Published in: 2021 IEEE 7th World Forum on Internet of Things (WF-IoT), New Orleans, USA, June 2021.
DOI: 10.1109/WF-IoT51360.2021.9596046

How Green Networking May Harm Your IoT Network: Impact of Transmit Power Reduction at Night on NB-IoT Performance

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***Abstract*—While green networking saves energy and money on base station sites, the impact on IoT devices must also be studied. Signal strength measurements show that in NB-IoT networks base stations reduce the transmit power at night or even shut-off, forcing NB-IoT devices to switch in remaining cells with worse signal strength. Therefore, this paper analyzes the impact of downlink transmission power reduction at night on the latency, energy consumption, and battery lifetime of NB-IoT devices. For this purpose, extensive latency and energy measurements of acknowledged NB-IoT uplink data transmissions have been performed for various signal strength values. The results show that devices experience increased latency by up to a factor of 3.5 when transmitting at night, depending on signal strength. In terms of energy consumption, a single data transmission uses up to 3.2 times more energy. For a 5 Wh battery, a weak downlink signal at night reduces the device battery lifetime by up to 4 years on a single battery. Devices at the cell edge may even lose the cell connectivity and enter a high power cell search state, reducing the average battery lifetime of these devices to as low as 1 year. Therefore, transmit power reduction at night and cell shut-offs should be minimized or avoided for NB-IoT networks.**

***Index Terms*—Green Communication, IoT, NB-IoT, Latency, Energy Consumption, Measurement**

I. INTRODUCTION

The Internet of Things (IoT) with billions of connected devices worldwide enables many new use cases such as intelligent waste management, connected street lights, and extensive environmental monitoring. Each day new use cases are introduced, adding more devices to the networks. While some IoT devices are connected via Bluetooth or ZigBee over short ranges, other, more distributed sensors need wide area network solutions like cellular networks. For easy deployment many IoT devices are designed to run on a single battery for many years, adding efficient communication as an additional challenge to wide area communication.

To address the IoT requirements on high energy efficiency and good coverage Low Power Wide Area Networks (LPWAN) have been developed. In addition to solutions operating in license-free frequency bands, Narrowband IoT (NB-IoT) has been introduced as a cellular-based IoT solution. NB-IoT has been designed to provide deep indoor penetration e.g. for sensors in basements, while still providing 10 years of battery lifetime and a maximum latency of 10 s (Fig. 1). Based on LTE, NB-IoT can be deployed on existing LTE infrastructure and is already available in many countries worldwide.

While NB-IoT has been designed to provide high energy efficient User Equipment (UE), the networks themselves also aim for energy efficiency. To provide environmental friendly mobile communication networks, Mobile Network Operators (MNOs) implement more efficient network equipment and cooling [1]. While base station sites consume the most energy, base stations provide the highest reduction potential to enable green cellular networks. Since most cellular networks are designed to provide enough capacity for heavy traffic hours by day, at night the provided capacity isn't used [2]. Therefore, MNOs switch off base stations at night, effectively reducing the overall power consumption [3].

While green networking is an important topic in the current research, the impact of reduced signal strength is often underrated. Base stations that are shut down at night may have a limited impact on smartphones and quality of service since most people aren't active at night anyway, the impact on IoT devices that may operate at night (or in terms of log transmissions and firmware upgrades especially at night), needs to be addressed as well. LPWAN solutions like NB-IoT have been designed to provide extensive coverage with a high battery lifetime, but rely on decent network infrastructure.

This paper addresses the impact of green cellular networks on IoT communication solutions such as NB-IoT by providing extensive measurements of latency and energy consumption from real-world NB-IoT networks and is organized as follows:

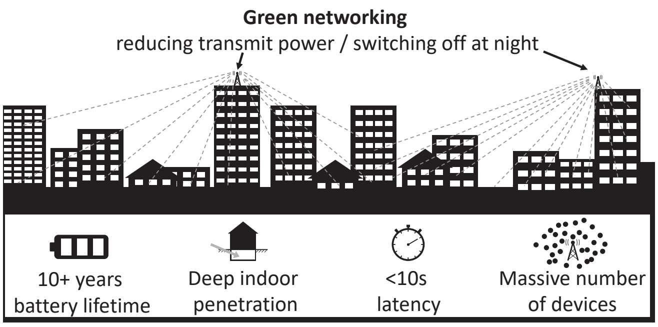


Fig. 1: Narrowband IoT objectives meet green networking

Section II briefly outlines previous works on green networking and its impact on UEs, while Section III gives a short overview of techniques for power saving and coverage extension used by NB-IoT. Section IV goes into detail on network-related behavior that has been observed in NB-IoT networks. It is followed by an analysis of the impact of green networking on NB-IoT UEs in section V and finally, the results are concluded in section VI.

II. Related Works

Green networking is an important topic in the research of communication networks. Therefore, many approaches have been introduced. [2] gives an overview of different green cellular network approaches. Besides shutting off base stations, concepts of improved hardware components, sleep mode techniques as well as a more advanced network planning and deployment are shown. In [4] the authors propose a battery lifetime-aware switching-off strategy for base stations, with which a better trade-off between base stations and UEs such as smartphones is possible. The authors in [5] introduce a switch on/off algorithm for base stations, that achieves up to 10% better performance than random switch on/off algorithms and still provides up to 29% energy saving. In [6], the authors provide an analytical model for the NB-IoT performance which demonstrates the generally strong sensitivity of the performance of devices experiencing huge path loss on the degradation of battery and latency. Also [7] discusses the impact of different channel situations in terms of varying SNR, yet dynamically changing SNR conditions based on green networking strategies are not yet considered. The scalability analysis introduced by [8] demonstrates, amongst other aspects, how the increasing number of users lead to a performance degradation of NB-IoT. This is relevant for this paper, as green networking strategies may also lead to an aggregation of user in fewer cells, once some cells are switched off during night times.

III. Modelling the NB-IoT behavior

To assess the characteristics of NB-IoT during nighttime green networking measurements, the following NB-IoT features have been considered in a dedicated model:

A. Increasing the Battery Life

With the reduction of the device power consumption, NB-IoT addresses one of the major challenges in the IoT. Enabling cost-efficient scenarios like Smart Waste Management or Environmental Sensing, devices need to provide several years of battery lifetime. Therefore two new options are used in NB-IoT:

1) Power Saving Mode (PSM): When using PSM the device enters a power-saving state in which it reduces its power consumption to a bare minimum [9]. In PSM the device remains registered to the network and maintains its connection configurations. When the device leaves PSM it does not need to newly attach to the network but reestablishes the previous connection, which leads 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 mobile originated events. 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.

2) Extended Discontinuous Reception (eDRX): The eDRX mode extends the DRX (Discontinuous Reception) cycle to allow a device to remain longer in a power-saving state between paging occasions [9]. The advantage over PSM is that the device remains periodically available for mobile-terminated services and thereby reduces the latency for downlink transmissions. Fig. 2 shows an NB-IoT transmission cycle including eDRX and PSM. Note that the device may not enter eDRX immediately after data transmission on Connected state, but needs to wait for the network to be released after an UE inactivity timer, determined by the network, expires. Concerning a low power consumption, this timer should be as low as possible.

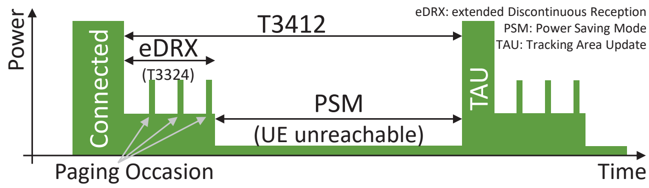


Fig. 2: NB-IoT transmission cycle

B. Increasing the Coverage

NB-IoT also addresses the challenge of high coverage. While legacy LTE devices can normally operate to a maximum of 142 dB Maximum Coupling Loss (MCL), NB-IoT is designed to enable an MCL of 164 dB. To fulfill these requirements, NB-IoT supports up to 2048 repetitions in the downlink direction and 128 repetitions in the uplink direction [9]. As each repetition transmits similar data, the application data rate decreases drastically and devices will consume more power compared to a transmission without repetitions. Additionally, in the uplink direction, the transmission bandwidth can be reduced to increase the spectral power density, resulting in longer transmission ranges. Though with a decreased transmission bandwidth the transmission time increases, which results then again in an increased power consumption.

C. Deployment Flexibility

NB-IoT supports three deployment modes. The commonly used deployment mode is the In-band mode. For that, an existing LTE cell provides one Physical Resource Block (PRB), which can be used by an NB-IoT carrier. This PRB is then not used for LTE transmissions, but exclusively for NB-IoT transmissions. The second deployment mode is Guard-band mode, where NB-IoT uses unused resources between

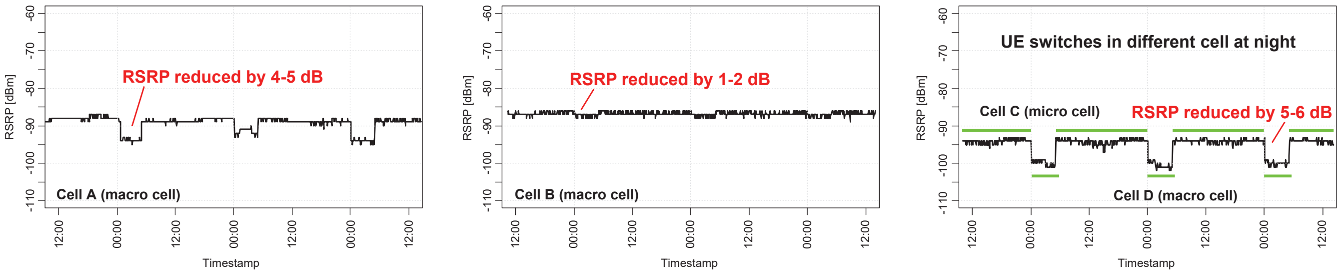


Fig. 3: Results of Received Signal Reference Power (RSRP) long term measurements in different cells of same network operator

different LTE channels. Since this mode doesn't occupy LTE resources but still uses existing channels, it is very spectral efficient. The third mode is the Stand-alone mode. NB-IoT can refarm existing GSM spectrum by reusing 400 kHz channel bandwidth for an NB-IoT carrier.

These NB-IoT specific features were implemented in an analytical model, which emulates the channel access procedure as well as uplink and downlink transmission in very detail. The model has been introduced in [10] and will be used in section V for an extended analysis of the impact of the night setback on the NB-IoT performance.

IV. Long-Term Signal Strength Measurements

Many publications on green networking in cellular networks have introduced algorithms and strategies for complete shut-offs of base stations to reduce the overall energy consumption. Since LTE (and therefore NB-IoT) base station coverage is often overlapping, devices may be able to switch into a different cell when the previous cell is shut off at night. Although devices in basements, which operate at the edge of the cell coverage, may not be able to switch into an alternative cell. To examine the impact of base station shut-offs a long-term measurement of the signal strength is carried out, whose results will be presented in this section.

A. Measurement Setup

In this paper, all measurements are performed with Quectel BG96 NB-IoT modems. For each measurement location, two NB-IoT modems are connected to a Raspberry Pi single-board computer, which coordinates the signal strength and quality measurements and transmits the measurement results via NB-IoT to a server. To determine differences between MNOs, both NB-IoT modems use other networks, henceforth called MNO1 and MNO2. Both modems measure and transmit the following values each 5 minutes:

- Reference Signal Received Power (RSRP)
- Reference Signal Receive Quality (RSRP)
- Received Signal Strength Indicator (RSSI)
- Signal to Interference and Noise Ratio (SINR)
- Cell ID

Since observed characteristics may rely on a single cell, 6 sets of single-board computers and NB-IoT modems are deployed to different locations in Dortmund, Germany. Thus measurements are performed in different NB-IoT cells, as the transmitted Cell IDs confirm.

B. Night Setback and Shut-Off in NB-IoT cells

The measurements ran for four months and produced 140,000 signal strength and quality measurement samples. Fig. 3 shows an extract from three different installation sites using MNO1 as a provider. On the left plot, the RSRP is reduced by 4-5 dB each night from approx. 12 a.m. to 6 a.m. The results are repeatable and therefore intentional behavior. The middle graph shows results from a different cell, where the night setback is limited to 1-2 dB at night. This indicates that while all examined cells from MNO1 deploy night setbacks, the extent differs between cells. The third plot gives other results. While the NB-IoT modem is attached by day to a cell which can be classified as a micro-cell, it switched each night into a different, overlay cell with macro coverage characteristics. Since the RSRP of the daytime cell is good, a night setback by 5 dB wouldn't result in losing the connection to the base station. This indicates that some NB-IoT base stations are shut off at night, forcing UEs to switch in different cells at night. As stated in section I and III NB-IoT is mostly deployed using the In-band mode which requires an existing LTE base station. Since some MNOs shut off their LTE base stations at night to reduce energy consumption, the NB-IoT cell is shut off as well. In our measurements, the switch into a different cell results in an RSRP reduction of 5-6 dB. Note that in areas, where the base station density is lower, the impact of base station shut-offs can be significantly higher.

While night setbacks are observed in all cells of MNO1, UEs using MNO2 can't confirm such behavior, since the signal strength and quality measurements are constant without any night setbacks. This demonstrates that these effects depend on the MNO and do not apply to all available operators.

V. Impact of Transmit Power Reduction on NB-IoT Performance

In section IV measurements show reduced transmit powers at night from the base stations as well as night shut-offs in some locations, resulting in a reduced transmit power of up to 6 dB. Since NB-IoT is designed to enable a high communication range by using repetitions and therefore trading energy efficiency and data rate performance, a reduced transmit power will result in a more limited performance in all IoT relevant design objectives. This section presents results of coverage, latency, and energy consumption when taking night setbacks into account.

A. Cell coverage

One of the design objectives of NB-IoT was an improved coverage by extending the Maximum Coupling Loss (MCL) from 144 dB to 164 dB [9]. Recent studies on basement penetration of LTE and NB-IoT show that up to 58% coverage gain in basements can be achieved when using NB-IoT instead of LTE [11]. When the MCL is reduced by 5 dB at night, the network coverage may not be sufficient to reach all devices on challenging installation sites.

In Fig. 4 the COST Hata radio propagation model is used to estimate communication ranges [12]. To provide deep indoor penetration ranges the COST Hata coupling loss is supplemented with 15 dB additional building entry loss derived from [13]. While an MCL of 164 dB can provide up to 3.8 km basement penetration range, this range is reduced by -26% to 2.8 km for 159 dB MCL and will not provide full coverage.

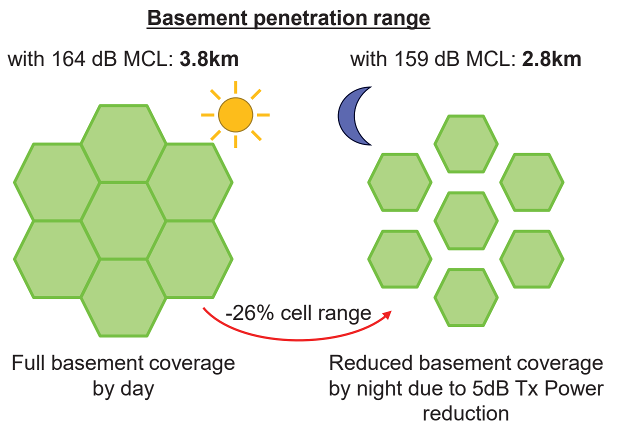


Fig. 4: Impact of Tx power reduction by 5dB on cell coverage (based on COST Hata model + 15dB basement loss)

B. Latency

Devices that aren't affected by a full signal loss are still suffering from reduced latency and energy consumption performance. To study the impact of a reduced base station transmit power, end-to-end latency measurements are performed in MNO1 NB-IoT networks. Therefore, the single-board computers that have been used for signal strength and quality measurements (ref. section IV) as well as the data receiving server are equipped with Adafruit MTK3339 GPS units for precise time synchronization. Measurements show that the time offset between the single-board computers and the server is below 20 μs. A digital attenuator is used between the NB-IoT Modem RF port and the antenna to affect the signal strength in UL and DL direction. Since NB-IoT is designed to work with very small signal strength, the setup is additionally placed in a Rohde&Schwarz CMW-Z10 RF shielding box. With this setup, the RSRP can be varied and the UE can be virtually placed at various locations such as cell edges. The results are presented in Fig. 5.

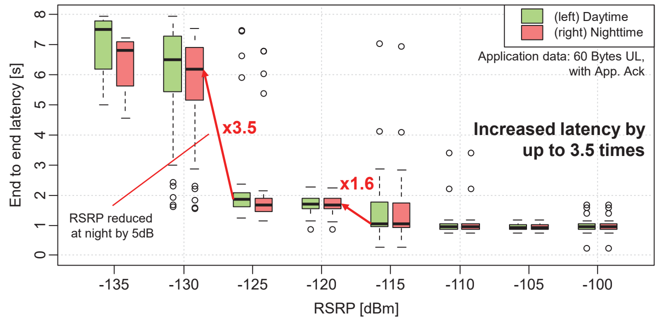


Fig. 5: Results of end to end latency measurements in real NB-IoT networks

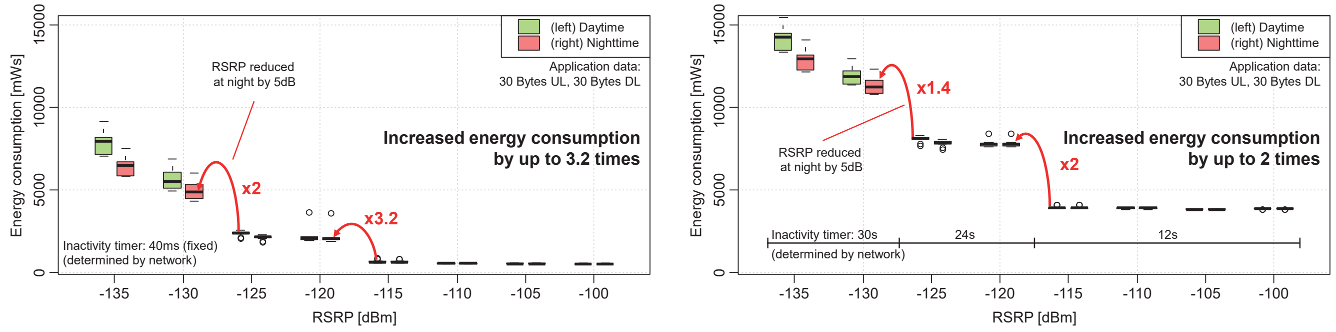
The box plots on the left side show latency results in normal networks at daytime, where a base station (downlink (DL) direction) and UE (uplink (UL) direction) both using their maximum transmit (Tx) power at day. With decreasing RSRP, the end-to-end latency increases due to a more robust signal modulation and coding as well as increasing repetitions. Between RSRP = -115 dBm and RSRP = -120 dBm as well as between RSRP = -125 dBm and RSRP = -130 dBm a significant step in the end-to-end latency is noticeable. By decoding the NB-IoT broadcast signals of MNO1, especially System Information Block 2 of NB-IoT (SIB2-NB), with an Ettus USRP B210, an overview of the network configuration is given. NB-IoT cells can configure up to two RSRP thresholds that are used by the UE to select the Random Access configuration appropriate for its coverage class [9]. The SIB2-NB of MNO 1 defines these RSRP thresholds at -116 dBm and -128 dBm, which explains the observed steps in the latency.

To evaluate the impact of a 5 dB night setback of the base station transmit power on the latency, it should be noted, that this night setback only affects the DL transmit power of the base station, but not the UL direction from the UE. That means while the DL needs at night a more robust modulation and coding as well as increased repetitions, most of the uplink transmissions are unaffected since the UE can still use its maximum transmit power. Only the Random Access signaling in UL direction is affected as well since its configuration depends on the RSRP.

To take the different DL and UL behavior into account, the measurement results are adjusted by RSRP-dependent factors that are derived from an NB-IoT simulation model [10] and are presented on the right side of each RSRP measurement (marked as nighttime). The results show that at night the latency can increase significantly up to 3.5 times due to switching the RSRP coverage class and longer DL transmissions due to a weaker signal.

C. Energy Consumption

While latency is negligible for most NB-IoT use cases, energy consumption is essential. Therefore the evaluation is



(a) UE inactivity timer < 0.1s

(b) UE inactivity timer > 10s

Fig. 6: Results of energy consumption measurements in real NB-IoT networks for different implementations of Inactivity Timer

extended to an energy consumption measuring sequence. Fig. 7 gives an overview on the measurement setup.

In addition to the digital attenuator and the shielding box, that have been introduced in subsection V-B, the measurement setup is complemented by a Hitex PowerScale power measurement device. The power measurement device can synchronously measure voltage, current, and power consumption for up to 4 channels. Since the Quectel BG96 NB-IoT Modem as the Device Under Test (DUT) provides two separate power supplies for the device's baseband and RF part, both supplies need to be measured at the same time. Therefore, the PowerScale with two external power probes is well suited for energy consumption measurement.

Fig. 6 gives an overview of the energy consumption results for different implementations of the UE Inactivity Timer. The UE Inactivity Timer is defined as the duration after a data transmission that the UE remains connected to the network until it is released to the eDRX power-saving state (ref. III-A2). To increase power efficiency, this timer should be as low as possible for NB-IoT UEs. Fig. 6a shows the energy consumption for a single, acknowledged data transfer for different RSRP values in a network like MNO2 with a short UE Inactivity Timer of 40ms. Unfortunately, MNO1 uses UE Inactivity Timers up to 30s, resulting in a drastically increased power consumption compared to MNO2.

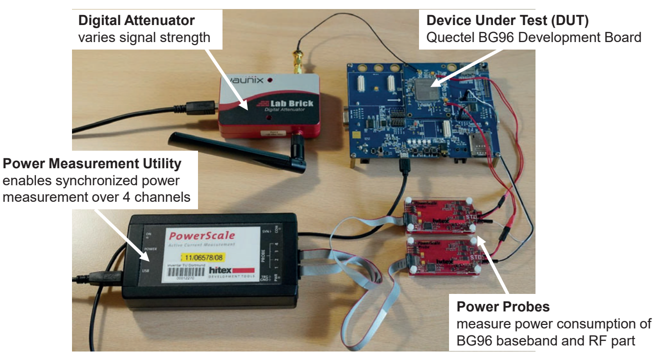


Fig. 7: Setup for energy consumption measurements of Quectel BG96 NB-IoT device in real NB-IoT networks

Besides the consequence of different UE Inactivity Timers, the impact of night setbacks on energy consumption is analyzed. Again, to take the different DL and UL behavior into account, the night setback measurement results are adjusted by RSRP-dependent factors that are derived from an NB-IoT simulation model [10] and are presented on the right side of each RSRP measurement (marked as nighttime).

As in the latency measurement results, two significant steps in the energy consumption are noticeable, caused by the network-determined RSRP thresholds for different coverage classes. Besides these steps and as expected, the energy consumption increases with decreasing RSRP due to a more robust signal modulation and coding as well as increasing repetitions, leading to longer transmission and reception times. As for the impact of the night setback, the energy consumption increases significantly up to 3.2 times due to switching the RSRP coverage class and longer DL transmissions caused by a weaker signal.

D. Battery Lifetime

In the previous section, the results of the energy consumption measurement were discussed. For the user, the battery lifetime is a more concrete metric to illustrate the impact of a base station night setback. Therefore the battery lifetime model introduced in [10] is used to derive the UE's battery lifetime for different RSRP values, base stations with and without night setbacks as well as networks with short and long UE Inactivity Timers. The results for an application that transmits data once a day and a 5 Wh battery are presented in Fig. 8.

While the solid line in Fig. 8 provides the battery lifetime of UEs in networks without night setbacks or preferred daytime transmissions, the dashed line represents the battery lifetime of UEs transmitting under the influence of base station night setbacks. The results show that the battery lifetime is decreased by up to 4 years. Devices operating at the cell edge (RSRP = -135 dBm) by day lose the cell connection at night due to the night setback and maintain in a high energy consuming cell search state. With an average power consumption of 283 mW during the cell search and assuming the worst case where a cell edge device is scheduled right to the beginning of the

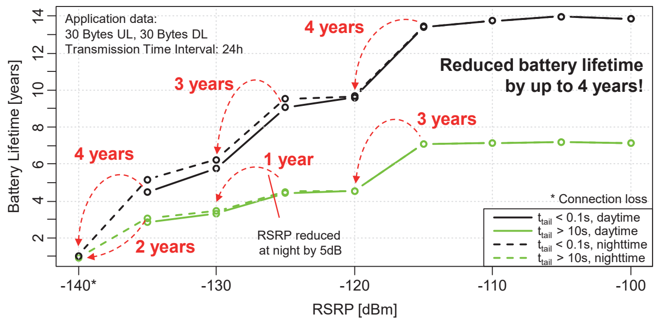


Fig. 8: Results of battery lifetime based on energy consumption measurements in real NB-IoT networks

night setback, the device performs 6 hours of cell search each night and thereby drains its battery in only 3 days.

VI. Conclusion

Green networking has been an important topic in research on mobile communication networks for years. Both the environment and the operator benefit from reducing the energy consumption of e.g. radio equipment of cellular networks. Therefore, many approaches have been introduced in the past years, most of them discussing the shut-off of less used base stations at night. To evaluate the impact of base station shut-offs on the performance of NB-IoT devices, signal strength was measured over 4 months in several cells and for different mobile network operators. The results show that one operator provides a constant signal strength level for all base stations even at night, while another operator reduces the transmit power of NB-IoT base stations by up to 5 dB at night and even partially shuts off single NB-IoT base stations, which triggers the NB-IoT devices to switch in remaining cells with lower signal strength.

Since green networking approaches can save energy and thus money for the operator, reducing the downlink transmit power at night, called night setback for short, may harm the performance of NB-IoT devices. Therefore, measurements for latency and energy consumption are performed, and the results are then transferred to a battery lifetime model. Taking into account that the night setback only affects downlink transmissions and partially uplink transmissions, the results show that devices experience an increased latency up to a factor of 3.5 when transmitting at night, depending on the signal strength. In terms of energy consumption, a single data transmission uses up to 3.2 times more energy. For a 5-Wh battery, a weak downlink signal at night reduces device battery life by up to 4 years on a single battery. Devices at the cell edge can even lose the cell connectivity at night and switch in a high-power cell search state, reducing the average battery lifetime of these devices to 1 year.

The measurements and analyses show that an NB-IoT base station transmit power reduction of 5 dB at night can cause a huge impact on the performance of NB-IoT devices and should be avoided. While LTE users are not greatly affected by shut-offs or night setbacks, IoT devices operating day and night suffer from these energy-saving strategies. The costs of green networking in NB-IoT networks are then paid by devices and users especially in shorter battery lifetimes. While increased energy efficiency at base stations for green networking should not be targeted through night setbacks to the disadvantage of battery-powered IoT devices, more base stations should instead be equipped with on-site renewable energy sources such as solar photovoltaic (PV) systems. According to the 2019 Vodafone Sustainable Business Report only 1,200 of 167,200 base station sites and buildings are equipped with on-site renewables [1], which indicates the great potential of future efforts for greener networking while still providing the best performance for NB-IoT networks and users.

Acknowledgment

This work has been carried out in the course of the PuLS project, funded by the Federal Ministry of Transport and Digital Infrastructure (BMVI) under grant agreement no. 03EMF0203B and was supported by the Collaborative Research Center SFB 876 Providing Information by Resource-Constrained Analysis, project A4.

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