Anchor Carriers

As stated in Section III-A, the bandwidth of an NB-IoT carrier is very limited. However, NB-IoT can use up to 15 additional 180 kHz carriers at different frequencies, called non-anchor carriers. While broadcast transmissions like Master Information Block (MIB) or System Information Block (SIB) are limited to the anchor carrier, user-specific transmissions like NPRACH and Narrowband Physical Uplink Shared Channel (NPUSCH) in Uplink (UL) direction and Narrowband Physical Downlink Control Channel (NPDCCH) and Narrowband Physical Downlink Shared Channel (NPDSCH) in Downlink (DL) direction can be scheduled in non-anchor carriers [16]. Thus the overall capacity of NB-IoT networks can be drastically increased.

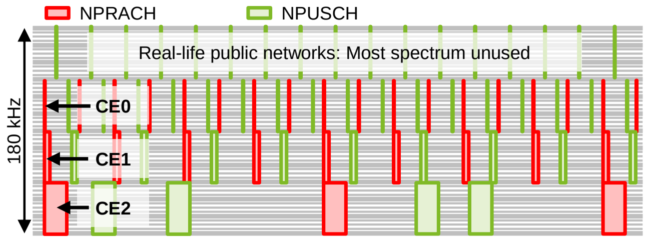
C. Random Access

Independent from the used transmission mode, devices that need to transmit or receive data have to leave RRC idle mode and reconnect to the network. The first message transmitted (therefore called Message 1 or Msg1) is in every mode a contention-based RA preamble. To not interfere with other uplink transmissions like NPUSCH, the RA preambles can only be transmitted in periodic time and frequency windows, called RA windows.

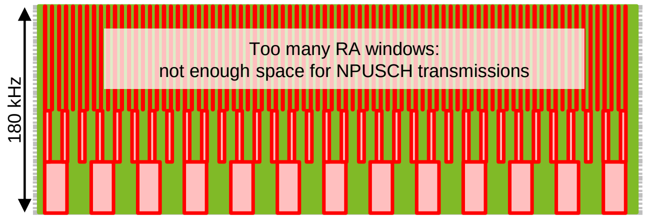
To comply with LPWAN devices in different coverage conditions, NB-IoT networks can define up to three different coverage enhancement levels, called CE0 to CE2, with specific RA parameters like the number of repetitions or periodicity. Figure 3a gives an example of available RA windows, based on an NB-IoT Radio Resource Configuration derived from a German public NB-IoT network.

Since most devices are in good coverage conditions and therefore use CE0, it uses a more frequent periodicity. CE2, on the other hand, has a significantly longer period due to fewer devices, but each RA window is notably longer to comply with the large number of repetitions required by these devices in poor coverage conditions.

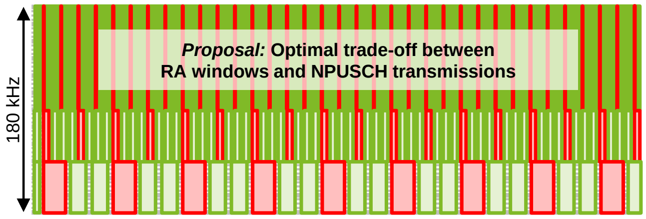
Overall, parameters like the RA periodicity directly influence the maximum number of devices that can successfully transmit an RA preamble without colliding with transmissions of other devices. In [5] this RA parametrization from public networks has been identified as the bottleneck in high-scaled NB-IoT networks, since only 4.5% of the uplink spectrum are preoccupied by RA windows. The number of RA collisions massively increases at 1 million transmissions per day, which results in a significant drop of the packet delivery rate. However, when the overall spectrum utilization is considered, more than 50% of the spectrum are unused (cf. Figure 2). One possible reason for this is that current NB-IoT networks are still based on parameters that are not optimized for small data transmissions, but for legacy multimedia transmissions,



(a) Configuration in real-life networks leads to overflowing Random Access windows while most spectrum is unused



(b) Maximizing the Random Access window interval will leave not enough space for other uplink channels



(c) Our configuration proposes an optimized trade-off between Random Access windows and NPUSCH transmissions

Fig. 3: Comparism of different Random Access configurations with too little, too much and optimal Random Access windows

which do not require an RRC connection reestablishment for every transmission. However, since small data transmissions will make up a large fraction of all IoT use cases in the future, the parametrization must be adapted accordingly.

Figure 3 introduces two exemplary RA configurations besides real-life configurations from public networks. Figure 3a demonstrates the current configuration in public networks. RA windows are widely distributed, leaving most spectrum unused. In Figure 3b RA windows occupy too much spectrum, leaving not enough spectrum for regular transmissions like NPUSCH, which will again result in a low packet delivery rate. Our work proposes an optimal trade-off between resources for RA and resources for NPUSCH transmissions as shown in Figure 3c.

IV. ANALYTIC RANDOM ACCESS MODEL

With LENA-NB, our NB-IoT simulation framework for the network simulator ns-3 [17], the full protocol stack of NB-IoT networks can be analyzed. Simulation frameworks like ns-3 are very detailed, which makes them applicable for specific evaluations. However, they require high computational performance, which results in weeks to months of simulation time for different parameters and statistical significance, and are not suitable for optimizations of large parameter ranges. On the other hand, empirical measurements are ultimately realistic but require massive amounts of hardware for high collision probability and significant results. Additionally, hardware-in-the-loop measurements also result in weeks to months of measurement runs.

For this work, we will use an analytic approach for optimizing the RA parameters as well as comparing them to real-world parameters. With several models of the NB-IoT RA available, we will focus on the model provided in [10], which supports relevant NB-IoT characteristics such as different CE levels, size of backoff windows, preamble repetitions, and different number of subcarriers in each CE level.

Figure 4 illustrates the basic idea of the multiband multichannel slotted ALOHA model in [10]. Each transmission is assigned to an initial timeslot, in this case, an RA opportunity, and to an initial CE level matching its current coverage condition. In this example devices B and C have a weaker signal strength than device A and therefore start at CE1 resp. CE2. Since NB-IoT defines a maximum number of transmission attempts per CE level, devices will switch to a higher, more robust CE level, called band in this model, when the maximum number of attempts is reached for this specific level. The device retries, until it was successful, or the total number of attempts is reached.

For more details on the analytic model used in this work, refer to [10].

V. EVALUATION AND RESULTS

Using the analytical model presented in Section IV, the RA scalability in public NB-IoT networks as well as in optimized networks is evaluated using a smart urban and a private high-density scenario.

A. Scenario definition

All smart urban evaluations are performed in NB-IoT networks with a diameter of 2.5 km, which is the average cell size in the German smart city Dortmund, awarded European

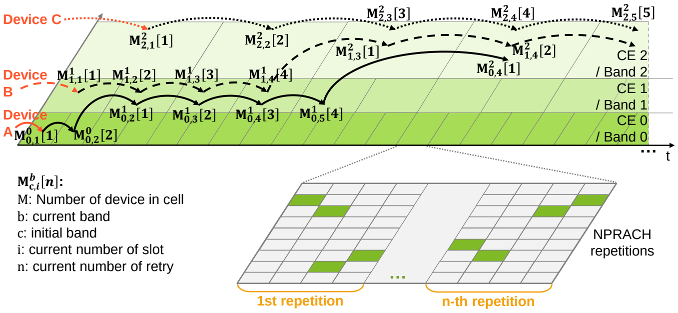


Fig. 4: Multiband multichannel slotted ALOHA analytic model for Random Access evaluations: Devices switch to more robust RA windows when failing repetitively

Real life Random Access Configuration	MNO Configuration A			MNO Configuration B			MNO Configuration C		
	CE0	CE1	CE2	CE0	CE1	CE2	CE0	CE1	CE2
NPRACH Periodicity	320 ms	640 ms	2560 ms	160 ms	640 ms	2560 ms	640 ms	640 ms	640 ms
NPRACH Start Time	256 ms	256 ms	256 ms	512 ms	512 ms	512 ms	8 ms	64 ms	128 ms
Number of Subcarriers	12	12	12	12	12	12	12	12	12
NPRACH Repetitions	1	8	32	1	16	32	2	8	32
Attempts per CE	10	10	10	5	5	5	4	4	4
Attempts Total	10			8			10		

TABLE II: RA parameters derived from public NB-IoT networks used as benchmark configuration

Capital of Innovation 2021 [18], and is derived from base station positions as given in the Dortmund mobile radio register [19]. Using the Winner+ empirical path loss model with additional indoor and deep indoor losses based on [20], and an equal distribution of outdoor, indoor and deep indoor devices, 66.4% of all devices will initially use CE0, while 32.5% resp. 1.1% of all distributed devices will use CE1 resp. CE2. Since private micro cells like solar thermal power plants are limited to a smaller area, we assume that in private NB-IoT micro cells only CE0 devices are used.

For extracting RA information from public NB-IoT networks, we used an Ettus Universal Software Radio Peripheral (USRP) B210 Software Defined Radio (SDR) with srsRAN [21]. Three different parametrizations of live NB-IoT networks are used to demonstrate the influence of the differently parameterized networks on the overall performance. Note that the parameters given in Table II are included in the information elements *nprach-ParameterList-r13* and *ue-TimersAndConstants-r13* from the System Information Block Type 2-NB, as defined in [13].

B. Validation of Analytic Model

Before evaluating optimal RA parameters, we validated our implementation of the analytic model from [10] with our ns-3 NB-IoT simulation framework LENA-NB [17], using the parameters from Mobile Network Operator (MNO) A, given in Table II. 17 scenarios with different device quantities and a total of 1.6 million NB-IoT transmissions were simulated on a high-performance simulation server with 192 CPU cores and 117 GB of memory over a period of six weeks. The results are shown in Figure 5.

Since both the analytic model as well as the simulation result in a similar RA failure rate, the model is validated and can be used for the following evaluations.

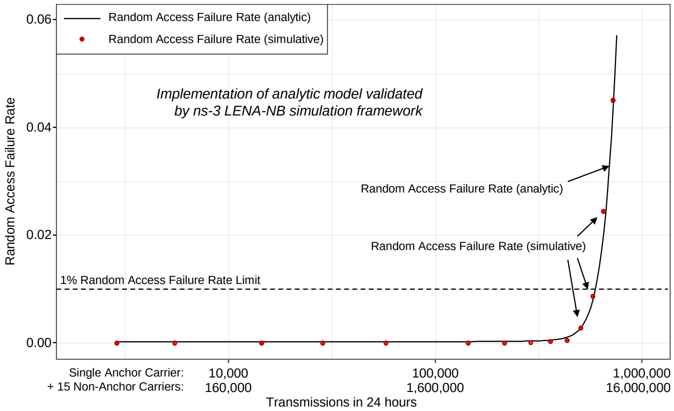


Fig. 5: Validation of analytic RA model using LENA-NB extension for simulation framework ns-3

C. Scalability Results for Smart Urban Networks

Figure 6a presents the results for different RA parameters. Based on assumptions given in [12], a Block Error Rate (BLER) of 1% is used as an upper boundary for comparing the RA capacities. Using the RA parameters given in Table II, up to 12 million transmissions are supported for RA per day with 1% failure rate when all 16 available NB-IoT anchor and non-anchor carriers are used. This results in 139 successful RA preambles per second.

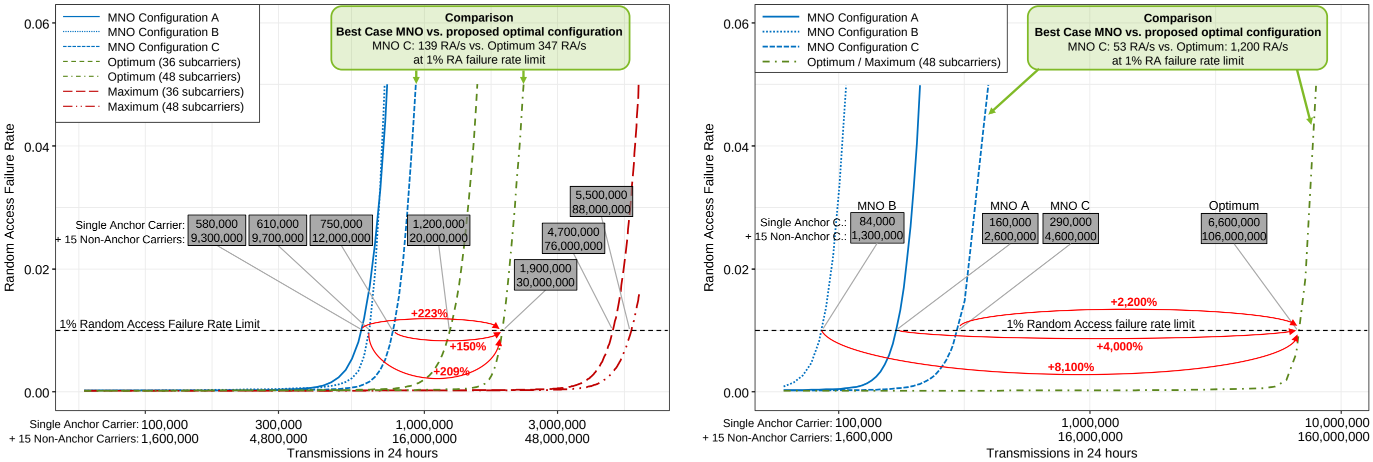
Since the NPRACH periodicity has a major impact on the overall performance of RA, it is set to the most frequent setting possible to identify the absolute maximum of supported RAs in a single cell. Using the parameters for smart urban maximum configuration from Table III a maximum number of 88 million RA preambles can be transmitted per day when all 48 subcarriers are used for RA windows. While this result is very promising for a successful RA in massively scaled networks, the RA windows use too many uplink resources as mentioned in III-C. In this case, other uplink transmissions like NPUSCH and NPUSCH F2 can not be carried out for all devices, which is why a feasible balance between RA windows and remaining resources for NPUSCH must be identified. When taking resource requirements of all uplink transmissions and different signal strengths [12] into account, a Smart Urban optimum parametrization is identified and given in Table III. With these optimal RA parameters, 30 million RAs per day, or 347 RAs per second can be carried out in a single cell, which is an improvement of up to 150% compared to the best MNO based parametrization.

D. Scalability Results for Private Micro Cells

In private high-density micro cells, the networks using MNO parameters from Table II perform worse than in smart urban scenarios. This accounts for the missing distribution of devices in different CE levels. While in urban environments 66.4% of devices will perform an initial RA in CE0 windows, 32.5% will perform the initial RA in CE1 windows. This distribution reduces the probability of RA collisions and therefore enables more devices to a successful RA. Since in micro cells all devices will initially perform the RA in CE0, the CE0 RA window will overflow with fewer overall transmissions.

Proposed Random Access Configuration	Smart Urban *Optimum*			Smart Urban *Maximum*			Private Micro Cell Opt./Max.		
	CE0	CE1	CE2	CE0	CE1	CE2	CE0	CE1	CE2
NPRACH Periodicity	160 ms	240 ms	2560 ms	40 ms	80 ms	2560 ms	40 ms	-	-
NPRACH Start Time	8 ms	64 ms	128 ms	8 ms	64 ms	128 ms	8 ms	-	-
Number of Subcarriers	12/24	12	12	12/24	12	12	48	-	-
NPRACH Repetitions	1	32	128	1	32	128	1	-	-
Attempts per CE	10	6	8	10	10	10	20	-	-
Attempts Total	10			10			20		

TABLE III: Proposed optimized RA parameters for smart urban scenarios and private high-density micro cells



(a) Random Access failure rate in smart urban networks

(b) Random Access failure rate in private high-density micro cells

Fig. 6: Random Access failure rate in high-scaled networks with RA parameters from public networks and optimized parameters

However, since no resources for CE1 and CE2 have to be reserved, CE0 RA windows can be much more frequent and use all 48 subcarriers, which ultimately decreases the probability of RA preamble collisions. While the best MNO RA configuration can only provide 53 successful RA per second, optimized parameters will enable 1,200 RAs per second and therefore increase the network capacity by 2,200%. These results underline the significance of proper network configurations, especially when setting up private networks.

VI. CONCLUSION

Smart cities around the world integrate lightweight IoT applications. In these high-density scenarios, billions of IoT devices around the world will be integrated into Low Power Wide Area Networks, which leads to a great challenge for these networks. While cellular networks use exclusive spectrum and are usually centrally coordinated with a low probability of transmission collisions on the air, the transmission of the first message for a connection setup, called Random Access preamble, or Message 1, is likely to interfere with preambles from other devices, especially in high-scaled networks. With 3GPP Release 15, a new transmission mode called Early Data Transmission in LTE networks, or Small Data Transmission in 5G NR networks, including 5G RedCap, has been introduced for spectral efficient transmissions with reduced signaling overhead. This requires an optimization of the Random Access parameters for small data transmissions in public and private NB-IoT networks. In previous work, we found that the configuration of Random Access parameters is not optimized for IoT-specific small data transmissions and limits the scalability of networks. Since Cellular IoT solutions like NB-IoT are derived from LTE, the parameters for Random Access are currently not well suited for small data transmissions.

Based on these findings, we evaluated different sets of Random Access parameters found in public NB-IoT networks and proposed optimal parameters for smart urban networks as well as for private high-density micro cells, based on a detailed analytic Random Access model. When using maximum parameters, up to 88 million Random Access preamble transmissions are feasible with additional 15 non-anchor carriers and 1% BLER. Since uplink resources are shared between RA and other uplink transmissions like NPUSCH, a balance must be found between all uplink transmissions, resulting in an optimal RA configuration with 30 million transmissions per day, or 347 transmissions per second in smart urban environments. Compared to configurations in public networks, the capacity is increased by 150% to the best public configuration and even tripled to the worst public configuration. When it comes to private high-density micro cells, up to 1,200 Random Access preambles per second are supported, which is between 23 and 82 times more than with legacy configurations from public networks. The results demonstrate the relevance of well-configured NB-IoT networks, especially for contention-based channels like Random Access. For further increasing numbers of IoT devices in the future, networks must be adapted for better spectral efficiency and better support of small data transmissions, as shown in this work.

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