Performance of TCP and UDP over Narrowband Internet of Things (NB-IoT)

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***Abstract*—NB-IoT extends LTE by low power WAN functionality for IoT applications. Strengths of the standard lie in the already existing infrastructure, an ubiquitous availability, and the low power consumption and costs. NB-IoT supports both TCP and UDP as transport protocols. However, TCP is sensitive to delays and packet losses during data transmission. This affects the commonly used messaging protocol MQTT, as it uses TCP as its underlying transport protocol. In this paper the role of UDP as a possible transport layer protocol for NB-IoT in conjunction with MQTT-SN is discussed and compared to TCP with standard MQTT. Using TCP for a typical NB-IoT application resulted in a packet loss of about 90%, whereas UDP achieved a packet loss of only around 3%. Additionally, the current state of NB-IoT installations in Germany and their functionality are evaluated. Coverage, signal quality and power saving functionality are monitored and analyzed as well.**

***Index Terms*—NB-IoT, MQTT, MQTT-SN, UDP, TCP**

I. Introduction And Related Work

While offering many advantages, popular IoT communication standards often require the setup and maintenance of additional infrastructure, e.g., local gateways in LoRaWAN. This investment can be avoided by using cellular IoT (cIoT) standards such as NB-IoT, enhanced Machine-Type Communication (eMTC), or Extended Coverage GSM (EC-GSM). Here, the tasks of installation, operation, and maintenance are provided by the network operator. Registration, security, and power saving mechanisms are optimized and available networks and hardware of operators can be utilized. Unlike other mobile communication standards cIoT allows a communication even with constrained devices. Both eMTC and NB-IoT support UDP and TCP transmissions. eMTC provides data rates of up to 1 Mbps in both the up-link and down-link, while NB-IoT only reaches 25% of this value. eMTC introduces less delay and with its higher data rate supports a wider variety of applications. NB-IoT is not usable for delay-sensitive applications, as even small-sized data transmissions can take up to several seconds. Both standards may use present LTE infrastructure. However, up to now in Germany only NB-IoT has reached an acceptable level of coverage.

With NB-IoT's delays in data transmissions, TCP is heavily unreliable, although it is supported by the standard. In IoT applications data is usually transmitted to one or more servers. The server stores the message content in a database and possibly allows the user to access visualizations and downloads. Protocols like Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP) or Lightweight M2M (LwM2M) are commonly used to convey the messages. CoAP and LwM2M, sometimes also used in combination, both support UDP. MQTT on the other hand requires TCP unless the adaptation MQTT for Sensor Networks (MQTT-SN) is employed.

UDP is the recommended transport protocol for NB-IoT applications. The susceptibility of TCP to delays in data transmissions is high which was confirmed by our experiments. The use of TCP is preferred for reliable connections but it introduces further delays due to its requirement of a handshake and bidirectional connectivity. TCP therefore increases the energy consumption and the total delay of transmission. The use of UDP on the other hand requires a messaging protocol that supports it. The evaluation of the experiments described in our work shall show the real usability and reliability of the two transport protocols in an example application. The application implies a periodic transmission of small packets as in common sensor applications. The results are specific to the used operator network, present signal quality and the location. However the inferior reliability of TCP with NB-IoT is unlikely to be ignoreable for most applications as even when data loss is acceptable, higher power consumption is not.

UDP when compared to TCP trades less reliability with lower latency and load on systems. The commonly used messaging protocol MQTT requires TCP. The alternative messaging protocol, CoAP, allows the utilization of UDP for constrained applications. CoAP was compared to MQTT in [7] and found to perform better in NB-IoT applications. In this paper MQTT-SN is used instead to test the performance of UDP transmissions over NB-IoT.

In [1] the power saving and coverage enhancement mechanisms are described and discussed. An important result of their experiments regarding delays in NB-IoT message transmissions is that the delay does not depend on the message size. The message delays are generally in the range of 0 to 39 seconds and can reach up to 270 seconds in some cases. This leads to higher power consumption. It is shown that a simple handshake to establish a TCP connection can take up to several minutes.

Scheduling algorithms impact the delay especially with a large number of UEs per cell. Algorithms that are used in NB-IoT networks have been evaluated in [8]. Results show that an ordered prioritisation based on clusters of UEs improves

978-1-7281-2516-9/19/$31.00 ©2019 IEEE

network performance and reduces congestion.

A concise calculation of the power consumption of NB-IoT applications is complex and in most cases can only be determined empirically. This is due to the high variability in power consumption based on the network, signal quality, and size and time of up-/down-link transmissions. Consequently, the maximum battery lifetime of a NB-IoT device can only be given as an estimation and does not have to correspond to reality as the operator and other UEs are an uncontrollable factor. A careful configuration of the timers which control NB-IoT's PSM and eDRX is required to achieve a long battery lifetime. A power consumption model for estimation of the battery lifetime in NB-IoT applications is proposed in [4]. A similar model but only for active and connected UEs has been created in [9].

The rest of this paper is organized as follows: Section II summarizes some basics of the NB-IoT standard and the MQTT protocol supporting the understanding of our measurement results. The measurement setup for the NB-IoT coverage test as well as for the performance comparison of MQTT with TCP and MQTT-SN with UDP are presented in Section III. Measurement results are given in Section IV. Finally, Section V concludes this paper with a short summary and possible future work.

II. Background

A. Narrowband Internet of Things (NB-IoT)

NB-IoT is a radio interface first specified by 3GPP in Release 13 and enhanced in the following releases 14, 15 and 16. It is added to the LTE platform and inherits as well as enhances several features. NB-IoT is targeted to stationary applications insusceptible to delays in data transmission. This comprises IoT applications such as smart meters, smart parking systems, and a variety of other sensor-based services. NB-IoT operates in licensed spectra of LTE or GSM frequency bands. It uses small bandwidths of only 180 kHz for bi-directional radio transmissions. A new sub-carrier spacing of 3.75 kHz was introduced which fits into the LTE sub-carrier spacing of 15 kHz. As for LTE a NB-IoT multi-tone transmission uses 15 kHz sub-carrier spacing whereas single-tone transmissions require a bandwidth of 3.75 kHz. In the down-link NB-IoT employs QPSK modulation and OFDMA, in the up-link either QPSK or BPSK with SC-FDMA. Data rates are between 600 bps and 250 kbps both in down-link and up-link.

NB-IoT can be deployed in three different modes of operation: It can either utilize an existing LTE deployment by using Resource Blocks (RBs) within a LTE carrier (in-band operation) or employ unused RBs in the guard-band (guard-band operation). The third mode of operation is based on the deployment of re-farmed GSM carriers.

There are two possible Radio Resource Control (RRC) states in NB-IoT: *RRC Connected* and *RRC Idle*. When a UE first connects to an eNodeB it changes to *RRC Connected*. If the eNodeB releases the connection the UE switches to *RRC Idle*. A connection is released when no data transmissions have occurred for a given duration of time. This parameter is not controllable by the user. During *RRC Idle* the UE saves the negotiated security configurations and parameters towards Access Stratum (AS) [1]. This reduces the signaling overhead and saves power each time a connection is resumed. While being connected the UE cannot perform handovers. Cell re-selection without new registration is possible only after transition to state *RRC Idle*.

Once the RRC has released the connection two power saving modes of NB-IoT can be entered: eDRX or PSM.

1) Extended Discontinuous Reception (eDRX): eDRX is an adaptation of the existing Discontinuous Reception (DRX) enhancement of LTE. Unlike PSM eDRX can be used both when in both states of the RRC. In eDRX the UE is idling in a low power mode and receives paging updates in fixed intervals. The UE will receive down-link data at the end of each cycle. The cycle duration is the sum of the sleep time and the paging time window (PTW) in which down-link data is received. The down-link reception delay is variable depending on the cycle duration and time of down-link transmission in the ongoing cycle. DRX cycles are ranging from 1.28 to 10.24 seconds [1]. In NB-IoT the maximum cycle duration is increased to almost 3 hours with eDRX, but only available in state *RRC idle* [1]. The power consumption of the used NB-IoT module in eDRX can be specified by two states. The idle NB-IoT modules, between down-link receptions in eDRX consumes about 2 mA. The module consumes about 60 mA while receiving [3].

2) Power Saving Mode (PSM): During the PSM UEs enter a sleep state to reduce their power consumption. Power consumptions of only a few μA result for this state. UEs can exit the PSM at any time to perform data transmissions. No re-registration with the eNodeB is needed after exiting the PSM. However, data transmission is not instantaneous since the eNodeB first needs to confirm the transition from *RRC idle* to *RRC connected* state. The PSM is activated once the activity timer (T3324) expires. This timer is configurable by the user [1] and has a maximum value of 186 minutes. During PSM the UE cannot receive down-link transmissions, i.e. no externally initiated wake-up is possible. Another timer (T3412) is used to set the length of the sleep time after which the UE is activated to perform Tracking Area Updates (TAUs) [1]. The maximum duration for this timer (T3412) is around 413 days. TAUs are sent from sleeping UEs to the respective eNodeB in order to keep them registered. After wake-up from PSM no further transmissions for registration with the eNodeB are necessary. This saves additional power. As modules allow to control both timers their configuration is crucial for the battery lifetime of an NB-IoT device.

3) Coverage Enhancement Mechanisms: There are three different coverage enhancement levels (ECL) in which messages are re-transmitted to accomplish a successful message transfer. ECL can be used in the down-link and the up-link. The lowest level ECL0 corresponds to normal operation. ECL0 is active when the UE reports a high SNR value above a threshold defined by the eNodeB. ECL2 is used for the worst case connectivity below a minimum value of the reported SNR set by the network operator. The number of repetitions ranges

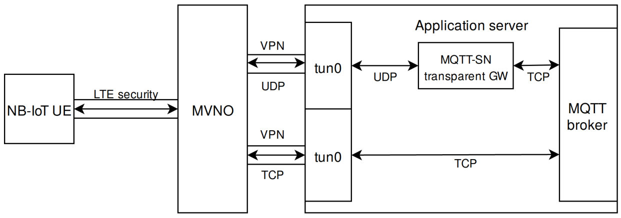

Fig. 1. Network topology used for the measurements

from 2 to 128 (2^i with i=1...7) [1]. In multi-tone transmissions ECL repetitions are sent out simultaneously over different sub-carriers rather than subsequently over time as this is the case for single-tone transmissions [1].

B. MQTT For Sensor Networks (MQTT-SN)

MQTT utilizes TCP/IP as its underlying transport protocol. This may be a problem for constrained devices with performance or memory restrictions. Additionally, bad wireless links extends the message transfer due to packet loss or delays in transmission. An adapted version of MQTT called MQTT-SN was introduced to allow a communication with constrained devices in non-TCP/IP networks. Compared to MQTT MQTT-SN uses different message formats and procedures to avoid the need for TCP and its flow control, error correction, and re-transmission mechanisms. MQTT-SN eris characterized by shorter message lengths and adaptations to unreliable links. It is designed to be compatible to MQTT. MQTT-SN introduces gateways to translate MQTT messages into the MQTT-SN format and vice-versa. MQTT-SN is designed to be independent of the underlying network which has only to offer packet delivery to network addresses with error detection [2]. MQTT-SN introduces an additional QoS level -1 (minus one) specially for constrained devices [2].

In MQTT-SN QoS level -1 the client "does not care whether the gateway address is correct, whether the gateway is alive, or whether the messages arrive at the gateway" [2]. This is well suited for UDP since no connection is established and no reception acknowledgements are sent. Publishing with QoS level -1 requires no set-up procedures or handshakes with the gateway before data transmissions [2].

III. Measurement setup

A battery-powered embedded system including a Quectel BC95G and a GPS module has been implemented for measurements. SIM cards running in the network of Telekom Germany were utilized to access NB-IoT. Data transmissions utilize MQTT QoS 0 for TCP and MQTT-SN QoS -1 for UDP. An antenna with a gain of approximately 1 dBi for LTE band 8 was chosen. The control of the NB-IoT module uses AT commands defined by 3GPP and the module manufacturer. The functionality of the NB-IoT module includes publishing via MQTT-SN (UDP) or MQTT (TCP). The MQTT protocol is included in the BC95G's firmware and therefore only requires the transmission of AT commands. No further MQTT client library is needed to utilize the protocol. The MQTT-SN client library has been written to accommodate the features of the MQTT-SN specification version 1.2 [2]. The topic ID and network addresses are known to both the client and the MQTT-SN gateway. The software implementation has a very small footprint since the configuration is fixed and only QoS level -1 is used. This allows constrained devices to use MQTT even when there is no down-link connection.

An application server was set up containing the MQTT broker, the MQTT-SN gateway, and a web application for data visualization (see Fig. 1). The web application writes messages received by the MQTT broker into a database. MQTT messages can reach the server on a specific port while another port is used for UDP packets received from the MQTT-SN gateway. TLS is not used. Incoming traffic is encrypted by a 128/256 bit key for data transmissions between UE and eNodeB [6]. The eNodeB forwards the data to the cIoT Serving Gateway Node (C-SGN) which transmits the data to the destination [6] using an IPSec-tunnel. The first destination is the server of the mobile virtual network operator (MVNO) who provides the SIM card. Traffic from this server to the application server is secured by a VPN tunnel. The web application is based on Flask, a web microframework for Python. A SQLite database is used to store any data that is received via MQTT. A map was embedded in the web application to visualize the coverage measurements. Markers are automatically created at the transmitted GPS coordinates and carry further information regarding NB-IoT. Messages without available GPS coordinates are not shown on the map but saved in the database, too.

IV. Measurement Results

Measurements of the performance of NB-IoT with MQTT-SN are described and evaluated in this section. The goal of the tests was to investigate the usability of NB-IoT in its current state of deployment in Germany as well as to test its performance when using the transport protocols TCP or UDP. In a first step a NB-IoT coverage measurement for NB-IoT in the Cologne area was conducted. Several NB-IoT parameters were recorded for later analysis of the mechanisms and the behavior of UE and eNodeB in a NB-IoT network. Then the usability of TCP and UDP as transport protocols in conjunction with MQTT and MQTT-SN, respectively, was investigated. This included a long-term measurement of both transport protocols under similar conditions. For both cases the packet loss rate and its dependence to the underlying protocols and NB-IoT mechanisms was evaluated.

A. NB-IoT Coverage Test

The NB-IoT coverage in Germany has improved heavily since mid of 2018. Vodafone DE and Telekom Germany are the main driving forces. Coverage maps indicate a coverage level in the range of approximately 90 % of Germany's surface area. Most major urban areas and cities of Germany are covered. Our tests revealed that the current installation uses existing LTE networks exclusively. No re-farmed GSM carriers were used in the measurement locations. Areas without LTE

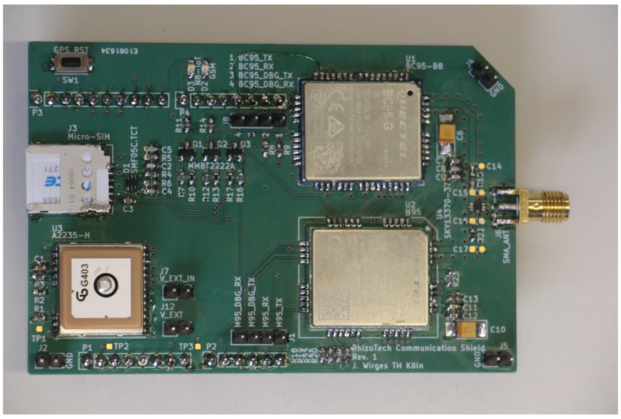

Fig. 2. Hardware setup used for the measurements

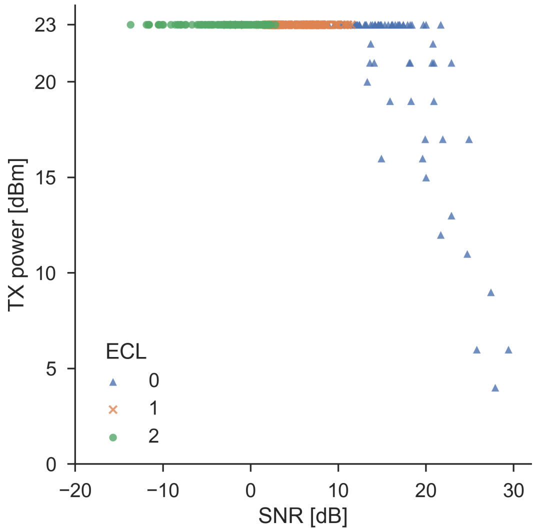

Fig. 3. TX power and ECL as function of the SNR (378 measurements)

coverage are almost always outside of NB-IoT coverage. However, with NB-IoT's coverage enhancements this is not always the case. Measurements revealed a variable level of coverage even in metropolitan areas. Locations without coverage have been identified in some urban areas around Cologne. No LTE coverage was given for these cases, too. The results show that in the considered area the LTE and NB-IoT coverage are quite similar. In total 378 measurements distributed over a distance of 250 kilometers were taken. The coverage was measured in 85 different cells. The data indicates that only a small part of the functional spectrum of NB-IoT defined in Release 13 is currently offered by the network operator. This may be due to the low number of installed NB-IoT devices. Most functionality is related to scalability. All measurements indicate that the same frequency band and mode of operation is used in all cells. The NB-IoT module and its configuration through AT commands did not restrict the parameter selection. Its capabilities and configuration support a wider range of options.

All measurements contained several other parameters related to NB-IoT and signal quality. Information on the functionality of specific NB-IoT mechanisms can be gathered from these parameters. The dependency of TX power and coverage enhancement levels (ECL, see Section II-A3) with varying SNR values are depicted in Figure 3. At a low SNR, more re-transmissions are initiated to ensure a successful message transfer. At SNR values below 0 dB the highest ECL (2) is used exclusively. High SNR values above 13 dB implicate the use of the lowest ECL (0). At SNR values above 13 dB, the TX power of the UE is decreased by the open loop power control of NB-IoT. In total there were 27 measurements at a transmission power below 23 dBm.

The power consumption of the Quectel BC95G NB-IoT module in LTE band 8 can be reduced by 41 % when decreasing the TX power from 23 dBm to 12 dBm and by 68 % when setting it to 0 dBm [3]. Depending on the frequency of up-link data transmissions the battery lifetime may be doubled by reducing the TX power to below 10 dBm compared to a TX power level of 23 dBm. The signal quality threshold which allows the decrease of TX power levels is not configurable by the user. The open loop power control and its parameters are configured by the operator.

The registration time (hereinafter referred to as t_r) is the time from the start of the boot process of the NB-IoT module to the completion of its registration to the NB-IoT network. During this time no data transmissions can be performed. Re-registrations can be avoided by using NB-IoT's PSM. For our measurements t_r varied in a range between 15 to 80 seconds. The average registration time is around 30 seconds. The two histograms in Figure 4 show the distribution function of the Reference Signal Received Quality (RSRQ) and t_r value in the measurements. RSRQ is a signal quality parameter calculated from the Reference Signal Received Power (RSRP) and the Received Signal Strength Indicator (RSSI). It is defined by the following equation:

$$RSRQ = N \cdot \frac{RSRP}{RSSI} \tag{1}$$

The RSRP measures a single reference carriers signal power inside a specific reference bandwidth. N denotes the number of RBs used in the RSSI and RSRP measurements. RSRQ is usually given in dB. At a first glance the data indicates that a high RSRQ may lead to a a lower t_r. There is a minimal correlation between RSRQ and t_r, as can be seen in Figure 5. Both figures, Figure 4 and 5, are created with identical data from the coverage measurements. Outliers of both values in Figure 5 show that there is no fixed dependency between signal quality and t_r for the full range of values. A t_r lower than 38 seconds was not achievable in the measurements with a RSRQ below -18 dB, as can be seen in Figure 5. A lower t_r can be reached by improving the RSRQ. If the RSRQ is above -14 dB, t_r may be reduced by an improvement of the signal quality. Other factors such as the load on the eNodeB from other UEs may be the reason for variations of

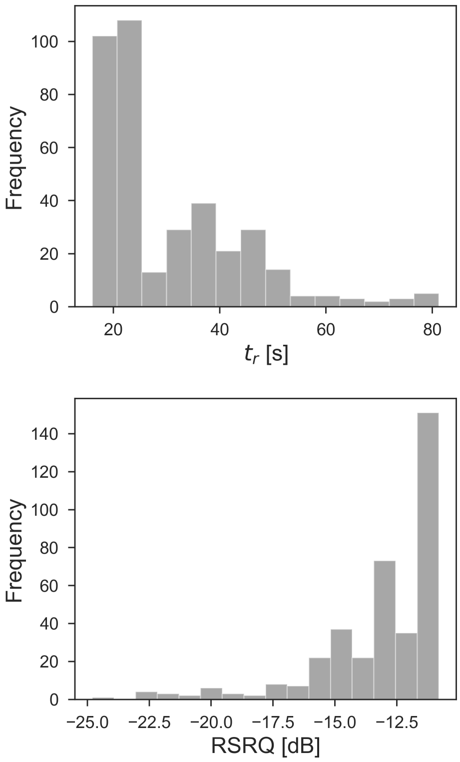

Fig. 4. Distribution of RSRQ and registration delay t_r

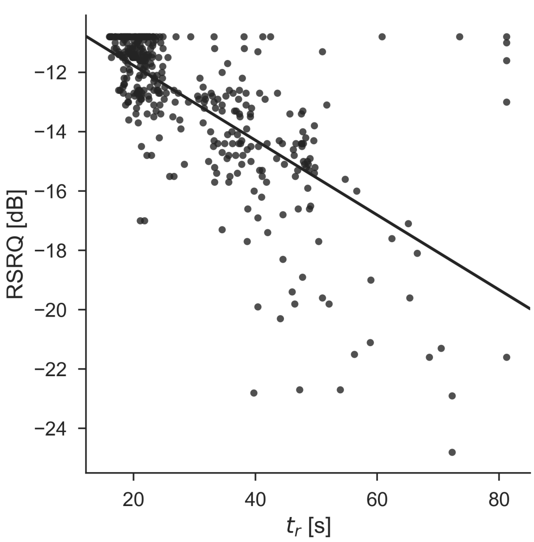

Fig. 5. RSRQ versus NB-IoT network registration delay t_r

t_r with RSRQ values $>$ -14 dB. As signal quality and t_r are slightly correlated it is encouraged to place the antenna of the UE in a optimum position as this may significantly reduce the power consumption in each single registration process. Handshakes between UE and eNodeB are necessary for each registration in the network. If a handshake fails, the module has to re-attempt the registration. The registration process includes transmissions, receptions, and idle times of the UE. The power consumption therefore varies during the process. However the overall power consumption is increased with a higher t_r.

The results show that even with good RSRQ values a long registration period delays the data transmissions heavily. PSM decreases the power consumption and leads to a reduction of the delay before transmission as registrations are not performed as often.

TABLE I
PACKET LOSS RATE OF MQTT/MQTT-SN MESSAGES

	MQTT	MQTT-SN	Total
Transmissions	9003	9003	18006
Receptions	936	8666	9602
Packet loss rate	89.60 %	3.74 %	53.33 %

B. *MQTT And MQTT-SN Via NB-IoT*

UDP is not sensitive to delays which may interrupt the connection. Additionally it introduces less overhead when compared to TCP. The effect of variable delays in NB-IoT data transmissions provides an argument to choose UDP instead of the also supported TCP. Especially the three-way handshake is problematic since timeouts and loss of connection become more likely. On the other hand UDP offers no mechanisms to guarantee the arrival of an error-free message at the destination.

For the test both MQTT-SN and MQTT messages have been periodically transmitted over a period of one week. Directly before and after the measurements NB-IoT and signal quality parameters have been recorded. The transmitter was located in a lab room on the eighth floor of the university building. Both the MQTT and MQTT-SN packets were sent to the same broker. The payload of the packets had a size of 16 bytes for MQTT and 18 bytes for MQTT-SN.

In the test approximately 18000 MQTT (TCP) and MQTT-SN (UDP) messages were sent to the application server via NB-IoT. A pair of one MQTT and one MQTT-SN message was transmitted by the NB-IoT UE with a spacing of about 67 seconds. The spacing inside the messages is varying based on the duration of the TCP connection establishment, which is required by MQTT. The number of received messages together with other parameters was recorded. The main results are shown in Table I. As shown by the data, approximately nine out of ten MQTT messages are not reaching their destination at all or without errors. The recorded losses of TCP packets are in general evenly distributed over time even though longer periods without any working TCP transmission have been recorded. The longest period of full packet loss had a duration of approximately three hours. Four more outages between one and three hours were recorded. Signal quality parameters were recorded during the packet loss measurements. The average RSRQ was -12.13 dB with a standard deviation of 0.17 dB. For this average RSRQ value ECL1 was set by the operator throughout all measurements. NB-IoT is designed to work

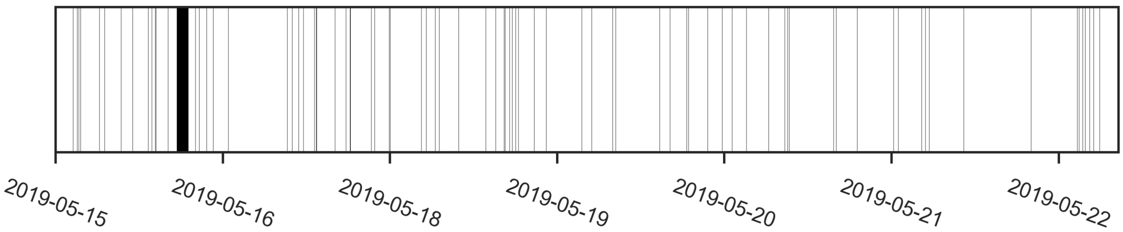

Fig. 6. UDP packet losses in the measurement period (May 2019)

under even worse signal conditions. In this case the ECL and as a consequence the number of re-transmissions as well as the delay are increased. This further impairs the packet loss rate of TCP. For transmissions of sensor data used for statistical purposes where losing a small percentage of data is acceptable UDP should be used instead of TCP. The loss of MQTT-SN messages via NB-IoT is shown in Figure 6. On the second day the NB-IoT network was not responding for a time of approximately 1 hour and 34 minutes. This was the longest continuous outage and also the only outage of a duration of more than five minutes for MQTT-SN. The application server and the MQTT broker were fully functional during this interruption. It is unclear whether the application server of the SIM card provider or the network of the cellular operator was responsible for the problem. Their states could not be monitored during the interruption of the data transfers. Further shorter interruptions in the range of four to five minutes were observed, which might be critical for specific IoT applications. Service interruptions like these occurred five times during the measurements. Apart from this, UDP shows an acceptable packet loss rate. The MQTT-SN message loss rate can be reduced with its higher levels of QoS.

V. Conclusions and Future work

In this paper, the performance of UDP over NB-IoT was evaluated and compared to TCP over NB-IoT. The goal was to evaluate the reliability of both transport protocols and find reasons or solutions for the unreliability. MQTT and MQTT-SN were chosen as messaging protocols. Tests of coverage and reliability of the data transmissions show that NB-IoT in conjunction with UDP is well suited for IoT applications which are unsusceptible to varying delay and tolerate packet loss rates below <5 %. In contrast TCP based message transfers resulted in packet loss rates of about 90 %. This makes a reliable and energy efficient operation for battery powered end devices nearly impossible. The measurements also show that unlike with other communication standards good signal quality is mandatory for a high battery lifetime of the end devices. Having a good signal quality NB-IoT UEs may lower their TX power level and perform less re-transmission. Transactions such as network registration and down-link data transfers are completed quicker, too, further reducing the power consumption.

During long term measurements outages of the NB-IoT service up to several minutes were recorded. However, for a variety of sensor applications NB-IoT seems to be a reasonable choice and shows to be superior to other LPWANs in several aspects. These are the already existing infrastructure as well as the inherited security and control functions.

Packet loss measurements indicate that a handshake mechanism may improve the situation. This can be implemented either on top of UDP or by using higher QoS levels in MQTT-SN. This could be significant for specific purposes as firmware or security updates. For the sensor data this may not be needed. As several locations without NB-IoT coverage were found during the measurements, the use of GSM as a fall-back may be recommended for the time being. The addition of a simple acknowledgment without the use of MQTT's QoS levels would also increase the reliability of UDP message receivals. This acknowledgment could be used only when necessary as with the above mentioned purposes of e.g. updates of the firmware. An implementation then requires bidirectional connectivity preferably with the use of eDRX. The increased reliability comes with increased power consumption.

Some general rules should be followed to optimize the throughput and to minimize the packet loss rate when using NB-IoT. If the application is tolerable against packet losses and delay variations UDP in conjunction with MQTT-SN or CoAP should be selected on top of NB-IoT. The power consumption can be minimized by optimum placement of the end devices and the use of an external antenna if possible. Additionally, the choice of long PSM periods and the caching of the sensor data in the end device may significantly extend the battery life time by reducing the number of registration processes and transmissions. Other measures to reduce the transmission delay and the number of re-transmission could be implemented by the network operator. The results and recommendations for NB-IoT usage from this paper are based on empirical observations. Through experiments in collaboration with network operators reasons for the delays can be found. Alternatively, experiments with network emulators could be conducted. For users of the network the critical part of the transmission path is opaque. With additional information from the network operator users may be able to adapt and improve the reliability of their NB-IoT applications.

ACKNOWLEDGMENTS

This work was partly funded by the RheinEnergie Stiftung in the framework of the project RhizoTech that is carried out in cooperation with the Cluster of Excellence in Plant Sciences (CEPLAS) at the University of Cologne (Prof. Marcel Bucher).

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