NB-IoT Network Field Trial: Indoor, Outdoor and Underground Coverage Campaign

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***Abstract*—Recent advancements in cellular technologies allow discrete computing devices embedded with sensors to communicate over long distances with low-cost and low-energy consumption. This could drastically impact the future internet of thing (IoT) ecosystem. In this regard, Third Generation Partnership Project (3GPP) has introduced a new cellular-based technology called Narrowband Internet of Things (NB-IoT) which is one of the potential technologies for enabling IoT application in vehicular, health-care, industry 4.0, etc. However, NB-IoT technology is still in its infancy and so far it is unclear whether it is sufficiently reliable to complement or replace existing short-range and cellular technologies to enable such use-case scenarios. Therefore, this paper presents a preliminary investigation of the coverage of NB-IoT in three different scenarios i.e., outdoor, indoor, and underground with empirical measurements, one of the key performance indicators in which operators are most interested. The measurements were conducted on Tallinn University of Technology (TalTech) campus and nearby residential areas within a range of 700 m. The obtained results indicate that NB-IoT is able to provide good connectivity to meet the IoT application requirements in outdoor and indoor environments. However, for an underground scenario with the beam enabled for 700 m, it is only possible to provide connectivity to the devices up to 400 m. Furthermore, it is also observed that NB-IoT is able to provide connectivity to devices with a received signal strength indicator (RSSI) value as low as -105 dBm as compared to -95 dBm as in long-term evolution (LTE).**

***Index Terms*—NB-IoT, coverage, RSSI, IoT, outdoor, underground, indoor, deployment, measurement campaign, IoT cloud platform, cumulocity**

I. Introduction

The recent advancements in wireless technologies for enabling low-power and low-cost communication over long-range open a plethora of possibilities to introduce diverse applications (i.e., smart cities, industry automation, logistic, health-care, etc) for the Internet of Things (IoT) ecosystem [1], [2]. Many key industrial players and academics have shown immense interest in enabling recently introduced low-power wide area network (LPWAN) technologies. The landscape of LPWAN is diverse and is constituted of several competing technologies such as SigfoX, LoRa, LTE-M, NB-IoT, Weightless, Ingenu, Telensa, etc [2], [3]. Among these technologies, NB-IoT is considered to be the most promising as it outperforms other LPWAN technologies in terms of coverage, energy efficiency, and cost due to the ease of utilizing the already existing cellular infrastructure.

NB-IoT is a variant of the long-term evolution (LTE) for supporting the diverse requirements of IoT applications. The core of NB-IoT is based on orthogonal frequency-division multiple access (OFDMA), similar to LTE. However, the total system bandwidth support is limited to 180 kHz which corresponds to one physical resource block (PRB) of LTE. Such a meager bandwidth requirement enables NB-IoT to be deployed in three different modes, namely Standalone, In-band and Guard band. The choice of the mode selection is critical and has an impact on the overall network coverage, quality of service (QoS) as well as capital expenditure (Capex). To support the flexibility and switching between the modes, NB-IoT extensively uses the LTE design such as OFDM in downlink and single carrier frequency-division multiple access (SC-FDMA) in the uplink. However, to meet the requirements set forth by expected IoT applications, some design changes have been introduced such as retransmission for coverage extension, scheduling delay for computational complexity reduction, a power boost for downlink transmission, as well as control channel design. The control channel design changes are primarily due to the limited system bandwidth, as in the case of LTE control channels were span on multiple PRBs. The main target of these changes is to satisfy the need of IoT applications and to ensure the best coexistence with the existing LTE system while reusing the same infrastructure. The detailed design changes along with the key insight on the technology can be found in the standard [4].

A. Motivation and Related Work

NB-IoT operates within the LTE frequency band in case of in-band and guard band deployments; therefore, it is really important to investigate the expected coverage supported by this technology, particularly from the perspective of telecom operators. This will help them estimate the expected cell sites required to cover a specific area and the number of devices connectivity support. NB-IoT aims to enable IoT applications which are outdoor (i.e., autonomous cars), indoor (i.e., smart home, smart grid) and underground (i.e., smart drainage systems), where each scenario has particular requirements in terms of coverage due to different penetration losses. This calls for detailing the coverage analysis of these scenarios.

However, so far, few efforts have been done for NB-IoT coverage analysis. In [5], the evaluation of NB-IoT coverage and outage probability in outdoor, indoor and underground setups is presented through computer simulations with an average inter-site distance of 6.2 km. It is concluded that for the underground scenario the outage probability is significantly higher for practical deployment purposes. In [6], the authors provide a simulation-based comparison of different technologies such as GPRS, LoRa, SigfoX, and NB-IoT in outdoor and indoor setups located in both rural and urban areas. Similarly, in [7], the authors present the simulation based coverage analysis of NB-IoT on different maximum coupling losses (MCL) and compared that with LTE. It is shown that for some scenarios, NB-IoT provides up to 20 dB coverage extension as compared to LTE. A coverage analysis based on link-level simulations for the different control channels of NB-IoT is presented in [8]. Furthermore, a simulation-based comparison of LoRa and NB-IoT coverage for the smart drainage system and smart metering is presented in [9], [10]. Moreover, a detailed analysis of NB-IoT link-level performance in both in-band and standalone deployment for smart grid application is also presented in [11].

As claimed in the standard and in most of the simulation results presented above, NB-IoT provides 20 dB coverage extension as compared to LTE; however, to test this hypothesis, it is important to test the technology with real deployments.

B. Contribution

To help deploying NB-IoT for practical applications, this paper presents a practical investigation of NB-IoT coverage in all the possible scenarios i.e., outdoor, indoor, and underground, with an extensive experimental measurement campaign using Telia's base station and TalTech NB-IoT sensor node named as DORM (integrateD cOmpact naRrowband platforM) based on commercially available NB-IoT compliant devices. To the best of our knowledge, this is the first empirical measurement campaign in the open literature to study the coverage of this technology. We believe that this study facilitates realizing and developing practical IoT applications based on NB-IoT. Furthermore, the results of this study will also help the operators to plan cell deployments and to estimate Capex costs.

The remainder of the paper is structured as follows. Section II presents the measurement and experimental setup that include the detailed area under study, the type of device used for measurement and the base station settings and location. Section III presents the comprehensive results of coverage in terms of received signal strength indicator (RSSI) and packet loss percentage for outdoor, indoor, and underground scenarios. Finally, concluding remarks are drawn in Section IV.

II. Experimental Setup and Measurement Campaign

The measurement campaign for this paper is done at Tallinn University of Technology (Taltech) and the neighboring residential area. It should be noticed that all the required permissions from the residents have been obtained to place the devices in indoor and underground locations accordingly. The locations of the devices along with the covered area which is approximately 700 m, is shown in Fig. 1. The covered area includes residential buildings which are mostly three to five storey apartment buildings. However, some of these building have a single storey such as shops, etc; therefore, for indoor scenario, the ground floor is selected for all locations. Furthermore, for the buildings that lack an underground or basement, the nearest possible option is considered. The measurement campaign is carried out with 20 NB-IoT compliant devices. It is worth to note that Telia's base station at TalTech is configured with NB-IoT; however, the neighboring base stations are still operating on LTE and the results in this study are expected to be impacted by the interference from the neighboring cells.

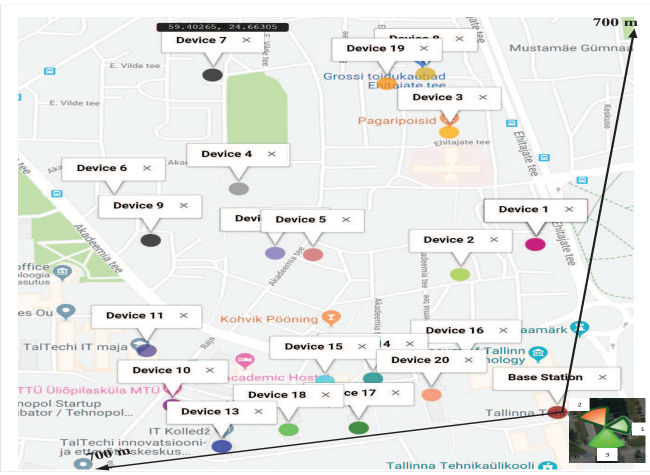

Fig. 1. Area under study. The bottom-right corner presents the available Telia's beams with their respective coverage area. The measurement campaign is conducted with beam 2.

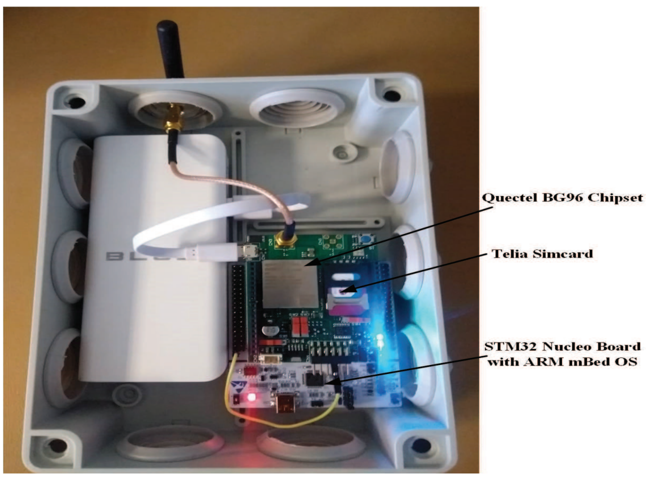

Fig. 2. NB-IoT enabled DORM node.

A. NB-IoT Node

The Avnet Silica NB-IoT shield [12] sensor nodes used in the measurements are built around Quectel BG96 chipset. These are used in conjunction with STM32 Nucleo boards which support mbed OS for quick development and leverage free stacks like SSL, MQTT, COAP etc., as shown in Fig. 2. During the measurements, the NB-IoT nodes are deployed in various locations for more than 12 hours, where each device transmits data packets containing the distance, RSSI and Signal-to-interference-plus-noise ratio (SINR) after every 10 minutes through the base station to the cloud server.

B. Telia's Base Station

For the base station, we have used Telia's commercially enabled NB-IoT base station with in-band deployment mode, which is installed at the premises of Taltech main building. The antenna of the base station is mounted approximately at a height of 20 m from the sea-level. Moreover, the base station is configured in a tri-sector antenna mode with three beams, each reaching around 700 m. However, for this experiment we have used only one beam; the corresponding selected area is colored in orange, as presented in Fig. 1. We use one beam only due to the lack of buildings in the coverage area of the two other beams (the corresponding areas are mostly made up of forest with no possibility for indoor or underground setups).

III. Performance Evaluation

This section presents the coverage analysis of NB-IoT in outdoor, indoor, and underground scenarios for one cell sector enabled with the commercial base station and NB-IoT compliant devices. The aim of this investigation is to test the hypothesis set by the simulation results in the literature and the NB-IoT standard that each beam is able to reach at least 700 m and able to support device connectivity with RSSI value below -110 dBm. Therefore, the deployment of NB-IoT by Telia aims to reach 700 m and so far the cell deployment is done accordingly. Moreover, a comparison of LTE and NB-IoT is also presented based on RSSI to test the claim that NB-IoT is able to extend the coverage by 20 dB.

Fig. 3 presents the coverage results for the outdoor scenario in terms of RSSI in the form of a radio signal heat map (created with Excel Power Maps analytic tool) with visual aggregation set as an average. It can be observed that the RSSI values range from -60.5 dBm to -110 dBm and the setup is able to cover almost all of the area. However, it is interesting to highlight that out of 20 devices, 1 device is in outage as shown in Table I. However, before drawing any conclusion, we have done the measurement of the particular device for approximately 1 week and we observed that connectivity in that area is not possible. Therefore, to reflect this in the results, we have assigned the device with an RSSI value of -110 dBm (which is equivalent to no coverage). It can be noted that the distance is measured using Google Maps (i.e., ground-to-ground level); if we consider the antenna height and elevation to the device (as most of the devices are on ground level), it

TABLE I
NUMBER OF DEVICES IN OUTAGE.

Scenario	Total devices deployed	Devices in Outage
Outdoor	20	1
Indoor	20	3
Underground	20	8

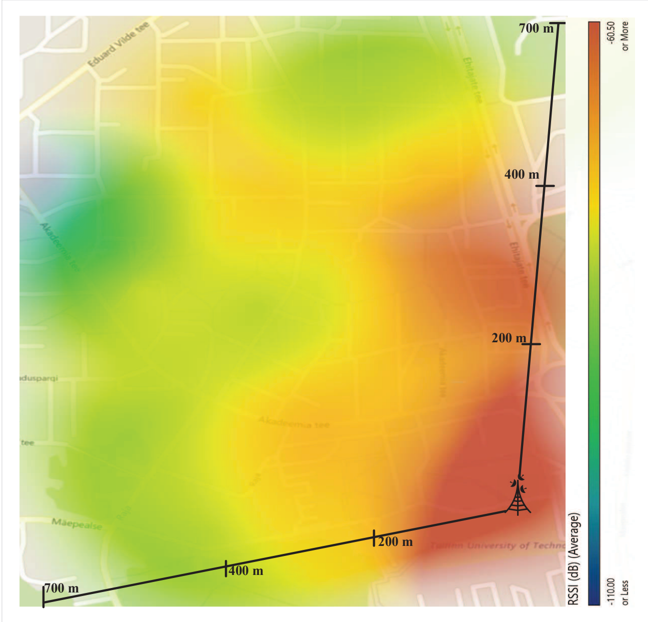

Fig. 3. Coverage of NB-IoT for outdoor scenario in terms of RSSI.

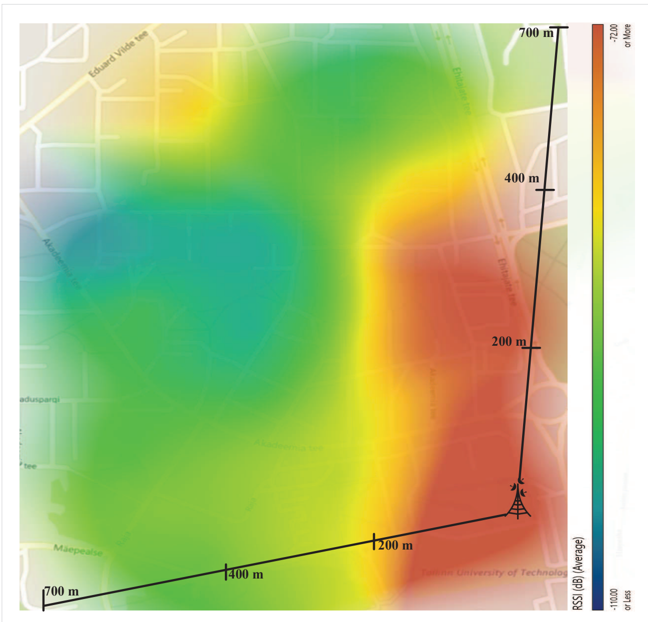

Fig. 4. Coverage of NB-IoT for indoor scenario in terms of RSSI.

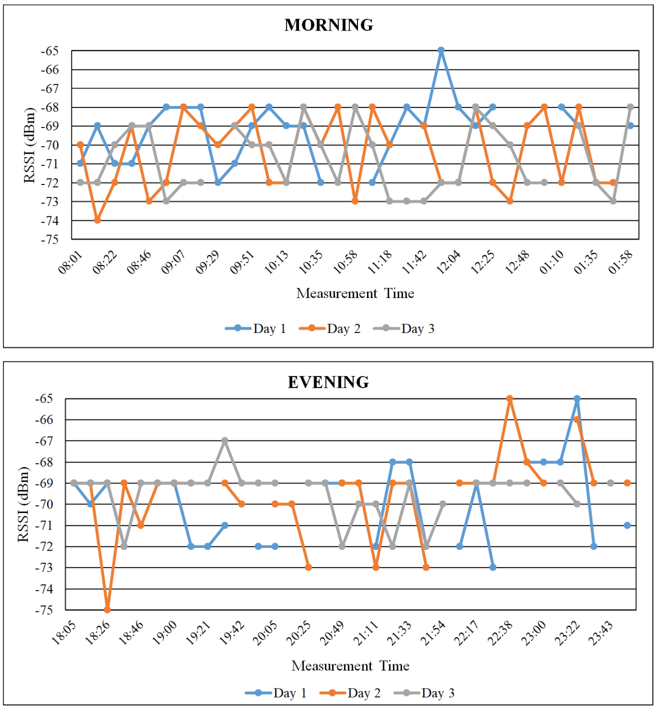

Fig. 5. Temporal link dynamic of Device 4 in an indoor scenario for 6 hours in the morning and evening, respectively, in terms of RSSI

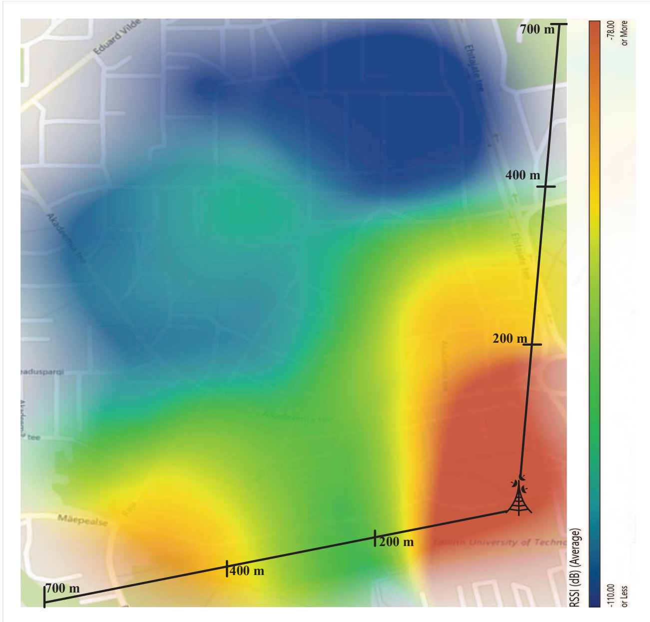

Fig. 6. Coverage of NB-IoT for underground scenario in terms of RSSI.

is logical to conclude that NB-IoT is able to cover the devices within 700 m although some portions are with poor signal strength of down to -92 dBm.

Fig. 4 shows the NB-IoT coverage in the indoor scenario; the impact of penetration losses due to buildings or other obstacles is obvious as the RSSI ranges from -72 dBm to -110 dBm and the number of devices in outage increased to 3, as shown in Table I. During the measurement campaign, it has been noticed that a number of factors influence the signal strength and RSSI such as building material and structure, position with respect to beam direction, proximity to antenna, etc. To see the temporal link dynamics and the impact of environment, we have placed Device 4 which is around 400 m from the base station for three consecutive days for 6 hours in the morning and evening, respectively, as presented in Fig.5. It can be noted that the RSSI value varies significantly, particularly in the morning time when there is more activity going on in the neighboring environment, i.e. more abrupt variations in RSSI is observed as compared to the evening. Furthermore, blank points in Fig.5 represents the corresponding packet losses. It can be concluded from Fig.5 that even though the device's RSSI ranges from -65 dBm to -75 dBm, still significant packet losses are observed.

Fig. 6 presents the underground scenario and it is important to highlight that for the measurements, locations that are one level down from the ground are considered. It can be seen that the coverage of NB-IoT for the underground scenario is worse as compared to the indoor and outdoor scenarios, with an RSSI range from -78 dBm to -110 dBm and with 8 devices in outage as presented in Table I. It is seen from the results that after 400 m, most of the devices are in complete outage.

To further investigate the underground scenario in detail, we have placed 3 devices at a short distance from each other and on different angles or positions within the beam; for these, significant differences in RSSI are observed. The devices are placed in the TalTech underground parking space of around 100 m and located within $350 - 400$ m from the base station. To be accurate, the underground parking located in an area between Device 17 and Device 18, as shown in Fig. 1. Among the three devices, one is still in outage and the other two are in low RSSI region, as shown in Fig. 7. The experiment is carried out in the evening for 6 hours and for 2 consecutive days. It has been observed that the device location within the parking impacts RSSI significantly i.e., depending on whether the device is behind a car, behind a pillar, in a corner, middle of the parking lot, etc.

Fig. 8 highlights the packet losses of the devices in all the three scenarios (outdoor, indoor and underground). It can be seen that the packet losses are quite high in the indoor and underground scenarios. Even if the RSSI is within the acceptable region, still significant packet losses are seen. The major reason for such behaviours is the placement of the devices, which can be observed by studying all the results collectively. The most important aspects that affect the performance are the building structure, the location of the device and not to forget the interference from the LTE users in the neighboring cells. It is further noted that the performance of NB-IoT is worse in the mornings as compared to the evenings due to more human activity during the day which affects the signal strength, the number of connected users, and the corresponding traffic in the neighboring cell which are all typically higher during the

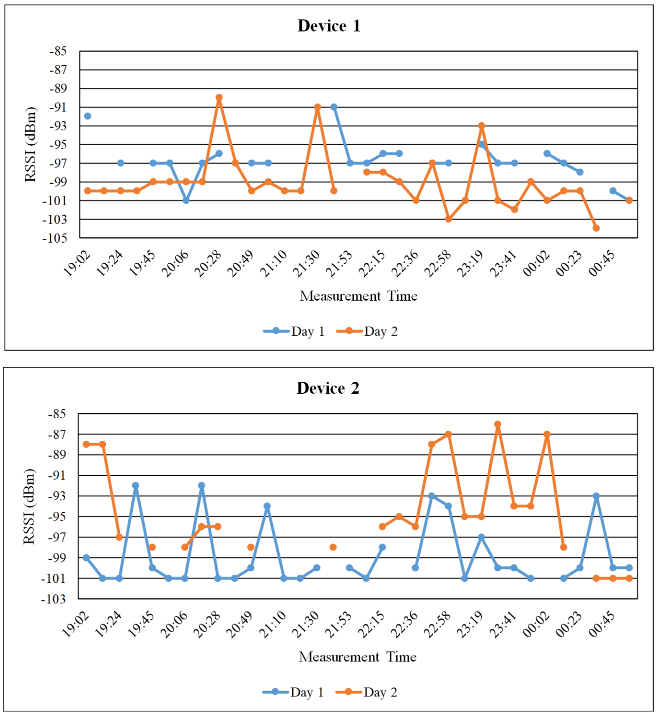

Fig. 7. Temporal link dynamic of Device 1 and Device 2 placed in an underground parking lot in terms of RSSI.

morning hours.

Lastly, Table II presents a comparison of the expected coverage between LTE and NB-IoT in terms of RSSI, as per the standard. In practice, it can be seen from all the results that NB-IoT is able to connect to devices even at an RSSI value of -105 dBm, whereas the maximum theoretical RSSI value supported by LTE is -95 dBm. On the other hand, observing Fig. 3, the excellent connection establishment in NB-IoT is when the RSSI value is greater than -60 dBm. Therefore, it can be noted that, NB-IoT is able to extend the coverage by approximately 10 dB in a real deployment as compared to 20 dB in standard according to our preliminary study. Therefore, for any LPWAN technology including NB-IoT, it is a challenge to provide ideal coverage to a certain geographical area and ensure connectivity in outdoor, indoor and underground scenarios simultaneously. To address this issue, one possible solution for the operators is to move to small cells which will potentially increase the Capex. The results presented in this paper are based on preliminary investigation based on a single type of hardware and using more sophisticated antennas or hardware may impact the results. However, the results presented in this work provide a holistic overview of the expected coverage in all these scenarios and can be used by operators as a reference point.

IV. Conclusion

To the best of authors' knowledge, this paper presents one of the first efforts to practically evaluate the feasibility of using a newly introduced LPWAN technology i.e., NB-IoT,

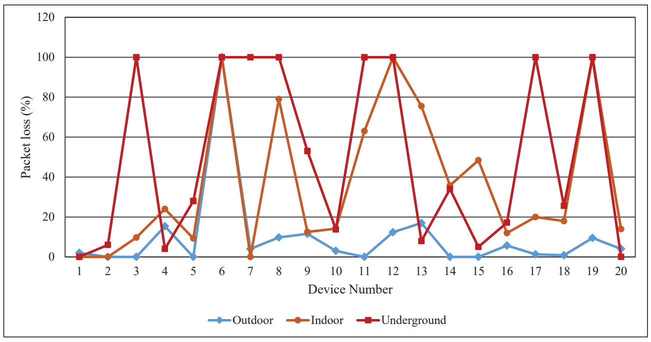

Fig. 8. Percentage of packet losses per device in outdoor, indoor and underground scenario for Device 1 and Device 2.

in outdoor, indoor, and underground setups. In this regards, we have presented the results of the empirical measurement campaign carried out at Taltech University, Estonia, to provide a comprehensive overview on the coverage of NB-IoT in an in-band deployment mode. Based on the results, it can be concluded that in practice NB-IoT extends the coverage as compared to LTE and is able to meet the IoT application requirements in outdoor and indoor scenarios. However, so far, the results for underground scenarios are not promising enough to support future IoT applications in such setups. Furthermore, it is also observed that by reducing the radius of the beam from 700 m to 400 m, NB-IoT is able to fully satisfy the requirements of any IoT application in outdoor, indoor, and also underground in a real-life environment. Further investigations with different hardware, environment conditions, and performance indicators such as energy efficiency and data rate are needed to fully evaluate the practical potential of this technology, which we aim at performing as future work.

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TABLE II
Comparison of received signal strength between LTE and NB-IoT [13].

LTE	NB-IoT	Signal Strength
> -65 dBm	> -60 dBm	Excellent
-65 to -75 dBm	-60 to -80 dBm	Good
-75 to-85 dBm	-80 to -95 dBm	Fair
-85 to -95 dBm	-95 to -110 dBm	Poor
≤ -95 dBm	≤ -110 dBm	Disconnect

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