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Power Consumption Analysis of NB-IoT and eMTC in Challenging Smart City Environments

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Abstract—**The upcoming Internet of Things will introduce large sensor networks including devices with very different propagation characteristics and power consumption demands. 5G aims to fulfill these requirements by demanding a battery lifetime of at least 10 years. To integrate smart devices that are located in challenging propagation conditions, IoT communication technologies furthermore have to support very deep coverage. NB-IoT and eMTC are designed to meet these requirements and thus paving the way to 5G. With the power saving options *extended Discontinuous Reception* and *Power Saving Mode* as well as the usage of large numbers of repetitions, NB-IoT and eMTC introduce new techniques to meet the 5G IoT requirements. In this paper, the performance of NB-IoT and eMTC is evaluated. Therefore, data rate, power consumption, latency and spectral efficiency are examined in different coverage conditions. Although both technologies use the same power saving techniques as well as repetitions to extend the communication range, the analysis reveals a different performance in the context of data size, rate and coupling loss. While eMTC comes with a 4 % better battery lifetime than NB-IoT when considering 144 dB coupling loss, NB-IoT battery lifetime raises to 18 % better performance in 164 dB coupling loss scenarios. The overall analysis shows that in coverage areas with a coupling loss of 155 dB or less, eMTC performs better, but requires much more bandwidth. Taking the spectral efficiency into account, NB-IoT is in all evaluated scenarios the better choice and more suitable for future networks with massive numbers of devices.**

Index Terms—**Internet of Things, eMTC, NB-IoT, Battery Lifetime, Data Rate, Latency, Coupling Loss**

I. INTRODUCTION

With the digitalization of everyday's life, current technologies are faced with new challenges. The Internet of Things (IoT) induces communication devices like smart sensors being highly energy efficient yet powerful in terms of availability and reliability. With the new challenges of good coverage even in courtyards or basements in Smart Cities as well as runtimes of battery powered devices of several years, existing technologies suffer from coverage blind spots, making the connectivity of IoT devices difficult.

The development of new technologies faces these challenges (Fig. 1). In the cellular context, two technologies have been introduced with 3GPP Rel. 13: Enhanced Machine Type Communication (eMTC) is mostly based on Long Term Evolution (LTE) but is refined to match the demands of IoT devices. With a reduced bandwidth of 1.4 MHz the device is far less complex and thus cheaper paving the way of massive numbers of devices. To enable a long runtime of battery powered devices such as smart waste containers or environmental sensors, eMTC introduces extended Discontinuous Reception (eDRX) for more relaxed timing restrictions on paging occasions. Additionally, a new Power Saving Mode (PSM) allows the devices to enter a sleep mode by pausing the monitoring of communication channels but still being registered to the network. These techniques extend the runtime drastically compared to legacy LTE devices. For an extended coverage, eMTC uses up to 2048 message repetitions enabling a maximum coupling loss up to 164 dB [1] for communication even in extreme coverage conditions.

Among eMTC, the 3GPP Rel. 13 has introduced with Narrowband Internet of Things (NB-IoT) a further radio access technology that reuses some technical components from LTE but also supports standalone operation by introducing an individual channel structure for an even better performance than in in-band or guard-band implementations [2]. NB-IoT is operable in a narrowband of only 180 kHz, or one Physical Resource Block (PRB). The 180 kHz are divided into subcarriers as narrow as 3.75 kHz to combine extreme coverage and high uplink capacity. eDRX and PSM are also supported as well as up to 2048 repetitions.

With both technologies being optimized for enhanced coverage, the application of repetitions conflicts with the objective of a long battery lifetime and needs to be evaluated in terms of data rate, power consumption and latency. Therefore this paper is organized as follows: Section II briefly outlines previous studies of NB-IoT and eMTC performance, while Section III gives a short overview of techniques for power saving and coverage extension used by NB-IoT and eMTC. Section IV introduces a novel power consumption model for

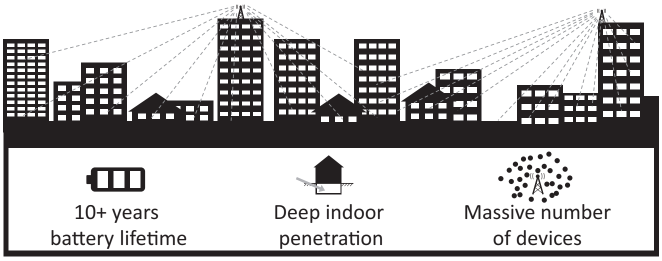


Fig. 1: Internet of Things communication challenges

both technologies with respect to different power states. It is followed by an evaluation of the performance in Section V and finally the results are concluded in Section VI.

II. RELATED WORKS

Introducing the new technologies, the authors in [2] provide detailed information about the NB-IoT and eMTC design. Following the technologie's introduction, the performance of eMTC and NB-IoT is evaluated. Although the analyses are detailed, the authors do not compare both technologies to identify the appropriate technology in equal conditions.

In [3] the authors present an empirical NB-IoT power consumption model for battery lifetime estimation. The authors use two different NB-IoT modems on a standard-compliant NB-IoT base station emulator and measure the device's power consumption for different energy states. The results are then compared to the values provided in the 3GPP NB-IoT technical specification, showing a difference of 10 % in the results.

[4] includes an energy consumption evaluation, where, based on electrical power and use case assumptions, the latency and battery lifetime for NB-IoT devices is calculated.

An open-source simulator for NB-IoT is presented in [5]. The simulator is derived from an existing LTE simulation tool and is adapted to NB-IoT resource configurations. Although the authors present first results of the achievable data rate and latency of NB-IoT devices, the simulator doesn't support repetitions. However, as we will show in this paper, this functionality has a major impact on the device's performance.

The authors in [6] also present an NB-IoT and eMTC simulator for power consumption, scalability and latency evaluation. The simulations show that in all scenarios, ranging from open area to urban, eMTC has a lower latency, but NB-IoT comes with a lower power consumption in poor coverage scenarios.

III. CELLULAR COMMUNICATION SOLUTIONS FOR THE IOT

The increasing interest in IoT-enabled devices leads to the development of various technologies that address the requirements to integrate intelligent devices, purposing low power consumption and wide area signal coverage. The following sections will give an overview of the techniques applied by NB-IoT and eMTC to meet the IoT requirements.

A. Increasing the Battery Lifetime

With reducing the power consumption of devices NB-IoT and eMTC address one of the major challenges in the IoT. Enabling cost-efficient scenarios with many sensors like Smart Waste Management or Environmental Sensing, devices need to provide years of battery lifetime to reduce costs of periodic maintenance to change or recharge the device's batteries.

Therefore two new power saving options are used in NB-IoT and eMTC:

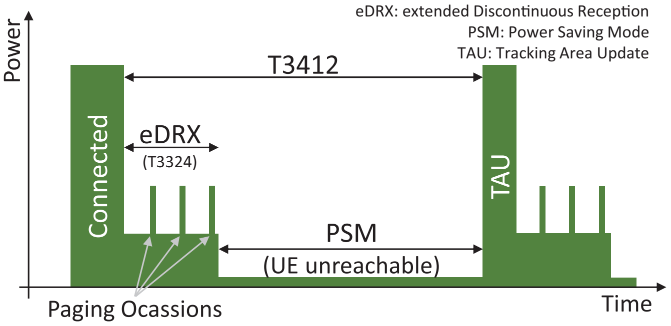


Fig. 2: NB-IoT and eMTC transmission cycle

1) PSM: When using PSM the device enters a power saving state in which it reduces its power consumption to a bare minimum [2]. In PSM the device remains registered to the network and maintains its connection configurations. When the device leaves the PSM it does not need to first attach to the network but reestablishes the previous connection leading to a reduced signaling overhead and optimized device power consumption. However, the device is unreachable for the network as long as it remains in PSM because it does not listen to the paging time windows. Mobile terminated services have to be suspended until the device reconnects to the network for a mobile originated event. Tracking Area Updates (TAU) also trigger the device to end PSM and reestablish the connection to the network. While performing a TAU the device listens to paging time windows and thus queued downlink transmissions. The maximum time between connections is given by the timer T3412. After T3412 expires, the device needs to wake up from PSM and perform a TAU.

2) eDRX: The eDRX mode extends the DRX cycles to allow a device to remain longer in a power saving state between paging occasions [2], to further reduce the power consumption. The advantage over PSM is that the device remains periodically available for mobile-terminated services and so reduces the latency for downlink transmissions. The time the device remains in eDRX is defined by the timer T3324. When this timer expires, the device will switch to PSM. Fig. 2 shows an NB-IoT and eMTC transmission cycle including eDRX and PSM.

B. Increasing the Coverage

NB-IoT and eMTC also address the challenge of high coverage. While legacy LTE devices can normally operate to a maximum of 142 dB Maximum Coupling Loss (MCL) [1], NB-IoT and eMTC are designed to meet an MCL of 164 dB.

To fulfill these requirements, eMTC introduces Coverage Enhancement (CE) Modes A and B. CE Mode A is mandatory and supports up to 32 repetitions while CE Mode B is optional and defines up to 2048 repetitions. NB-IoT also supports up to 2048 repetitions but does not divide the number of repetitions in different CE Modes, making all 2048 repetitions mandatory to all devices. Table I gives a detailed overview of the maximum number of repetitions for each NB-IoT and eMTC channel, which in turn lead to a reduced data rate.

This decreased data rate means that the overall time of a data transmission increases and will consume more power compared to a transmission without repetitions. The impact of repetitions on the battery lifetime will be analyzed later in this paper.

TABLE I: Maximum number of repetitions in eMTC and NB-IoT

eMTC Ch.	Repetitions		NB-IoT Ch.	Repetitions
	CE Mode A	CE Mode B		
PDSCH	32	2048	NPDSCH	2048
MPDCCH	16	256	NPDCCH	2048
PRACH	32	128	NPRACH	128
PUSCH	32	2048	NPUSCH	128
PUCCH	8	32		

PDSCH: Physical Downlink Shared CHannel
NPDSCH: Narrowband Physical Downlink Shared CHannel
NPRACH: Narrowband Physical Random Access CHannel
PRACH: Physical Random Access CHannel
NPDCCH: Narrowband Physical Downlink Control CHannel
NPUSCH: Narrowband Physical Uplink Shared CHannel
MPDCCH: Machine type communication Physical Downlink Control CHannel
PUSCH: Physical Uplink Shared CHannel
PUCCH: Physical Uplink Control Channel

While eMTC supports 2048 repetitions for both PDSCH and PUSCH, NB-IoT uses up to 2048 repetitions only for the NPDSCH. The maximum number of repetitions for the NPUSCH is 128. The reason for this is shown in Table II: While the NB-IoT downlink (as well as legacy LTE and eMTC) divides the time domain into fixed subframes with a transmission length of 1 ms, the NB-IoT uplink introduces a new time division, called Resource Units (RU). As introduced in Section I the NB-IoT bandwidth is divided into 12 subcarriers that can be allocated by an NB-IoT device. The fewer subcarriers a device allocates, the longer is the transmission time of one RU, spanning a time from 1 ms to 32 ms (Table II). The extension of transmission time increases the bit energy in a similar way than with repetitions, leading to a better transmission range.

IV. Power Consumption Model for NB-IoT and eMTC

To evaluate the power consumption of NB-IoT and eMTC devices, a power model is introduced, consisting of five power states (Fig. 3):

- *Connected*: After establishing a Radio Resource Control (RRC) connection the device transmits its uplink report.
- *Tail*: After transmitting the uplink report the device keeps active for a time period t_{tail} in case of possible downlink data. The tail time is defined by the network.

TABLE II: Length of NB-IoT Resource Units for different bandwidths

Number of Subcarriers	Device Bandwidth [kHz]	Length of Resource Unit [ms]
12	180	1
6	90	2
3	30	4
1	15	8
1	3.75	32

- *eDRX*: The device enters the eDRX mode. It goes in a power saving state and only wakes up in short periods for listening on potential scheduled downlink data.
- *PSM*: After a time t_{eDRX} defined by T3324 the device enters a deep sleep similar power saving mode where it is not reachable for the network. Because of the power down, the device only consumes several microwatts of power. Although the device chooses the length of T3324 by itself, the network limits the maximum time.
- *TAU*: To signal the network that the device is still alive, it needs to power up after a time t_{TAU} defined by T3412 to reconnect to the network for a tracking area update and to listen to scheduled downlink data. Although the device chooses the length of T3412, the network limits the maximum time.

While the latter four states are defined by fixed timers and are independent of the uplink report size and interval, the time spent in the Connected state varies in dependence of these parameters as well as the coupling loss, that determines the acquisition time of the synchronization signals (Narrowband Primary Synchronization Signal (NPSS), Narrowband Secondary Synchronization Signal (NSSS) for NB-IoT and Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS) for eMTC) as well as the number of repetitions for the RRC resume procedure and the uplink report transmission. Fig. 4 and Fig. 5 show the protocol overhead for NB-IoT and eMTC, respectively, caused by the channel access procedure at 164 dB coupling loss.

While this additional time spent in the Connected state is partly reception and therefore less energy consuming, the protocol overhead still makes up to 75 % of the time spent in this state [7] and is therefore taken into account as well.

The necessary transmission time for the uplink report depends on the uplink scheduling cycles aside from the uplink report size. Fig. 6 shows an NB-IoT uplink scheduling example with two NPUSCH repetitions including three resource

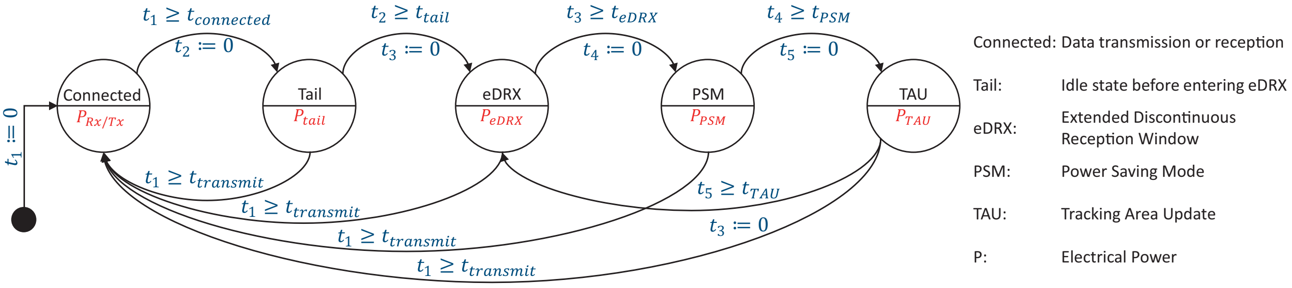


Fig. 3: State machine for power consumption evaluation

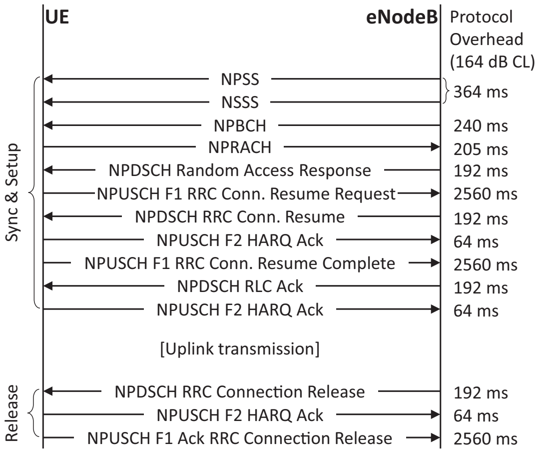


Fig. 4: Protocol overhead due to NB-IoT RRC procedure [8]

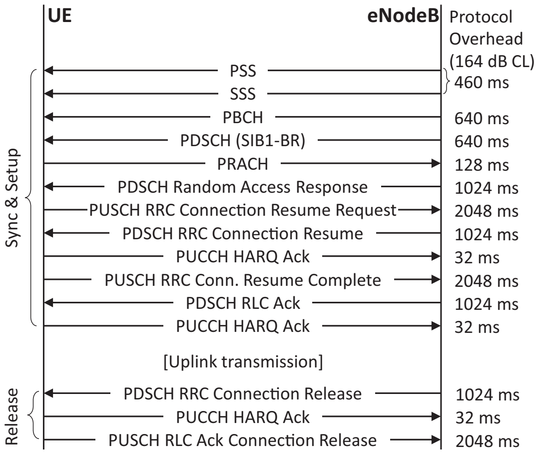


Fig. 5: Protocol overhead due to eMTC RRC procedure [7]

units per repetition [2]. Uplink report transmissions require at least an 8 ms transmission gap (TG) between the last Downlink Control Information (DCI) carried on NPDCCH and the first scheduled NPUSCH subframe. In this time the device decodes the DCI and switches from the reception to the transmission mode. After the transmission of the uplink report, the device switches back to reception mode in a further 3 ms transmission gap and gets ready for reception. Fig. 7 shows an eMTC scheduling example with three Hybrid Automatic Repeat Request (HARQ) processes [2]. Similar to LTE, after reception of a DCI carried on MPDCCH, a transmission gap of 3 ms is inserted before the device sends the uplink report. Afterwards an uplink-to-downlink transmission gap of 1 ms is inserted before the device is able to listen to further MPDCCH messages.

V. EVALUATION AND RESULTS

The consideration of the NB-IoT and eMTC RRC procedure as well as the scheduling gaps results in a detailed model. This model allows us to compare and evaluate the data rate, power consumption and latency of both technologies in an equal context. The results of this performance analysis are presented in this section.

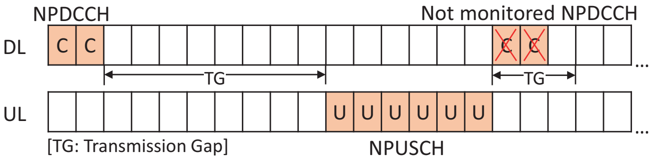


Fig. 6: Example of NB-IoT uplink scheduling

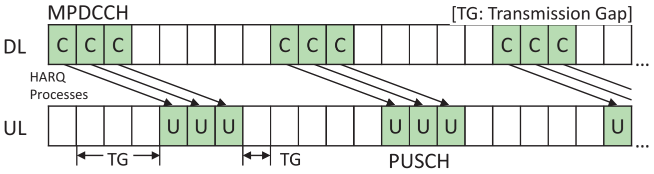


Fig. 7: Example of eMTC uplink scheduling

In order to bring the results of the analysis as close as possible to the real world, values of a real NB-IoT / eMTC modem are assumed for the electrical power. Table III lists the power consumption parameters for a Quectel BG96 device provided in [9]. Additionally, an ultra-low power microcontroller STM32L475 is considered to be used in an IoT device for sensor readings. Its power consumption in run mode and low power mode is added to the overall power consumption.

TABLE III: Power consumption parameters for battery lifetime evaluation [9] [10]

Power Consumption	NB-IoT	eMTC
Uplink Transmission @ 23 dBm	623.7 mW	709.5 mW
Downlink Transmission	62.5 mW	62.5 mW
eDRX s	3.63 mW	3.63 mW
PSM	10 µW	10 µW
Microcontroller Run Mode	1 mW	1 mW
Microcontroller Low Power Mode	1.4 µW	1.4 µW

In addition to the real-life power consumption parameters, typical IoT Smart City use cases are considered. As shown in Fig. 1 Environmental Sensing, as well as Waste Management, are battery powered IoT use cases. Especially in old buildings, water meters do not necessarily have a power supply available, so they may be battery powered as well. Table IV lists these use cases as well as the uplink report interval and size for each use case. Note that besides application data the uplink report size includes also the overhead of application, transport, internet and link layer protocols.

TABLE IV: IoT application requirements [11] [12]

Application	Uplink Report Interval [hours]	Uplink Report Size [Bytes]
Environmental Sensing	1	10 bytes
Waste Management	24	10 bytes
Water Metering	24	200 bytes

In the first step of the evaluation the data rate of NB-IoT standalone implementation and eMTC is analyzed using common IoT coupling losses of 144 dB, 154 dB and 164 dB as defined in [4], [7] and [8]. The results are shown in Table V and Table VI.

TABLE V: NB-IoT uplink physical layer data rates [2]

Coupling Loss	144 dB	154 dB	164 dB
Transport Block Size Index	7	6	6
Subcarrier spacing	15 kHz	15 kHz	15 kHz
Number of subcarriers	3	1	1
Number of resource units per repetition	8	10	10
Number of repetitions	1	4	32
Total Transmission Time Interval required for uplink transmission	32 ms	320 ms	2560 ms
Block Error Rate	10 %	10 %	10 %
Physical layer data rate	18.7 kbit/s	2.6 kbit/s	343 bit/s

Due to the use of only 3 subcarriers, NB-IoT uses one repetition at 144 dB coupling loss, resulting in a data rate of 18.7 kbit/s. Although eMTC has to use 16 repetitions to achieve a coupling loss of 144 dB, the data rate is still more than double the data rate of NB-IoT due to a shorter subframe time and less transmission gap times as mentioned in Section III. In the case of 164 dB coupling loss the data rate relations between NB-IoT and eMTC are reversed: NB-IoT achieves a physical layer data rate of 343 bit/s, while the eMTC data rate drops to 167 bit/s when using 2048 repetitions. Even with the longer Transmission Time Interval (TTI) of NB-IoT compared to eMTC, the NB-IoT transmission uses a Transport Block Size Index (TBSI) of 6, resulting with 10 RU's per repetition in a Transport Block Size (TBS) of 1000 bits. eMTC uses a TBSI of 8 and one PRB which results in a TBS of 392 bits and therefore a lower data rate. Note that with NB-IoT using only 32 repetitions at 164 dB coupling loss, the maximum coupling loss can be further extended using 128 repetitions, giving a even larger communication range with a data rate of 88 bit/s.

TABLE VI: eMTC uplink physical layer data rates [2]

Coupling Loss	144 dB	154 dB	164 dB
Transport Block Size Index	9	9	8
Number of PUSCH resource blocks	6	2	1
Number of repetitions	16	256	2048
HARQ processes	1	1	1
Total Transmission Time Interval required for UL transmission	21 ms	268 ms	2116 ms
Block Error Rate	10%	10%	10%
Physical layer data rate	40.1 kbit/s	3.1 kbit/s	166.7 bit/s

TABLE VII: Latency results for 84 Bytes data size [8] [7]

Coupling Loss	144 dB	154 dB	164 dB
eMTC	0.2 s	0.6 s	8.5 s
NB-IoT (standalone)	0.4 s	0.7 s	5.1 s

The next analysis focuses on the power consumption of NB-IoT and eMTC. When considering the devices being supplied by a standard 9V Alkaline battery, 3 Wh of energy are assumed to be available. Therefore the power consumption can be transferred to a battery lifetime as shown in Fig. 8. The results show the estimated battery lifetime for varying uplink report intervals and sizes. Additionally to the coupling losses of 144 dB, 154 dB and 164 dB, the battery lifetime of devices with even lower coupling losses and thus the maximum available data rate for both technologies is shown. It should be noted, that eMTC comes with a 4 % better battery lifetime than NB-IoT when considering 144 dB coupling loss. When getting near to the cell center and thus having less coupling loss, the battery lifetime only slightly increases. At 164 dB coupling loss, NB-IoT outperforms eMTC in battery lifetime. With increasing uplink report sizes, the difference between NB-IoT and eMTC enlarges further due to the larger data rate of NB-IoT, making NB-IoT the better technology for extreme coverage conditions.

The analysis of the latency shows the same characteristics as the previous evaluations (cf. Table VII). Considering a coupling loss of 144 dB, NB-IoT and eMTC latencies are 0.4 s respectively 0.2 s. When facing 164 dB coupling loss, the latency increases to 5.3 s and 8.5 s. This makes NB-IoT the better technology for extreme coverage conditions, again.

The results of the data rate, battery lifetime and latency analyses are summarized in Fig. 9 for an uplink report interval of 24 hours and an uplink report data size of 84 Bytes. Note

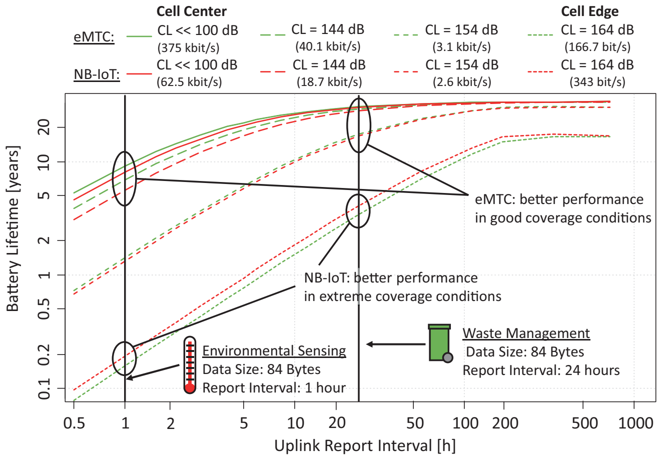


Fig. 8: Comparison of NB-IoT and eMTC battery lifetime for different uplink report intervals

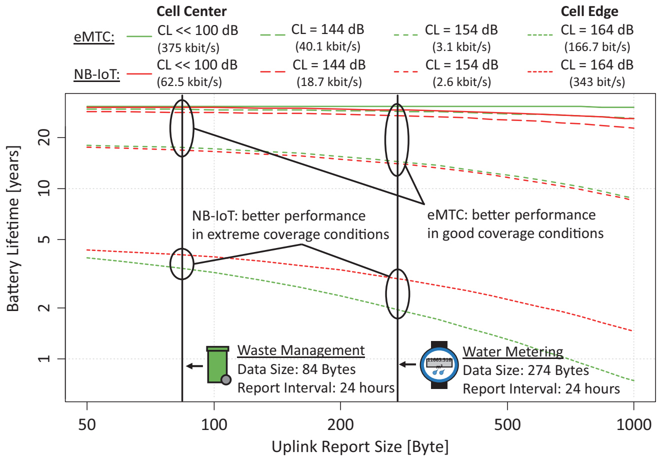
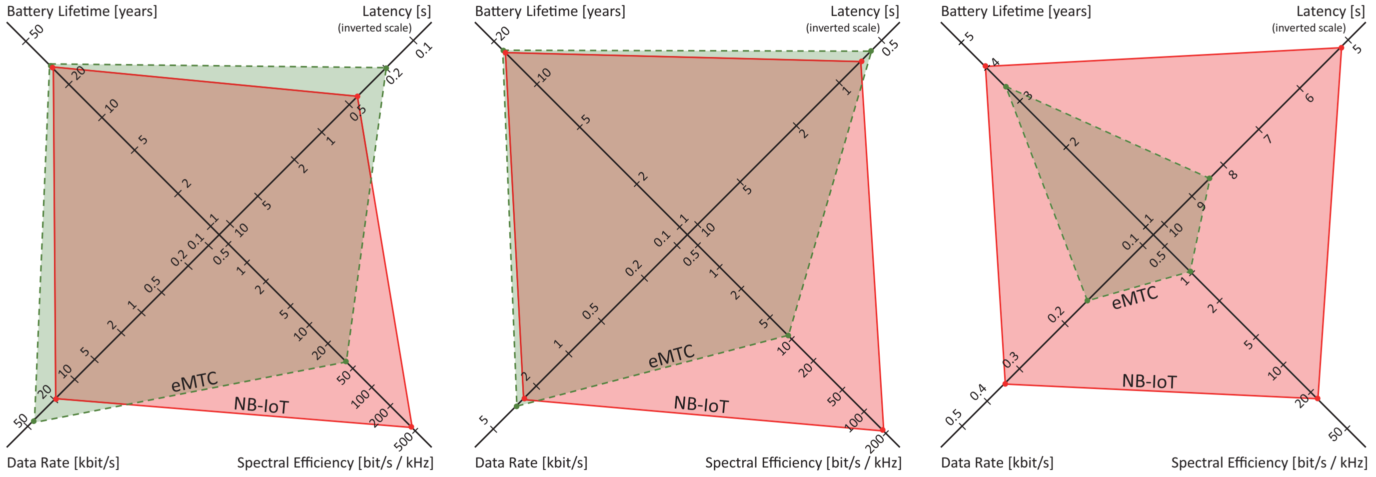


Fig. 9: Comparison of NB-IoT and eMTC battery lifetime for different uplink report sizes



a) 144 dB coupling loss **b)** 154 dB coupling loss **c)** 164 dB coupling loss

Fig. 10: Comparison of NB-IoT and eMTC devices for 84 Bytes uplink data every 24 hours in different coverage conditions

that a larger area in general means better performance. As stated before, eMTC performs better in data rate, latency and battery lifetime in both 144 dB and 154 dB coupling loss assumptions, while NB-IoT is the better choice for coupling losses in ranges of 164 dB. Fig. 9 also includes the communication bandwidth used for the data transmission. It should be noted, that eMTC requires a 12 times higher bandwidth than NB-IoT in terms of 164 dB coupling loss. Though when it comes to spectral efficiency, NB-IoT clearly outperforms eMTC, because NB-IoT uses 12 times to 24 times less bandwidth in all three scenarios.

VI. CONCLUSION

Facing the new challenges of long battery lifetime and deep coverage introduced in the Internet of Things, new technologies have been evolved. As a further development of LTE, 3GPP has introduced NB-IoT and eMTC. Both technologies come with power saving techniques such as eDRX and PSM, enabling battery powered devices lifetimes of several years without replacing the battery. For enhanced coverage repetitions are used. While using repetitions increases the coverage, the transmission time drastically increases as well, leading to a higher power consumption and shorter battery lifetime.

In this paper, NB-IoT and eMTC are subject to a performance analysis that evaluates and compares the data rate, battery lifetime, latency and spectral efficiency of these cellular IoT technologies. The results show that eMTC performs slightly better in 144 dB and 154 dB coupling loss assumptions than NB-IoT. In the case of 144 dB coupling loss eMTC performs better, providing more than a doubled data rate as well as 4 % more battery lifetime than NB-IoT. Additionally the latency of eMTC results in 0.2 s and thus being only half of NB-IoT's latency. However, the extreme propagation conditions of 164 dB coupling loss show a better performance of NB-IoT, which gets along with less repetitions and can thus provide a higher data rate. When taking the spectral efficiency into account, NB-IoT clearly outnumbers eMTC by allocating much less bandwidth and is therefore more suitable for future networks with massive numbers of devices.

ACKNOWLEDGMENT

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