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Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area

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***Abstract*—The 3GPP has introduced the LTE-M and NB-IoT User Equipment categories and made amendments to LTE release 13 to support the cellular Internet of Things. The contribution of this paper is to analyze the coverage probability, the number of supported devices, and the device battery life in networks equipped with either of the newly standardized technologies.**

The study is made for a site specific network deployment of a Danish operator, and the simulation is calibrated using drive test measurements. The results show that LTE-M can provide coverage for 99.9 % of outdoor and indoor devices, if the latter is experiencing 10 dB additional loss. However, for deep indoor users NB-IoT is required and provides coverage for about 95 % of the users. The cost is support for more than 10 times fewer devices and a 2-6 times higher device power consumption. Thus both LTE-M and NB-IoT provide extended support for the cellular Internet of Things, but with different trade-offs.

I. Introduction

The Internet of Things (IoT), where physical objects are connected, is predicted to grow rapidly in the coming years. For example Cisco estimates a 38 % compound annual growth rate from 2015 for cellular Machine-to-Machine connections leading to more than 3 billion connected devices by 2020 [1]. In order to provide the cellular connectivity there are multiple challenges, which the 3GPP standardization organization has worked on addressing. The challenges include achieving a low device cost (below 5 USD), limited uplink latency (less than 10 s), support a massive number of devices (40 per household), long battery life (10 years), and enhanced coverage (20 dB better than GPRS), [2], [3], [4]. In this work the focus is on the latter three challenges in a site specific network deployment.

The 3GPP has targeted these challenges in release 13 by introducing new User Equipment (UE) categories and changes to the standard in terms of lower transmission bandwidth, repetitions in time, enhanced Discontinuous Reception, Power Spectral Density boosting, and other network architectural updates [3], [5]. Specifically an LTE-M1 UE category has been defined to support a Maximum Coupling Loss (MCL) of 156 dB, achieving 1 Mbps in 1.4 MHz bandwidth [6], and a NarrowBand IoT (NB-IoT) UE supporting a MCL of 164 dB in 200 kHz bandwidth achieving about 100 kbps physical layer throughput [5], [7].

The question is what kind of coverage and capacity can be achieved in a realistic scenario, when applying the updated LTE release 13 and the new UE categories? In [8] it is reported that a coverage trial at 900 Mhz is ongoing, but besides that only simulation results of 3GPP scenarios and traffic models are available to the best of the authors' knowledge. For example [9] provides a simulation study of LTE-M coverage in the traditional 3GPP suburban macro-cell scenario at 900 MHz. The results indicate the improved LTE-M coverage is required for less than 10 % of the users, but is this also the case for a rural scenario, where IoT could provide many benefits?

The contribution of this study is to analyze how LTE-M and NB-IoT may provide improved coverage and capacity for Machine Type Communication (MTC) devices in a rural area, using commercially deployed LTE sites' configuration and location. We calibrate the simulation using drive test measurements. In addition, we study the UEs' expected battery life, depending on application type and experienced path loss.

The paper is structured as follows; in section II we describe our simulation methodology followed by the results in section III. Finally we provide a discussion of the results and the conclusion in sections IV and V, respectively.

II. Methodology

In this study the overall radio deployment performance is evaluated by including all MTC UEs within radio coverage for LTE-M and NB-IoT. The system level Key Performance Indicators (KPIs) which are analysed are:

- i Radio coverage probability, quantified in terms of geographical location availability i.e. the UEs' coupling loss is not exceeding the minimum standardized MCL of 156 dB and 164 dB for LTE-M and NB-IoT, respectively.
- ii Radio capacity, quantified as the maximum number of supported UEs per sector for a specific traffic type.
- iii The UE power consumption per day.

In this section the coverage and capacity evaluation methodologies and simulation assumptions are described.

A. Radio Coverage Analysis

The radio coverage analysis is based on a study of a rural area in Denmark. The base station (BS) locations and configurations, including tilt, transmit power, and antenna pattern, are implemented according to the commercial LTE deployment of a local operator. The area under study comprises approximately 800 km^2 and 71 sectors. The target is to study the best achievable coverage and therefore all BSs are assumed to be operating in LTE band 20 ($\approx$800 MHz) i.e. BSs, which in reality are operating in 1800 and 2600 MHz bands are updated with a band 20 antenna pattern.

The BSs are implemented in WinProp ProMan, which is

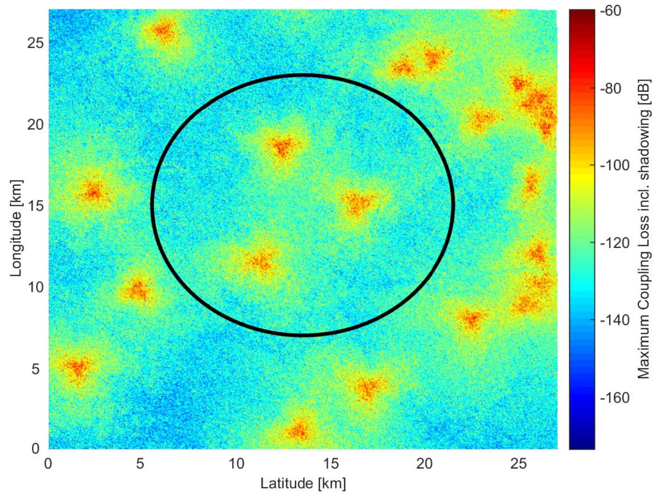
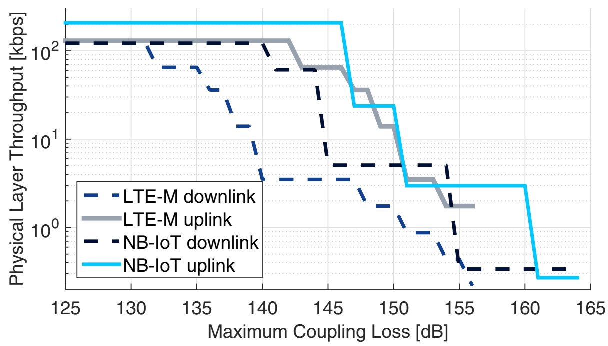


Fig. 1: MCL for the area under study. Users within the encircled area are studied if they are served by one of the 3 central BSs (the 3 red areas in the circle).

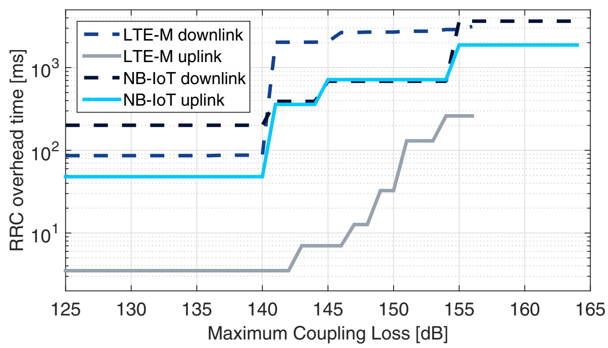
a wave propagation tool relying on the rural Dominant Path Model [10]. In addition to the BS configuration, a digital elevation map was also implemented in WinProp ProMan. The 10 m resolution map is from [11], but converted to a 50 m grid in order to reduce simulation complexity, and still comprising 540x600 pixels. The Dominant Path Model was calibrated using drive test measurements in the area, where the Reference Signal Receive Power was measured from 21 sectors, deployed with LTE band 20, using the R&S SwissQual QualiPoc Freerider III system. In total more than 450k samples covering more than 10k pixels were used for the calibration.

The calibrated WinProp ProMan provides a MCL estimate per BS sector for each pixel in the simulated area, but does not include the effect of shadow fading. Therefore, the MCL estimates were compared with the original drive test measurements. The difference between the estimate and the measurement has a log-normal distribution with -1.5 dB mean and 8.7 dB variance, and thus corresponds well with 3GPP shadow fading models having 8 dB variance [7]. Using the 8.7 dB variance, shadow fading was applied with a site correlation of 0.5 and sector correlation of 1 [7]. To avoid edge effects an 8 km radius circle was made around the 3 central BSs as illustrated in fig. 1. Only the users within that encircled area, who are served by one of the 3 central BSs, are studied, amounting to about 70 % of the pixels within the circle. The serving BS is selected based on maximum receive power.

The final step of the radio coverage analysis was to assign indoor and outdoor users to specific pixels. The location of indoor users is based on the OpenStreetMap, [12], by marking pixels that contain a house address, which in total corresponds to ≈3 % of the pixels in the rural area. In accordance with [7] the penetration loss was set to 10, 20 and 30 dB. The outdoor users are the combination of the indoor pixels, but without penetration loss, and road users, in total ≈20 % of the pixels. The road users are the pixels that contain at least one road element, based on INSPIRE_TN RoadLink [11].



(a) Uplink and downlink physical layer throughput mapping to MCL using 1 Physical Resource Block (PRB) for LTE-M and NB-IoT.



(b) Signaling overhead per packet transfer for LTE-M and NB-IoT.

Fig. 2: System level assumptions for throughput and overhead.

B. System Level Analysis

The system level performance KPIs are estimated from link-level data rate results corresponding to a set of average path loss conditions, similar to the procedure used in the 3GPP studies for LTE-M and NB-IoT [4], [7]. The link level data rates are optimized for a transmission block error rate (BLER) target of 10 %. Note HARQ and RLC retransmissions are not modeled. The PHY and MAC characteristics and overheads specific to the system under investigation, LTE-M or NB-IoT, are included in the link level calculations. An interference margin factor is also considered corresponding to an average 60 % carrier load factor. The uplink (UL) and downlink (DL) physical layer throughput as a function of MCL is illustrated in fig. 2a for LTE-M and NB-IoT, both using half-duplex. Note that full link adaption is not applied to interpolate between the simulated points. The impact of coverage enhancement techniques are accounted for in these results according to the standardized LTE-M or NB-IoT specific mechanisms [7]. Similar link-level performance values are summarized in the reference [4]. Note NB-IoT uses single-tone transmissions at high MCL, but the scheduler is currently not able to allocate more than one NB-IoT device per PRB even though the 3.75 kHz subcarriers would allow more users to share one PRB.

In order to account for DL and UL radio signaling overheads in the system level results, we have included the transmission delays for all phases of the radio connection set-up: DL synchronization, LTE random access procedure, and minimum

UE/eNB processing times. These delays are evaluated for the idle, transmit, and receive operating modes of the UE. Fig. 2b shows the overhead per packet transfer as a function of MCL.

The UE power consumption is determined using the evaluation procedure from 3GPP, where the estimated duration of the idle, transmit, receive and power saving mode (PSM) states are used [7]. A conservative power amplifier efficiency of 40 % is assumed which pertains for low-cost low-complexity devices.

The methodology can be summarized as follows:

1) System specific, LTE-M or NB-IoT, link-level data rates are generated for a set of average path loss conditions and a BLER target of 10 %.
2) Estimate the transmission delays for all phases of the radio connection set-up corresponding to each path loss value used in the link-level results.
3) Extract the path loss distribution from the site specific deployment scenario, described in section II-A, assuming the UEs are connected to the BS with the highest receive power. Shadow fading and clutter loss margins are included, depending on the outdoor/indoor UE locations.
4) Combine the outcome of step 2. and 3. to determine the cell average data rates, transmission delays, and the number of supported UEs in the given deployment scenario for a given application (see section II-C).
5) Utilize the outcome of step 4 to estimate the total UE power consumption.

C. MTC Applications

In this study the LTE-M and NB-IoT performance is examined for two MTC applications. The first application (app. 1) models a secure information exchange between the application layer on the UE and the server side. Therefore 4 payloads of either 128 or 256 bytes are sent in each link direction. The second application (app. 2) is based on the UE performing one UL transmission with a payload of 128 or 256 bytes, followed by an acknowledgment in DL of 29 bytes, which corresponds to the overhead of all protocols below the application layer [7]. App. 2 is similar to the Mobile Autonomous Reporting described in [7]. The two applications make it possible to study the benefit of using a data aggregator, which does not require a high security level and can apply the User Datagram Protocol.

Each application is expected to run 1, 2, 4, or 8 timers per day, using 1 PRB per transfer in both LTE-M and NB-IoT. Notice that LTE-M always applies 6 PRBs for DL control channels. The number of Random Access Channel opportunities is set to 300 per second per preamble.

The Radio Resource Control (RRC) Suspend and Resume solution for minimizing NB-IoT overhead is not applied, because the studied applications would not benefit from it.

The simulation assumptions are given in table I.

III. Results

The coupling loss distribution for the outdoor and road users, and the indoor users with varying penetration loss is given in fig. 3. The vertical lines indicate the minimum supported MCL for LTE, LTE-M, and NB-IoT. LTE provides coverage for almost 99 % of the outdoor and road users, while only supporting one third of the deep indoor users, experiencing an additional 30 dB loss. The LTE-M provides coverage for almost 99.9 % of the light indoor users, while only about 80 % of the deep indoor users can be served. Therefore, NB-IoT is an important update to 3GPP's MTC portfolio, but as the results in fig. 3 indicate almost 5 % of the deep indoor users cannot obtain the target data rates. Notice that the following results only include the users in fig. 3 that are actually in coverage by the given technology.

Using the evaluation methodology described in section II-B the system level performance, in terms of throughput, delay, and number of supported users, was studied. We provide the results for 1 session per UE per day and a 128 bytes payload, but the relative performance observations are similar when the number of sessions is increased up to 8 and the payload to 256 bytes, which are the maximums for this study, see table I.

Figure 4 shows the estimated session delay for the different user groups applying the two applications, described in section II-C. The session delay includes payload transfer, synchronization time overhead, and overhead due to RRC signaling. As expected, the app. 2, which consist of 1 UL transmission and an acknowledgment in DL results in lower delays than app. 1

TABLE I: Simulation assumptions.

Parameter	**Variable**
Scenario	71 sectors operating in LTE band 20 (800 MHz)
Shadow fading	σ=8.7 dB, sector correlation = 1, site correlation = 0.5
Power model	According to [7], 40 % power amplifier efficiency
Antenna configuration	BS: 1 Tx, 2 Rx; UE: 1 Tx, 1 Rx
BS receive diversity	6 dB gain (using Maximum Ratio Combining)
Indoor loss	10, 20, 30 dB in addition to the outdoor path loss
Carrier load	60 %
Available resources	1 PRB per device (180 kHz)
System Bandwidth	6 PRBs for LTE-M, 1 PRB for NB-IoT
Application 1	4 UL payload, 4 DL payload
Application 2	1 UL payload, 1 DL acknowledgment (29 bytes)
Payload	128 or 256 bytes
Application sessions	1, 2, 4, or 8 per day
RACH opportunities	300 per second per preamble

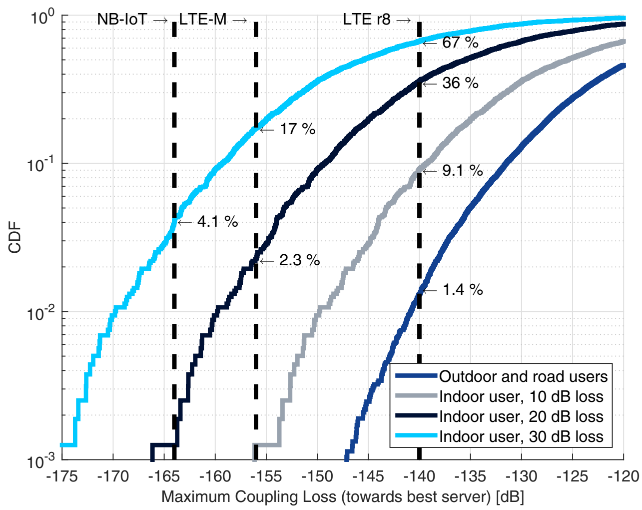


Fig. 3: MCL CDF for users in the rural area.

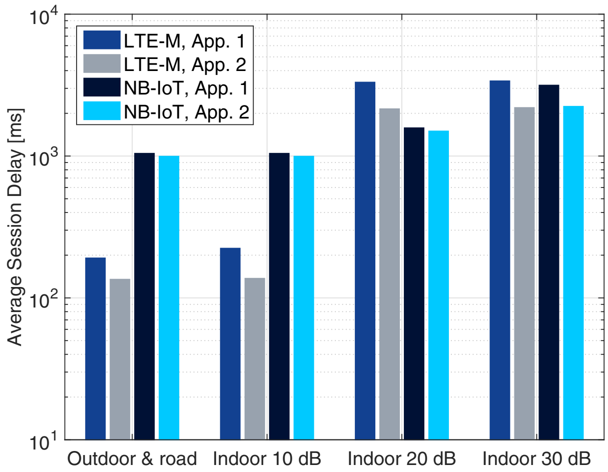


Fig. 4: Average session delay in the rural area.

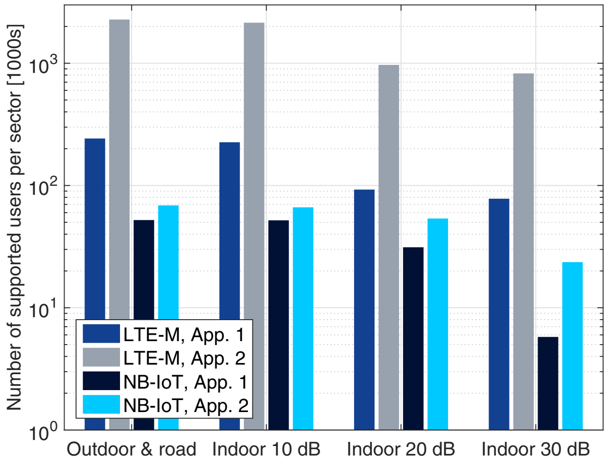


Fig. 5: Number of supported users per sector in the rural area.

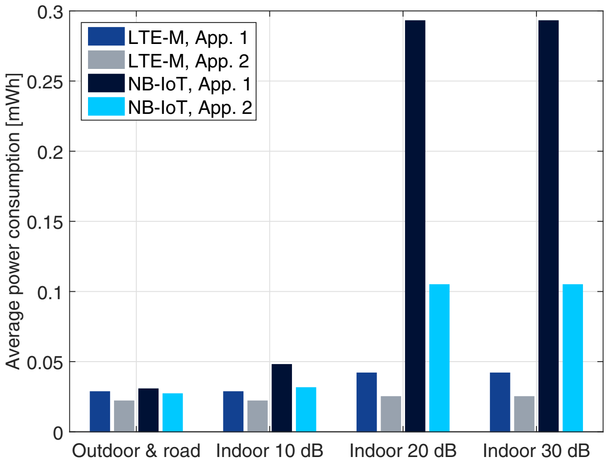


Fig. 6: Average device power consumption per day for UEs with MCL above 150 dB.

with multiple payloads in each direction.

The average MCL for the outdoor and road users is 124 dB for both technologies, and according to fig. 2a they thus achieve similar data rates. However, NB-IoT has higher overhead as illustrated in fig. 2b and therefore a longer delay. For the indoor users experiencing 10 dB penetration loss the average MCL for both technologies is about 133 dB and therefore the results are similar to the outdoor and road case, except a small decrease in LTE-M DL throughput. For the 20 dB penetration loss the average MCL is about 142 dB, and thus NB-IoT has a clear throughput and delay advantage in DL according to fig. 2a and 2b. This is reflected by the average session delay, where LTE-M is slower, especially for app. 1, which has multiple DL data transfers. The deep indoor LTE-M users have an average MCL of 145 dB, while it is 150 dB for NB-IoT, and since the throughput is similar they achieve similar delay performance.

Next the number of supported users per sector is calculated, based on the average MCL values and the estimated DL and UL delays excluding DL synchronization overhead. The number of users is a KPI for the future IoT as the number of devices is expected to increase [1]. As expected, app. 2 with 1 UL transmission and 1 DL acknowledgment allows to support the highest number of users for both technologies.

For the outdoor and road users, and the indoor users with 10 dB penetration loss, the LTE-M supports 5-8 times as many users as NB-IoT. The main reasons are the lower overhead, see fig. 2b for MCL 124-133 dB and thus the shorter delays, and the larger bandwidth, which allows to schedule 6 simultaneous users with 1 PRB each. For the indoor 20 dB loss users app. 1 with multiple payloads perform similar for both technologies, because the LTE-M DL delay is much longer than NB-IoT, but on the other hand also allows 6 simultaneous users to utilize 1 PRB each. Running the simple app. 2 on LTE-M UEs allows 20 times the number of devices compared to NB-IoT, because app. 2. is less affected by the low LTE-M DL throughput than app. 1. Similar observations are made for the deep indoor users, who experience long delays in NB-IoT due to the RRC overheads, and only have access to one PRB, which our scheduler does not allow single-tone users to share. Notice, that even though NB-IoT supports less users it will provide coverage for more than 95 % of the deep indoor users, while LTE-M "only" supports about 80 % as shown in fig. 3.

The final result is the average power consumption of the UEs, which will also be a KPI for the IoT, illustrated in fig. 6. The result is provided for the cell edge UEs, which are experiencing about 150 dB MCL for outdoor and road users and the indoor 10 dB users, while the indoor users with 20 dB and 30 dB loss are close to the MCL limits of 156 dB and 164 dB for LTE-M and NB-IoT, respectively. These users are selected in order to study the upper bound of the UE power consumption i.e. the minimum battery life time. The estimated power consumption is strongly correlated with the DL and UL delays, as these parameters define the time the UE is ON. As the NB-IoT UEs approach the 164 dB MCL limit the RRC overheads increase significantly, see fig. 2b, and this is reflected in fig. 6 where these users experience a power consumption 2-6 times higher than the LTE-M users. Assuming a CR2032 button cell battery, with a capacity of 600 mWh, even the NB-IoT UEs running app. 1, consuming 0.3 mWh per day, should be able to operate at least 5 years.

IV. Discussion

As indicated by fig. 3 the NB-IoT, which is currently 3GPP's state of the art in terms of supporting high MCL, will not be able to serve 4 % of the deep indoor users, experiencing 30 dB additional penetration loss. The issue can be addressed by using further repetitions in time, but this may cause the target delay to be violated, while another option is macro cell densification. However, the expected income from the 4 % users may not justify the expense. Another option is deployment of small cells or other local data aggregators. The results also show that a future fifth generation radio access technology should support at least the 164 dB MCL of NB-IoT in order to provide coverage for the future MTC devices. Besides the 3GPP's efforts to provide IoT connectivity there are standards available for unlicensed bands. One example is LoRa, relying on spread spectrum and thus processing gain, but similar to LTE-M and NB-IoT only limited empirical data is currently available. An outdoor coverage measurement determined 15 % packet loss when the LoRa transmitter and receiver are separated 2-5 km [13]. Further work is needed to determine if this is sufficient for the IoT.

The trade-off between obtaining the $164 - 156 = 8$ dB additional MCL for NB-IoT over LTE-M, is illustrated by the number of supported users per sector and average device power consumption in fig. 5 and 6. Therefore, it is important for operators to consider what coverage level they target to provide before deploying either LTE-M and/or NB-IoT.

A KPI for IoT is long UE battery life, and thus this metric's dependence on deployment and application scenario must be evaluated. Unfortunately, there are not yet any measurement-based energy models for the new LTE-M and NB-IoT UEs. In this work we used the 3GPP model [7], but it is worth noting that a recent contribution [14] addresses the issue that the power amplifier efficiency is a non-linear function of transmit power. In addition, the battery self-discharging must be included when studying battery life times of multiple years.

Finally is must be noted that this study assumed that all relevant LTE BSs were upgraded to LTE-M or NB-IoT. In most cases this will be possible via software upgrades, but if the carrier frequency of the existing BS is different from the target network the hardware must be changed. In future work the cost of such cell upgrades, and potentially the aforementioned macro and small cell densification, must also be examined to determine the economic feasibility of LTE-M and NB-IoT.

V. Conclusion

The Internet of Things is approaching and therefore this work examines whether current LTE deployments, possibly upgraded to LTE-M and NB-IoT, can provide sufficiently good indoor coverage to support the connected devices and their applications' requirements.

Our simulation results of a commercially deployed LTE network, calibrated using real drive test measurements, indicate that LTE will provide the expected data rates for about 99 % of the outdoor and road devices. However, LTE-M is required to provide 99.9 % outdoor coverage and if the devices are indoor, experiencing 10 dB additional loss, LTE-M can also support more than 99 % of the devices. If the device is located in the basement or deep indoor, experiencing 30 dB additional loss, LTE-M can only provide coverage for about 80 % of the devices. In this case NB-IoT can provide coverage for more than 95 % of the devices due to its Maximum Coupling Loss being 164 dB as compared to LTE-M's 156 dB.

Furthermore, the results show that if the devices are required to perform 4 UL and 4 DL payload transfers a day using the full security setup, i.e. connecting on application layer, then LTE-M and NB-IoT can support 80k and 5k devices per sector, respectively, in challenging indoor conditions. However, if the device is allowed to simply transfer its information, without using higher layer security, and only await an acknowledgment then LTE-M can support almost 1 million devices per sector, while NB-IoT may support around 25k devices.

The cost of providing deep indoor coverage up to a Maximum Coupling Loss of 164 dB with NB-IoT is not only a lower number of supported devices per sector, but also a 2-6 times higher device power consumption as compared to LTE-M. The main reason is the large Radio Resource Control delay overheads, but despite the higher power consumption the estimated NB-IoT device battery life is still above 5 years.

Acknowledgment

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