Opportunities and Challenges in using Energy-harvesting for NB-IoT

A. Haridas, V. S. Rao, R. V. Prasad
Delft University of Technology
Delft, The Netherlands
{A.Haridas@student.,V.Rao@}tudelft.nl,rvprasad@acm.org

R. Crutsen, F. Kanebi
VodafoneZiggo
Maastricht, The Netherlands
{roy.crutsen@,francis.kanebi@}vodafoneziggo.com

C. Sarkar
TCS Research and Innovation
Kolkata, India
sarkar.chayan@tcs.com

ABSTRACT

For the Internet of Things (IoT) applications that send a few bytes of sensor information infrequently, several long-range IoT technologies have been conceived. Narrowband IoT (NB-IoT) is one of them that stands out due to its extended coverage, high penetrability, and high reliability features. Among the primary goals set for the standard, low device power consumption is significant as the devices are typically deployed with batteries. In this paper, we characterize an NB-IoT device with respect to its energy consumption in different coverage classes for various scenarios. Based on the measurements, we estimate the lifetime of the device. We find that the lifetime of the device is significantly affected by the coverage class of the device. In order to augment the battery, we investigate the possibility of using ambient energy sources in the context of a smart home. For this we analyze real-world data sets, and find that the harvesting technologies can increase the average lifetime of the device. However, due to the spatio-temporal variations in the amount of energy that can be harvested, there are several challenges to be dealt with. We list the keys challenges of using energy-harvesting in NB-IoT, and those inherent to NB-IoT.

KEYWORDS

LPWAN, NB-IoT, Energy characterization, Energy-harvesting

1 INTRODUCTION

With the rise and projected scale of IoT, many technological solutions are proposed for various applications such as smart metering, smart cities and smart industry [7, 9]. Currently, an estimate of 6.4 billion IoT devices exist (without accounting for smart phones and laptops), with a projection that this number doubles in five years [2]. Contrasting to the earlier versions of IoT technologies with multiple hops, recent advances have enabled a simpler technological solution called Low Power Wide Area Networks (LPWAN) that offer low energy communication over distances of multiple kilometers, making sensors send data to the Internet backbone with only a few hops.

The main technologies in LPWAN are LoRaWAN, NB-IoT, and SigFox [6]. Narrowband-Internet of Things (NB-IoT) has been conceived by the 3GPP group as Release 13 [5]. It is an LPWAN technology that operates in the licensed band, and can be deployed with the existing LTE bandwidth (in-band or guard band) or by refarming a part of the GSM spectrum. NB-IoT envisions to connect up to a maximum of 67,000 devices/km^2 [4]. Similar to LoRaWAN, NB-IoT targets non-critical applications with infrequent and small payload transactions that can tolerate large latencies for massive IoT applications [14]. A key difference between LoRaWAN and NB-IoT is that the downlink in the latter is not restricted by duty-cycle regulations, and thus can also support IoT applications requiring actuation.

As with the other LPWAN technologies, NB-IoT has to be a low power technology. NB-IoT sensor devices (also called user equipment or UE) are usually powered with batteries due to the flexibility offered in deployment and portability for mobile applications. As is typical of 3GPP standards, each time a packet has to be sent, a request has to be made to the base station or eNodeB (eNB). Only after the request is accepted and radio resources are allocated, the data packet is sent. These signaling overheads imply that the battery is stressed, especially in deep coverage scenarios.

A high energy consumption rate leads to faster depletion of the battery, and therefore the UE does not operate as long as expected. In order to reduce the energy consumption in the UE, the standard proposes several techniques such as Power Saving Mode (PSM) and extended Discontinuous Reception (eDRX) [13]. With these modes, it has been theoretically calculated that an UE sending one message per day can last for more than 10 years [13]. However, these numbers may not be achieved in a practical deployment.

Since the devices are required to last long, techniques and solutions to increase the lifetime need to be investigated. A promising approach for a perpetual and sustainable network operation is to harvest energy from ambient sources, such as light, radio waves, temperature differences, vibrations, motion, salinity gradients, wind and water flows [15]. In this work, we investigate the possibility of using solar and ambient light sources for supplementing and recharging the battery in a smart home scenario. While we show that the lifetime of the devices can increase significantly, the variations in amount of energy harvested spatially or temporally pose challenges. By considering real-world datasets [8, 11] on the amount of energy that can be harvested, we estimate the increase in the device lifetime till the battery is emptied, after which the device remains switched off till it is recharged to a suitable level. Theoretically, the device can operate perennially. In this paper, we define the lifetime of the device as the duration taken by the device to initially empty its battery completely. Our contributions are listed as follows:

(1) We characterize an NB-IoT UE device (UBlox Sara N211 chipset) with respect to its energy consumption for various application scenarios, payload sizes, and time intervals in a real-world setting.

(2) We estimate the lifetime of the device with our measurement data. We find that the device does not match the expectation set by the NB-IoT specifications.
(3) We evaluate the possibility of increasing the lifetime by using ambient energy sources. Particularly, we investigate the indoor and outdoor light sources in a smart home setting with real-world datasets.
(4) We present critical challenges that need to be addressed in order to effectively use the ambient energy and enhance the lifetime of the NB-IoT UE devices.

This paper is organized as follows: Section 2 provides a brief description about NB-IoT. Section 3 describes the hardware setup and scenarios for lifetime estimations. Section 4 performs power and energy characterization of the UE for various conditions, and the lifetime estimations of the UE for different applications is presented in Section 5. In Section 6, we analyze ambient light energy data sets for the expected energy in a day and present the gain obtained in terms of additional payloads that can be served. Further, in Section 7, we indicate limitations and the challenges in energy-harvesting and NB-IoT. We conclude in Section 8.

2 AN OVERVIEW OF NB-IOT

In this section, we only provide a brief overview of how NB-IoT works, specifically on attach/payload exchange procedures and PSM/eDRX mode. For an in-depth discussion, we refer the reader to [13].

Attach and Payload Exchange Procedures. When an NB-IoT device is powered up, it needs to register with the network by setting up a radio connection with an eNB. However, a time-frequency offset may exist between the UE and an eNB. The downlink physical synchronization signals – NPSS and NSSS – helps to synchronize. The device then conducts an initial cell selection and identifies a cell to use. The UE performs a coverage class estimation and initiates the attach procedure by sending out a random access preamble in the physical uplink channel – NPRACH. Upon detection of a preamble, the eNB responds with a Random Access Response (RAR) containing scheduling information for the device to send the 'rrcConnectionRequest'. Upon receiving a connection request, the eNB resolves any contention between devices sending the same preamble, and sends the 'rrcConnectionSetup' message, which is followed by the UE sending the 'rrcConnectionSetupComplete' message [13]. The device moves into connected state at this point. If no activity, the device moves into the idle state with the expiration of appropriate timers. As the device wakes up from sleep, due to an event occurrence or periodic sensing, the UE raises a control plane service request and follows the same steps as the attach procedure. In order to reduce signalling overheads due to the setup of data radio bearers, as is done in the existing LTE network [13] , a control plane optimization is proposed which piggybacks short and infrequent messages as a part of the Non Access Stratum (NAS), 'rrcConnectionSetupComplete' message. Figure 1 shows a ladder diagram for both the procedures.

PSM and eDRX modes. In order to conserve and elongate the device operational lifetime, PSM and eDRX mode have been proposed in the standard. Discontinuous Reception (DRX) enables duty cycling based monitoring of the paging channel when the device is

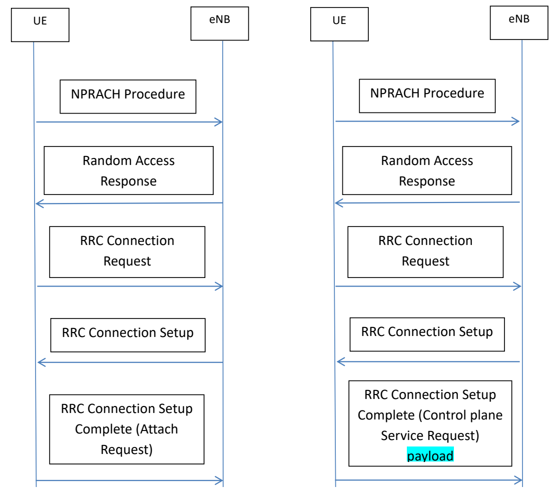

Figure 1: Attach Request and Payload exchange procedures

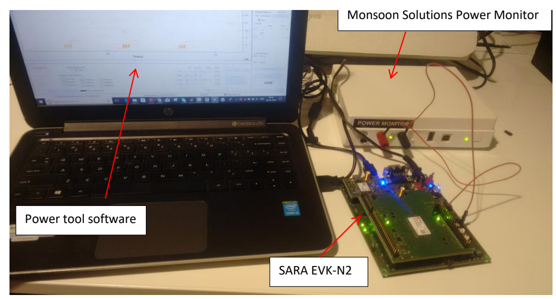

Figure 2: Current measurement using Monsoon Solutions power monitor tool

in idle mode. The DRX period can be set to a maximum of 10.24 s. The eDRX mode further extends the period to 174 minutes and 46 s. The PSM enables the UE to remain in sleep for a much longer period. The UE requests the timer values it requires for PSM and eDRX to the eNB. However, the maximum values are defined by the network operator. The power consumption during the PSM mode corresponds to the current consumed by a low power crystal, few active circuitries and due to leakage, and is typically 0.015 mW [4].

3 EXPERIMENTAL SETUP AND SCENARIOS

3.1 Setup

We use the evaluation kit from Ublox (EVK-N2) that contains the Sara N211 radio block [3] for our measurements. The Sara N211 radio is an industry-standard NB-IoT and commercially available chip. It implements the NB-IoT stack along with IP stack, which allows us to send UDP messages directly to an application server (or user's cloud server).

We use the power monitor from Monsoon Solutions [1] to measure the current consumption on the radio block. In our setup, we connect the power monitor to power only the radio block, while the development kit is powered through an external source. We ensured and validated that the radio block only draws power from the power monitor. The nominal voltage rating for the radio block is 3.6 V; we power the block with 3.7 V. In our measurements (see Section 4), there is an offset of 12 mA. This is due to the other current consuming circuitry on the radio block (such as LEDs). The offset is nullified from the measured values to obtain the true current drawn by the radio block.

The radio sends all the messages exchanged on the air interface to the microcontroller on the devkit, which in turn are sent to a computer over USB.

Coverage: We perform our experiments in two coverage classes: *good* and *deep* coverage. A good coverage class, as defined in the 3GPP specification, is when the Maximum Coupling Loss (MCL) is less than 144 dB [5]. In our measurements, we found the Received Signal Received Power (RSRP) values to range between -80 dBm and -74 dBm, with a signal to noise ratio (SNR) range of 20 to 30 dB. Similarly, an UE is said to be in deep coverage if the MCL is greater than 154 db and less than 164 db. In deep coverage, the RSRP measured in the UE ranged between -140 dBm to -130 dBm and the SNR ranged from -15 dB to -3.5 dB.

3.2 Scenarios

We consider the UE devices to be deployed in a smart home environment, where the NB-IoT devices could be used for gas, smoke, HVAC, smart electricity and water meter monitoring systems. Typically, these sensors are required to report periodically. However, there could be several events that occur occasionally, which also need to be reported. For instance, the smoke detectors going off or the smart water meter detecting the water consumption rate crossing a user set threshold. We, therefore, consider two types of scenarios:

(1) An UE periodically reports its sensors data;
(2) An UE reports its sensors data periodically, and additionally also reports any event that may occur in the smart home.

Furthermore, we consider two different periods of reporting: an UE can set its reporting period to once every hour, or once every day. Although typical NB-IoT applications will require once a day reporting, we consider a worse scenario in order to understand the limits of the UE.

4 UE POWER CHARACTERIZATION

We characterize the power consumption of our UE in the good and deep coverage scenarios. We consider three modes - active, idle and power saving (PSM) - to determine the power consumption. Every measurement provided in this section has been performed at least 20 times, and then the average is computed. In active mode, the device is either transmitting or receiving a packet over the air interface. The current measurement values are presented in Table 1. When in idle mode, the radio block is on and keeps performing paging operations periodically. The UE transits from the idle state to the PSM after the expiry of the 'Active timer'. The network can access the UE only after the expiry of the 'T3224 extended timer'.

Energy required for transmission. For most part of an UE's lifetime, the device spends time in PSM, wake up, transmit data and go back to PSM. Therefore, it is important to measure the power and time required for waking up from PSM and transmission of data. From the power monitor, we quantify the energy required in both deep and good coverage areas. These values are shown in Table 2 and Table 3 for two payload sizes (200 B and 50 B). We chose these payload sizes due to (a) 50 B would offer reasonable amount of space to send values from multiple sensors; and (b) 200 B is the payload size considered in the 3GPP specification for lifetime calculations. The energy required for attaching the UE in deep and good coverage scenarios are shown in Tables 2 and 3.

Table 1: Average current measurements

Coverage	RSRP	Transmission	Reception
Deep	-137 to -127 dBm	316 mA	59 mA
Good	-80 to -74 dBm	94 mA	59 mA

Table 2: Energy required and time taken, in deep coverage, for Attach and Payload exchange

	200 B	50 B	Attach Proc.
Energy	31.915 J	20.846 J	92.707 J
Time	158.4 s	136.8 s	352.8 s

Table 3: Energy required and time taken, in good coverage, for Attach and Payload exchange

	200 B	50 B	Attach Proc.
Energy	2.917 J	2.504 J	15.091 J
Time	70.92 s	70.2 s	173.16 s

Table 4: Battery consumption of the UE when in PSM (power consumption being 0.015 mW)

Period	Deep	Good
1 hour (in PSM for 0.956 hr)	0.052 J	0.053 J
1 day (in PSM for 23.956 hr)	1.294 J	1.294 J

5 UE LIFETIME ESTIMATION

Based on our current measurements, we can estimate the lifetime of an UE. The estimation is performed considering a 5 Wh battery, which has also been considered in the 3GPP calculations [4]. The battery is assumed to provide a constant voltage source of 3.7 V, provide a charge of 1400 mAh.

As mentioned in Section 3.2, we consider two intervals of reporting: once per hour and once per day. We calculate the energy spent in PSM mode for these intervals. The 'T3224 extended timer' value is set as 24 hours. If this value is not set as a multiple of the period, additional energy consumption due to network registration should also be accounted in the UE lifetime estimation. Table 4 shows the amount of energy consumed by an UE when in PSM for different durations.

We extend these calculations for different reporting intervals to deep and good coverage scenarios. We consider that a 200 B packet

Table 5: UE battery lifetime estimate when application consists of periodic and event messages

No. of events in a day	Estimated lifetime when the interval is one hour (days)		Estimated lifetime when the interval is one day (years)		Probability for λ - once every		
	Deep	Good	Deep	Good	day	6 hours	1 hour
1	23.546	252.530	0.941	7.602	0.367879	0.073262	$9.06 * 10^{-10}$
4	21.815	229.204	0.436	3.589	0.000763	0.195367	$5.219 * 10^{-7}$
8	19.868	204.070	0.254	2.106	$9.12 * 10^{-6}$	0.029770	0.000103
16	16.858	167.366	0.139	1.153	$1.758 * 10^{-14}$	0.011207	0.021862
24	14.640	141.852	0.095	0.794	$5.929 * 10^{-25}$	$8.309 * 10^{-12}$	0.081151

is used for reporting as in [4]. Note that these calculations includes the attach procedure energy, and payload sending procedures as described in Section 2. Furthermore, we also account for the energy required to move from idle mode to PSM. However, we have not considered leakages and battery degradation over time.

5.1 Periodic reporting application

We first consider a periodic reporting application, and evaluate the UE lifetime for different reporting intervals and coverage classes.

One UDP packet per hour: A payload of 200 bytes is transmitted every hour. The UE remains at PSM during all other times. Given the values from Tables 2,3 and 4, and a battery of 5 Wh, we find that a UDP packet can be sent every hour for 580.41 times and 6272.66 times, in deep and good coverage conditions respectively. This implies that the battery would last for 24.18 days in deep coverage and 0.716 years in good coverage.

One UDP packet per day: A similar calculation can be done when a UDP packet is send only once in a day, and the UE remains in PSM for the rest of the day. In this case, a total of 558.128 and 4423.75 packets can be sent in deep and good coverage, respectively. This implies that the battery would last for 1.53 years in deep coverage and 12.12 years in good coverage.

5.2 Periodic and event driven applications

Table 5 enlists the estimated lifetime of an UE with a 5 Wh battery for an application with periodic and event driven messages. We consider that events arrive as a Poisson process with an average rate λ. The calculations correspond to a varying number of events per day with a fixed periodic transmission scheme. The probability of occurrence of a certain number of events, given three average rates (once – every day, every 6 hours and every 1 hour), in the interval considered for each rate, is also presented in the table. This is also the probability to obtain the corresponding battery lifetime, given the rate of arrival of events and the periodicity of the normal messages.

The lifetime estimations obtained in our experiments show that the UE does not meet the expectations of the NB-IoT technology, as reported in [13]. The possible reasons of a significant difference could be:

(1) The timer values are different, resulting in more consumption. For instance, the 'Active Timer' value is set at 60 s, as opposed to 20 s in [13].
(2) The transmission power measured is 1169 mW in deep coverage and 347.8 mW in good coverage, and Reception power measured is 218.3 mW in both coverage conditions. In the lifetime estimation in [13], the transmission power is considered to be 500 mW (45% power amplifier efficiency, 60 mW for active circuitry and maximum transmission power of 23 dBm) in the deep coverage case, and 80 mW for reception.

Finding 1: We find that the lifetime of an UE device depends on the application's reporting rate and the coverage class. The main reason for this is due to the reliability features (coverage enhancement techniques) in the NB-IoT standard such as high repetitions of sub-frames / resource units and low modulation and coding rates (MCS) used in the physical layer .

Finding 2: We find a trend of drastic decrease in the UE lifetime, with the addition of a task to a periodic application, for both 'deep' and 'good' coverage conditions, when the period is one message a day. For instance, consider the case when the UE is reporting once per day and is in good coverage region. The estimated lifetime is around 12 years. However, with an additional event reporting a day, this number reduces to 7.6 years. The rate of decrease gradually subsides as the number of events and periodicity increases.

6 AMBIENT ENERGY TO THE RESCUE

Most deployment scenarios will not have accessible wired power sources for all the devices. Hence the devices depend on battery sources. By adopting energy-harvesting techniques, the devices gain autonomy with respect to energy. This also eliminates the laborious task of replacing the batteries. Of the several harvesting sources, the ambient light sources can provide higher power density [15]. NB-IoT devices in a smart home scenario can utilize the untapped ambient light energy sources (indoor and outdoor) in order to extend the *functional* lifetime (time to the first exhaustion of the battery) of the devices, .

6.1 Energy-harvesting profiles

In order to investigate the effectiveness of energy-harvesting with NB-IoT, we consider three sets of data: two corresponding to indoor conditions and one to outdoor condition. For each set of data, we split a day into 24 periods, and average the energy obtained, as a measure of charge (mAh), throughout the year, for each period. For calculating the energy obtained from the harvester, we consider a harvesting area of $100\,\text{cm}^2$, a conversion efficiency of 15%, and constant output voltage of 3.7 V in all the cases. High variance is expressed by the error bars, in all three cases.

Indoor radiance measurements Data is obtained from [8].

Window sill: Figure 3 corresponds to the expected energy in a day, in terms of charge, obtained when the measurement device is placed on the window sill and shading is used.

Book shelf: Figure 4 corresponds to the expected energy in a day, in terms of charge, when the measurement device is placed on the book shelf, away from the window such that the device receives direct sunlight for a short duration.

The book shelf scenario has a broader graph in comparison to the window sill case due to constant indoor light, but with a reduced peak. The former is exposed to sunlight for a very short duration, and hence has a low peak.

Outdoor radiance measurements Data is obtained from [11].

Outdoors: Figure 5 corresponds to the expected energy harvested in a day, in terms of charge, obtained in the city of Rotterdam for the entire year of 2017.

6.2 Converting energy into packets

In this section, we compute the average extension of the functional lifetime of a UE device whose battery is augmented with energy harvesters for the same scenarios as we did in Section 5. Figure 6 represents the gain in energy obtained from the energy harvester, represented in terms of additional application messages (200 B periodic message and 50 B event messages) that can be send in a day/year, in both 'deep' and 'good' coverage conditions. Figure 6 indicates that the expected energy obtained in a day is insufficient to serve additional payloads in 'deep coverage' conditions. However, with consumption rates such as 1 message per day in 'deep coverage', the device lifetime can be extended by **257.05%**, for the indoor data set. Further we observe that by the given data sets, 50% and 87.4 % of the capacity of the battery considered, is obtained in a year in indoors and in a day in outdoor conditions, respectively. With consumption rate of one message per hour in our example above, the harvester can help serve the application for slightly more than half a day, after which the transmission needs to stop to allow the battery to recharge.

7 CHALLENGES

7.1 Challenges in energy-harvesting

Though energy-harvesting solutions are quite attractive [16], the technology has its fair amount of limitations, depending on various factors such as the harvesting source, the harvesting technology, the application, etc. Incorporating energy-harvesting in IoT in general throws many challenges. We list them below.

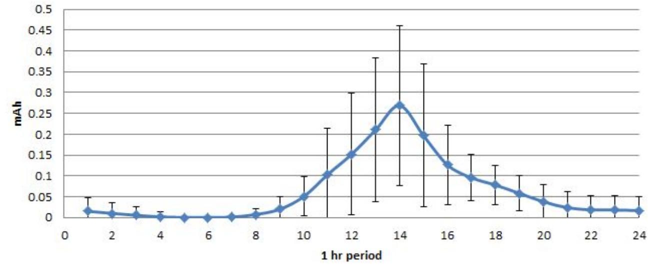

Figure 3: Window Sill - Averaged energy reading over 378 days for each 1 h period

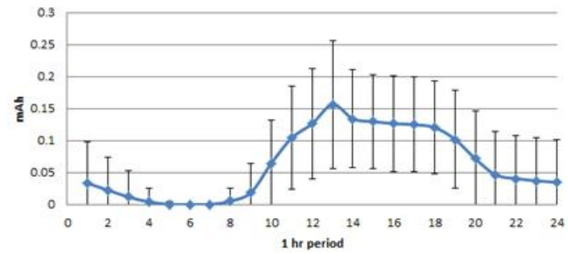

Figure 4: Book Shelf - Averaged energy reading over 341 days for each 1 h period

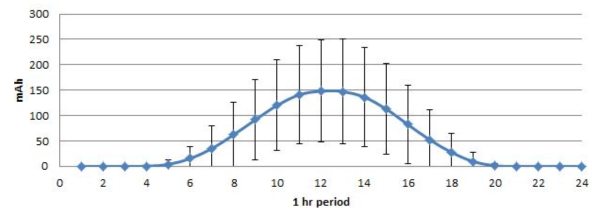

Figure 5: Outdoors - Averaged energy reading over 365 days for each 1 h period

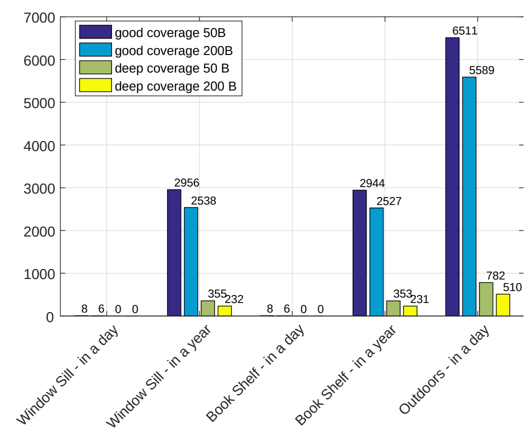

Figure 6: The gain represented in terms of additional packets that can be send

(1) *Design choice:* Determining suitable ambient energy sources for the given deployment scenario, the type of harvester (based on the ambient source, efficiency, application) and a suitable storage device (based on location of deployment, capacity, duration of storage, leakage, etc).
(2) *Ambient energy availability:* The energy harvesting opportunities depends on the physical placement and mobility of the devices. Furthermore, even in a static deployment, the amount of energy that can be harvested varies spatially and temporally [15]. Several external factors may also determine the energy harvesting opportunities, such as room occupancy and weather in case of ambient light energy source.

The above challenges have been well studied in the literature in the context of wireless sensor networks. Energy management algorithms [10, 12, 17] that adapt applications based on the energy availability, and multi-source harvesting systems [18] for devices exposed to less ambient energy from a single source are investigated. Furthermore, directions on choosing efficient harvesters, appropriate storage [15] and low-power hardware devices [16] are also presented. However, not all of these solutions are directly applicable to the case of NB-IoT. For instance, duty cycling is a common energy-management scheme [10, 17]. However, since the transactions in NB-IoT require establishment of radio link connection between the device and the base station, duty cycling would result in additional energy losses due to frequent attach procedures.

7.2 Challenges in NB-IoT

In order to use energy-harvesting technologies effectively, we need to address a few challenges. The main cause for the challenges is the energy requirement by the NB-IoT UEs. The power required for transmission and reception activities is high when compared to that obtained by the harvester. There is very little flexibility to scale down transmission power (determined by the eNB based on the coverage class) in the standards [5]. The following two tradeoffs must be dealt with.

(1) *Coverage vs. energy:* As shown in Section 5, the device energy requirement is dependent on the payload transmission rate and the coverage class of the device. A poor radio link between the UE and the eNB results in high transaction time resulting in more energy consumption than in good coverage.
(2) *Coverage vs. scalability:* The number of periodic reporting devices served is limited by the coverage class of the devices, as the devices in deep coverage consume the radio resources for a longer time.

Another requirement for the NB-IoT devices is localization. As per Release 14, this can be done by multi-lateration of the NPRS (Narrowband Position Referenece Signal) from base stations, with accuracy being limited by the base station density in an area. Another method is to use a GPS module. However, these modules come with their own energy requirements, further draining the device battery.

Accounting for energy of device while performing link adaptation (determining the number of repetitions per physical channel and adapting MCS index based on the radio link, done by the eNB based on the coverage class) in NB-IoT, optimizations on timer values such as 'Active timer', 'longDRXcycle' period, 'Inactivity timer' etc. to reduce time taken to reach PSM, can be adopted to reduce energy. Given the constraints and the tradeoffs, innovative solutions must be developed to make effective use of the harvested energy.

8 CONCLUSIONS

In this paper, we characterize the current consumption of an NB-IoT device in real-world settings We estimated the lifetime of the device for various application scenarios, under different coverage conditions. We showed that the difference between our estimations and those present in the specification are huge, and that the device may not last 10 years as expected. In order to increase the lifetime, we investigate the possibility of harvesting energy from ambient sources. We analyzed three data sets pertaining to ambient light in different areas of a smart home. We presented the gain obtained in terms of additional packets that can be served with the expected energy in all three scenarios. We found that in the best case that the device can operate perennially. However, this is highly dependent on the spatio-temporal profile of the energy sources. Therefore, we present the pressing challenges that need to be addressed in order to make the leap for a longer and sustainable NB-IoT solution.

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