Batteryless NB-IoT Prototype for Bidirectional Communication Powered by Ambient Light

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ABSTRACT

IoT use-cases aim to provide high-quality services where IoT infrastructures are always linked with the Internet. They require large scale deployment of small devices acting as sensors and actuators in different places. These devices need to be energy efficient and run sustainably. The maintenance of such large scale devices is difficult if they are powered by batteries that need to be replaced after some time. Moreover, disposing of these batteries also pollutes the soil and contaminates groundwater. Narrowband IoT (NB-IoT) is one of the long-range technologies that supports connectivity even in deep indoor closed areas such as underground parking lots, elevators, and tunnels. Therefore, in this article, the suitability of an NB-IoT device or User Equipment (UE) to be powered without any batteries to enable a long-term sustainable maintenance-free IoT network is demonstrated. We develop a prototype using a small photovoltaic solar panel for indoor light harvesting using sunlight or an artificial light bulb to power the NB-IoT UE. Due to the unpredictability of energy harvesting, the batteryless UE can experience frequent switches between the ON and OFF states. Therefore, we evaluate the performance of the solution where the UE communicates either uni- (uplink only) or bi-directionally (uplink and downlink) for different capacitor sizes at different artificial light intensities. We also evaluate the solution under dynamic harvesting power using natural light during daytime. The experimental results conclude that the batteryless NB-IoT UE supports a transmission interval of 60s without experiencing any restarts when harvesting 6mW or more, which can be harvested by placing a 6W artificial light bulb at a distance of 60 cm or less.

1. Introduction

NB-IoT is a long-range technology that supports a vast number of sensors that have low energy requirements. It benefits from the reuse of existing infrastructure of the Long-Term Evolution (LTE) network and uses one LTE Physical Resource Block of 180kHz. With the benefit of low cost, low power consuming devices and easy installation, NB-IoT accelerates the development of IoT initiatives and comes in the category of Low Power Wide Area (LPWA) network technology. There are a lot of tasks in IoT visions, ranging from basic services such as monitoring of water and electricity distribution, maintenance of street lights, city traffic management, and garbage management to advanced services such as safety and surveillance monitoring, smart healthcare, location-based services, and smart vehicular networking services. To support such services, a large volume of sensors, actuators and servers that communicate with each other over the Internet are required.

Recently, different LPWA network technologies have grown and differ in availability, range, efficiency, bandwidth, adaption and security. LoRaWAN and Sigfox are two such proprietary technologies developed by individual companies that operate in unlicensed bands. Whereas, NB-IoT uses licensed LTE frequency bands and is standardized by the 3rd Generation Partnership Project (3GPP). Being operated on unlicensed bands, LoRaWAN and Sigfox suffer from restrictions on channel usage [1]. It means it affects the data size and frequency, and a device can communicate. In contrast, NB-IoT has no restrictions on the amount of data and is operating on a licenced band, it can prevent interference from other devices. While LoRaWAN and Sigfox run with the risk of potential interference and the data loss can increase with the increase in data packet traffic [2]. We focus on NB-IoT which seems to be more robust, globally deployed, standardized and has an extensive device range.

The communication between an NB-IoT device (also called user equipment (UE)) and the NB-IoT network, via the Evolved NodeB (eNB) is controlled by the Radio Resource Control (RRC) layer. The RRC protocol defines two states, namely RRC Connected and RRC Idle [3]. The UE needs to be in RRC connected state for active data communication. However, it can switch to RRC Idle state to reduce its energy consumption. In the RRC Idle state, the UE experiences reduced energy consumption using two power-saving techniques, Extended Discontinuous Reception Mode (eDRX), and Power Saving Mode (PSM). eDRX is designed to save energy while waiting for any Downlink (DL) data using a mechanism known as paging, where the UE sleeps and periodically wakes up to check any incoming data. In the PSM state, the UE shuts down its RF components and therefore is inaccessible for DL data packets [4]. In the meantime, if there is DL data, the Serving Gateway (NB-IoT network component) caches them.

The Serving Gateway routes is also responsible for inter-eNB handovers in the user plane and provides mobility between LTE, NB-IoT and WCDMA networks.

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The delivery of these data is delayed until the PSM timer expires or the UE switches to the Connected state (e.g., when it wants to send UL data).

The NB-IoT power saving scheme is designed to extend the UE's battery life. However, batteries pose many challenges such as their shelf life, efficiency degradation at low temperatures, and most importantly the adverse effect on the environment after disposal. If batteries are disposed of in a landfill, the toxic chemicals leak into the soil and can pollute groundwater. Moreover, their production also leads to overall carbon emissions that range from 59-119 kg CO_2 eq/kWh battery [5]. Therefore, batteries can be replaced by an energy harvester in combination with a capacitor to store energy. Moreover, the world's interest is also moving toward energy harvesting from ambient sources, which can lead the way towards enabling batteryless NB-IoT UEs. Some popular ambient energy sources such as solar, wind, thermal, and radio frequency are options for harvesting. Although, based on the harvesting power, availability and easy accessibility, light energy has emerged as the most popular harvesting source for indoor and outdoor IoT devices.

We develop a working prototype to enable a batteryless NB-IoT solution that harvests energy using a small (few cm^2) indoor solar panel based on photovoltaic (PV) cells. As the instantaneous light source depends on time and weather, the harvested power is variable over time. Moreover, due to the low energy density of the capacitors, they cannot store a large amount of energy. Therefore, the UE can consume the stored energy in the capacitor much faster than it charges. This makes the UE intermittently turn on and off. This paper analyses the solution for diverse harvesting powers and capacitor sizes. In order to have predictable results, we analyze the batteryless NB-IoT UE prototype by harvesting from an indoor smart LED light whose intensity can be controlled (to adjust the harvesting power) of the solar panel.

Our contributions are listed as follows:

- The NB-IoT UE states are characterized based on their energy consumption and time intervals, in order to get an accurate view of the power requirements of an NB-IoT UE.
- We evaluate the batteryless UE performance in terms of data inter-arrival time, packet loss, restart count and outage time on a public NB-IoT network in Belgium.
- We validate the solution on natural light by placing the solar panel near the window-sill and evaluate its performance under dynamic harvesting power.

This paper is organized as follows: Section 2 provides a description of related work. Section 3 describes the hardware setup. And the software implementation is described in Section 4. In Section 5, we present the experimental setup and the performance analysis of the batteryless NB-IoT UE transmitting uni- and bi-directional data. We offer concluding remarks in Section 6.

2. Related Work

Batteryless solutions based on energy harvesting from ambient sources for NB-IoT have not been widely studied. There are only a few works in literature that talk about this theme. Some challenges and opportunities for energy harvesting solutions for NB-IoT UEs are pointed out by Haridas et al. [6]. They considered smart home use cases powered by ambient light, both indoors (devices on window sills and bookshelves) and outdoors. However, they aim to extend the battery lifetime without considering capacitor-enabled NB-IoT devices. Other than this, much literature only targets the analysis of NB-IoT power consumption, such as [7]-[8]. Gabelle, in his thesis [9], worked with the Nordic nRF9160 NB-IoT chip to measure the power consumption. This is the same chip also used in this paper. Gabelle used the Nordic DK board to do the measurement and measured only the radio power consumption. However, for our work we need to consider a full system with all the peripherals, the power consumption of a complete board needs to be considered.

Moreover, there are many available NB-IoT devices such as the Zolitron Z-node sensor [10], containing temperature, move, light, GPS, and magnetic field sensors, street light controller [11], liquid level sensor [12], asset tracker [13], movement tracker [14], air quality sensor [15], leakage sensor [16] and many more. Still, these products are powered by batteries. A solar-powered Asset Tracker based on NB-IoT is also designed by SODAQ [17], but this device is also powered by a 2400 mAh rechargeable Lithium battery. They also have a hybrid solution using a supercapacitor, and battery [18]. Xnor [19] has developed a camera prototype that is powered by solar energy. The device includes connectivity using NB-IoT to transmit data, but its NB-IoT connecting sensor uses a coin-size battery. The company is still exploring the extent of moving to solar or other batteryless options for NB-IoT data transfer. Other companies such as 8power [20], and Perpetuum [21] have future motivation toward using batteryless NB-IoT powered by vibration energy. The feasibility of using vibration energy for another long-range technology, LoRa, is studied by Orfei et al. [22] to monitor road traffic. The only completely battery-free NB-IoT products found are the vibration monitor and temperature monitor designed by AEInnova [23] [24] which are powered by waste heat. Their proprietary solution is always receiving heat energy from the running motor and sends only uplink data. The power harvesting estimates are not publicly available. Whereas, our work provides a study on how to configure a batteryless NB-IoT solution for the required data rate on both uplink and downlink data and is applicable for any energy harvesting techniques.

All the mentioned works mainly target to send UL data using a battery or batteryless device. In contrast, our work studies the ability of a batteryless device to perform both the UL and DL data communication. Furthermore, no work presents the evaluation of the battery-less NB-IoT UE. As such, this work is the first to study its performance using a designed prototype and public network.

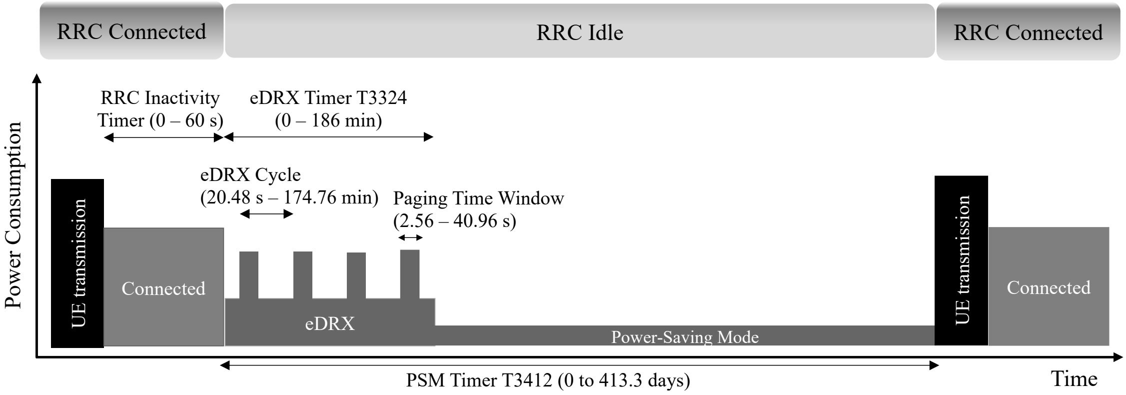

Figure 1: Overview of the NB-IoT UE Duty Cycle States

3. Overview of NB-IoT UE states

In this section, the NB-IoT power-saving states for the UE are discussed. The RRC layer controls communications between a UE and an Evolved NodeB (eNB) at the radio interface to set up, modify and release resources. It defines two states namely RRC Connected and RRC Idle, as shown in Figure 1. The data communication occurs in RRC Connected state where the eNB can directly allocate resources to the UE. Therefore, this state consumes more energy compared to the RRC Idle state. To save energy, the UE can negotiate with eNB the value of the RRC inactivity timer. Upon expiration of the RRC inactivity timer, eNB initiates an RRC Release message to the UE, which leads to switching the state to RRC Idle. This RRC inactivity timer is controlled by the eNB which resets it on each data transmission. A UE in RRC Idle state can always request for a UL grant to send UL data. On reception, it can switch to RRC Connected state. However, the procedure of switching to the Connected state from the Idle state is simpler than initiating a new attach procedure, as the UE context is saved upon its entrance to the Idle state. In the RRC Idle state, the UE can be in two power-saving modes, named eDRX and PSM.

3.1. Extended Discontinuous Reception

The eDRX is designed to save energy by putting the UE into sleep mode while waiting for any DL data. The timer T_{3324} defines the eDRX state time for the UE. It varies from 0 to 186 minutes [25]. During this period, the UE monitors the DL control channel Narrowband Physical Downlink Control Channel (NPDCCH), to receive the DL data notification or the UL data grant from the eNB. It periodically follows the eDRX cycle, which can be set up to 174.76 minutes [26]. An eDRX cycle consists of a Paging Time Window (PTW) time (between 2.56 and 40.96s) followed by a sleep time [27]. This listening mechanism is referred to as paging. If DL data arrives at the eNB in between paging events, the data is temporarily buffered by the network. The UE gets notified during paging and then can switch to the Connected state. However, upon expiration of T_{3324} without any activity, the UE can switch to PSM.

3.2. Power Saving Mode

In the PSM mode, a UE switches off most of its circuitry and therefore consumes the least amount of energy. The PSM mode is controlled by its timer represented as $T_{3412}\mathit{extended}$ which can take values up to 413.3 days [25]. The UE does not receive DL data while it is in PSM mode. However, the network temporarily buffers them for the UE during this time. This is notified to the UE using paging messages or when a Tracking Area Update (TAU) synchronization message is received from that UE. Therefore, it can receive DL data only when PSM ends, which happens when the PSM timer expires or the UE switches to the Connected state (e.g., when it needs to send UL data).

4. Energy Harvesting Prototype Setup

This section presents the designed protocol and software implementation based on Nordic Semiconductor nRF9160 module. The design aims to adjust the hardware design to support a batteryless device that is harvesting energy from the environment.

4.1. Hardware Prototype

Nordic Semiconductor provides the nRF9160 development kit board, but it is pre-certified, and they are in the process of optimizing its performance. Also, it is difficult to disable superfluous peripherals on the Nordic DK board. These peripherals consume power in the range of mW, which is undesirable for a batteryless device. Therefore, an in-house designed module based on the Nordic nRF9160 chip is used instead, as shown in Figure 2. It has a few interfaces such as a J-link probe (to flash the application), a serial port (to communicate externally mainly for debugging purposes) and an ISP adaptor which is leveraged to power the module.

Figure 3 shows the prototype used for the batteryless NB-IoT UE. The first piece of equipment is the solar panel that harvests voltage and current on light exposure. A 70x65 mm monocrystalline solar panel Mikroe is selected with a maximum of 400mW power [29], considering the maximum permitted power and voltage of the power management

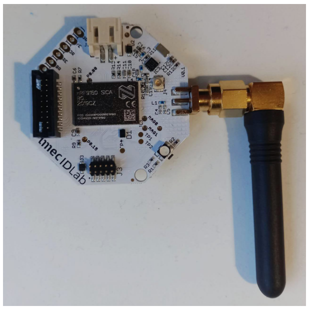

Figure 2: NB-IoT customized module

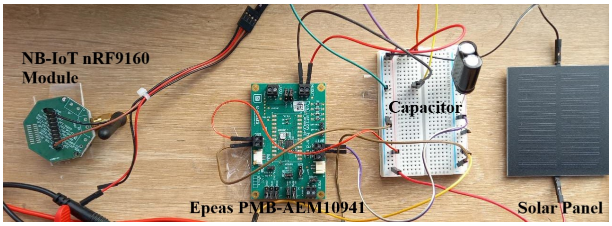

Figure 3: Batteryless NB-IoT prototype setup

board (PMB), Epeas-AEM10941 [28] (the green rectangular board) that can handle input power up to 550mW and a maximum voltage up to 5 V. The Epeas board charges the capacitor and powers our nRF9160 board using another in-house developed Octa board (green octagonal-shaped board), which acts as a serial port connector to distribute power.

We use an advanced PMB, Epeas-AEM10941 that equalizes the supply voltage, and only provides the device with power if the capacitor voltage is within certain minimum and maximum bounds. Whenever energy is harvested, the PMB is used to charge the connected capacitor to a maximum voltage point (V_{max}). The stored energy is then converted to a stable voltage to operate an NB-IoT module. The AEM10941 can be configured to supply different stable voltages (1.2, 1.8, 2.5 or 3.3V). The Nordic nRF9160 radio requires 3.3V [30]; therefore, using the default configuration, the Epeas board is configured such that the voltage thresholds as maximum, turn-on and turn-off voltages are set as 4.12V, 4.04V, and 3.6V, respectively. Once the capacitor charges up to the turn-on voltage (V_{turnon}), the device is powered by the supply voltage. Whereas, it is powered off when the capacitor voltage reaches turn-off voltage ($V_{turnoff}$). We chose the configuration which provides a maximum difference between turn-on and turn-off voltage because this provides the NB-IoT device to maximally use the energy available in the capacitor.

4.2. Software Implementation

The Nordic nRF9160 application is developed using the nRF Connect SDK, which is based on the Zephyr real-time operating system. The Nordic UDP sample application [31] is modified to support both unidirectional (uplink only) and bi-directional communication (available as open source on GitHub [32]). An external server is configured to always listen to a UDP port. For bi-directional communication, the server immediately sends a data packet back to the UE on each data reception (from the NB-IoT device).

On each reboot, the NB-IoT device first searches and attaches to the network. It then alternates between two states: RRC connected state and RRC idle state. In the RRC connected state, the NB-IoT device transfers data over a UDP socket to the server and in the RRC idle state, it saves power either by enabling the eDRX or PSM feature.

5. Experiments

In this section, we provide the overview of power consumption of the NB-IoT module in different radio states. The experimental setup and its parameters are also described. Finally, the results of unidirectional and bi-directional communicating batteryless NB-IoT UE are presented for both the artificial and natural light.

5.1. Power Consumption

The current profile of the device and its associated energy consumption are recorded using the off-the-shelf Nordic-Power Profiler Kit-II (PPK-II), which has a resolution of 0.1 μA [33]. We use the PPK-II connected with the NB-IoT module in source meter mode to measure the current consumption of each device state. The analysis is performed while the device is connected to the Belgian Orange NB-IoT network. All power-saving related network parameters were tested, and their effect on power consumption was evaluated. During this study, it is found that the Orange network does not support TAU-related T_{3412} $extended$ lower than 250 minutes, nor could an RRC inactivity time lower than 30s be configured. Therefore, considering the RRC inactivity timer of 30s, the best optimal configuration based on [35] for both the considered use-cases, uni- and bi-directional communication (when low power consumption is important) is to disable the eDRX timers (T_{3324}) and enable only the PSM timer (T_{3412} $extended$). Therefore, considering the network constraint, the UE is set to have T_{3412} $extended$ equal to 250 minutes to switch to the deep-sleep state. However, it can try to switch to the RRC connected state to send a UL packet whenever they are scheduled by the application. Figure 4 shows the current consumption and the state changes of the UE. It can be observed that the UE takes around 26s to connect to the NB-IoT network, consuming the maximum amount of current. The average current consumption for associating with the network is 17.4 mA. After this step, the UE starts communication by consuming 27mA current for 463 ms. The RRC inactivity timer for the Orange network as observed from Figure 4b is 31s, during which the UE sends periodic paging in an interval of 2s. During this time, the UE consumes 1.45mA current on average. At a Transmission Interval (TI) of 1s (Figure 4a), the UE never gets an opportunity to move to the PSM state and consumes around 33mA during 405ms

Table 1
Power consumption of different radio actions

Actions	Current Consumption (mA)	Time (s)	Energy Consumption (Wh)
Cell search and selection	36.09	8.45	279.5
Network Connection	17.44	25.9	414.05
Monitor 1 Paging channel	14.5	0.2	2.6
Tx 1 data packet	30.78	0.35	9.8
Rx 1 data packet	31.03	0.30	8.5
Tx + Rx 1 data packet	33.38	0.405	12.4
PSM wakeup + UL grant + Tx 1 data packet	13.36	2.145	26.27

(a) Transmission interval = 1s

(b) Transmission interval = 60s

Figure 4: Current consumption of the UE as measured from PPK-II sending only uplink data

to do bidirectional communication. Whereas, when the TI is 60s, it can switch to PSM state, which consumes only 6.93 A. Table 1 shows an overview of current consumption, time and energy consumption of the NB-IoT radio performing different actions.

5.2. Experimental Setup

In order to evaluate if indoor light harvesting can sufficiently power the NB-IoT device activities such as network acquisition, and message exchange, remain in RRC connected state or RRC Idle state, preliminary measurements to calculate the harvested power are performed. The Epeas board harvests power (P_{mpp}) at maximum power point (MPP), which can be calculated by measuring MPP voltage (V_{mpp}) and MPP current (I_{mpp}). P_{mpp} is computed from the solar panel directly facing a Philips smart bulb A67 (2700K) placed in a closed dark box. The intensity of the light is changed by the Android app provided by Philips. The voltage and current is measured using the digital multimeter (Keysight-U1281A) while the device is in operation.

Figure 5: Variation in capacitor voltage of 2.5F harvesting at 6mW and the UE communicates unidirectional.

Two practical use-cases for NB-IoT UE are set up as follows:

- Uni-directional UL only: The UE is expected only to send data to the server at a fixed interval.
- Bi-directional communication: The UE is expected to receive data from the server, as upon sending a data packet, it also receives back a DL packet.

Each data packet is considered to be unsegmented with a fixed payload length of 8 bytes. Also, after the data communication, the UE returns to PSM mode consuming a minimum amount of energy (6.2A) after the RRC inactivity timer of 30s. The connected state significantly impacts the overall power consumption of any device operating on the network as the UE needs to be active for 30 s consuming around 30 mA during this period.

The following performance metrics are considered to evaluate the batteryless UE in an NB-IoT network:

- Average Data Inter-arrival Time (IAT): The average time between the arrival of two consecutive DL or UL packets received by the server or UE.
- Lost Packet Percentage: The percentage of packets that are lost during communication.
- Restart Count: The number of times the UE restarts.
- Outage Time: The time during which the UE is in the OFF state after the first network acquisition.

Table 2 shows all the experimental parameters. The selection of the lowest capacitor size and harvesting power is determined experimentally. As shown in Figure 4, the network acquisition consumes most of the power, which is the bottleneck in choosing the lowest capacitor size and harvesting power. In the experiments to determine the lowest supported capacitor size and harvesting power, we evaluated capacitors between 100mF and 5F, and values for harvesting power between 500W and 50mW. It is noticed that a

Table 2
Experimental parameters

Parameters	Symbol	Value
Operating voltage	V_{op}	3.3
Application data size	N_{data}	8 bytes
Transmission Interval	TI	{1, 60}s
Capacitor Size	CS	{1.5, 2.5, 3.5}F
Harvesting power	harvesting power	{4,6,8,18,30,50 }mW
RRC inactivity timer	T_{RRC}	30 s

Figure 6: Outage time, which is equivalent to the capacitor charging time at different harvesting powers from 3.60 to 4.04V

capacitor size of 1.5F with a harvesting power of 4mW was the lowest that could support the acquisition phase. We use the capacitors manufactured by Cornell Dubilier Electronics with part numbers DGH155Q5R5, DGH255Q5R5 and DGH355Q5R5 [34]. The sensors attached to the device could impact the power consumption. The consumption depends on the type and number of sensors attached, but that accounting is outside the scope of the work.

Figure 5 shows the behaviour of the capacitor voltage when harvesting power is 6mW. It can be observed that the UE gets powered on when the capacitor reaches 4.04V, and its voltage decreases drastically for 26s (which is the network acquisition phase). Later, the UE starts communicating data packets until its voltage reaches the turnoff voltage. The time the UE remains in the ON state communicating data increases by increasing the capacitor size or the harvesting power or TI. Moreover, the same cycle continues repeatedly because the UE shuts down in RRC connected mode and on restart it needs to reacquire the network. Hence, a new IP address would be assigned. However, when the capacitor is less than 1.5F or harvesting power is less than 4mW, the ON state of the UE lasts less than 25s. Therefore, the UE restarts itself without communicating any data packet. Increasing the harvesting power, not only increases the ON state duration but also decreases the charging time.

5.3. Results

Once a batteryless device has started communicating, it will only move to the OFF state when its capacitor voltage goes below 3.6V ($V_{turnoff}$). Assuming that the device is continuously harvesting, it becomes active once the capacitor charges up to 4.04V (V_{turnon}). It means the time it takes to charge the capacitor from 3.6 to 4.04V contributes to the device outage time calculation. Figure 6 shows the charging time for different harvesting powers (4 to 30mW). It can be observed that the smaller the capacitor, the faster it recharges. The capacitor of 1.5F at harvesting power of 4mW takes 12.5 minutes, whereas 3.5F takes 29.6 minutes. Moreover, as the harvesting power increases, the charging time decreases exponentially.

(a) Data inter-arrival time

(b) Number of packet sent per hour

(c) Number of restart per hour

(d) Outage per hour

Figure 7: Unidirectional communication at TI=1s

5.3.1. Unidirectional UL only communication

Figure 7 shows the results for a TI of 1s. It can be observed that as the harvesting power increases, the IAT decreases and more packets are received by the server. By doubling the harvesting power from 4 to 8mW, it can be observed that the IAT is 3 times faster. The capacitor

(a) Data inter-arrival time

(b) Number of packet sent per hour

(c) Number of restart per hour

Figure 8: Unidirectional communication at TI=60s

voltage of the UE never decreases when it harvests at least 50 mW. With an increase in harvesting power, the outage time decreases and therefore, the UE can send more packets (Figure 7d). However, as a consequence, it experiences more restarts per hour. Moreover, as the capacitor size increases, it can support the UE for more time to do communication. Therefore, with an increase in capacitor size, more packets are sent, and fewer restarts are observed. But the restart count also decreases at certain higher harvesting power (30mW in Figure 7c) because then it takes longer for a capacitor to discharge. With the growth in energy density with the increase in capacitor size, the outage time as shown in Figure 7d decreases as it can support UE to be in active state for long.

The results for TI of 60s are shown in Figure 8. Increasing the TI to 60s, it provides more time for the UE to recharge its capacitor between transmissions. It can be observed that at a harvesting power of 6mW, the capacitor voltage never lowers below the turn-off voltage as shown in Figure 9a for unidirectional communication. Moreover, the larger the capacitor, the better performance can be gained. The difference between 2.5F and 3.5F is smaller than compared to 1.5F. Compared to the result of TI 1s, it can be observed that the restarts per hour count for TI 60s decreases from 4.85 to 2.11 for 1.5F capacitor size and from 1.85 to 0.47 for 3.5F at harvesting power equal to 4mW.

(a) Unidirectional communication

(b) Bidirectional communication

Figure 9: Variation in capacitor voltage of 3.5F harvesting at 6mW for TI=60s.

However, at harvesting power equal to 4mW, when the TI is increased from 60s to 600s, the batteryless UE shows no restart count (not shown in the Figures). It means that this low harvesting power is enough to support the TI of 600s.

5.3.2. Bidirectional communication

As the capacitor voltage variation in bidirectional communication as shown in Figure 9b is similar to the unidirectional communication (Figure 9a), the performance result for a TI of 1s for bidirectional communication as indicated in Figure 10 is also similar. Since, communicating bidirectional, the power consumption increases a bit compared to the unidirectional, the UE takes more time to maintain V_{max}. However, with increased power consumption, the IAT also increases compared to unidirectional communication. It can be observed that the IAT increases by 90% with 1.5F and by 25% with 3.5F for bidirectional communication at a TI of 1s compared to the unidirectional case. The UE needs to wait until it receives the DL packet after sending a UL packet. Therefore, the effective number of transmitted packets per hour is lower in bidirectional communication. At 50mW, when there is no restart, it can be observed that the maximum number of packets sent is 2800 per hour (Figure 10b), whereas for unidirectional it is 3600 per hour (Fig 7). Therefore, the number of restarts per hour also decreases for all the capacitors compared to unidirectional communication. The outage time of the bi-directional communication increases

(a) Data inter-arrival time

(b) Number of packet sent per hour

(c) Number of restart per hour

(d) Outage per hour

Figure 10: Bidirectional communication at TI=1s

for lower harvesting power (up to 8mW) and for higher harvesting powers it decreases when compared to the uni-directional results. This is because the higher harvesting powers can provide power to support DL communication such that the UE does not need to consume much from its capacitor. Moreover, it takes longer to perform one bi-directional packet transmission than uni-directional.

The result for a TI equal to 60s is shown in Figure 11, where it is also observed that the IAT increases compared to unidirectional for 4mW of harvesting power. However, the increase is less compared to a TI equal to 1s. With a 1.5F capacitor, the increase is only up to 8% and for 3.5F it is 4% compared to unidirectional communication.

(a) Data inter-arrival time

(b) Number of packet sent per hour

(c) Number of restart per hour

Figure 11: Bidirectional communication at TI=60s

5.3.3. Natural Light Experiments

The system is also tested using natural light to evaluate the performance of the system under dynamic harvesting power that changes over time. The batteryless UE and solar panel are placed on the west side window-sill with a 3.5F capacitor size in Antwerp, Belgium. The experiments are conducted in the fall season on cloudy and rainy days when the day length is around 12:45 hours [36]. The performance for both the DRs for bidirectional data communication is presented in Table 3. It is observed that at fast TI (1s) rain affects the number of packets per hour by 48%, which is not the case when the TI is 60s. This is because, at 60s TI, the capacitor spends more time in the PSM state (after spending 30s in RRC connected state), while at 1s TI, the UE is always in RRC connected state, which requires much more power to remain active. It also means that during the rain, the power harvesting is lower than on a cloudy day. It is assumed that the summer months with sunny days show the best performance results that can easily provide a harvesting power higher than 30mW and therefore less inactive time. The number of restarts is also less when TI is 60s. IAT at 60s is around 83s for both cloudy and rainy weather, which is similar to the 4mW fixed harvesting power. However, more packets can be sent with natural lights compared to fixed

Table 3
West-side Window-sill results using 3.5F capacitor for Bi-directional communication

Data rate	Date and Weather	1st packet time	Last packet time	Total experiment time (minutes)	Data IAT including inactive time (s)	Data IAT (s)	Number of packets per hour	Number of restart count (s)	Average inactive time (minutes)
1s	11 Oct 2021 (Cloudy)	09:26:15	18:04:33	518.3	15.27, 128.07	1.35, 0.38	235.94	30	15.75, 8.2
	12 Oct 2021 (Rainy after 13:00)	08:37:35	18:12:37	575.0	29.76, 245.8	1.42, 1.16	121.04	21	26.09, 16.46
60s	14 Oct 2021 (Cloudy)	09:33:42	17:32:04	478.4	83.9, 112.2	77.86, 5.38	43.01	1	35.85
	13 Oct 2021 (Rainy before 13:00)	09:22:40	17:53:29	510.8	82.6, 65.04	79.24, 4.77	43.69	1	22.14

harvesting power for both the DRs. The natural light during fall in Antwerp supports the UE to communicate for around 8 to 9 hours per day depending on external weather conditions.

Moreover, an energy-aware solution can maximize the energy efficiency and the operational lifetime of the UE by using harvesting energy during the day and use it for communication during the night. This can also reduce the number of restart count and thus save power in reacquiring the network.

6. Conclusion

In this paper, a working prototype of a batteryless NB-IoT UE is presented, which is powered by ambient indoor light. The UEs communicating uni- and bi-directional data are compared for different capacitor sizes and harvesting powers. It can be concluded that a TI higher than 60s can be easily supported in poor weather conditions or the availability of low intensity artificial light. However, the lowest capacitor size that supports NB-IoT acquisition on the evaluated Orange network is 1.5F. As the higher the harvesting power, the lower the time needed to recharge the capacitor. A harvesting power of 50mW is enough to keep the UE always on and communicating at a TI as low as 1s. At 50mW with 1.5 F, the UE can communicate 3580 packets per hour, whereas for bidirectional communication it is reduced to 2843 because it also needs to wait to receive DL packets. But as the harvesting power is reduced to 4mW, the average packet transfers per hour is reduced to 90 and 39 for unidirectional and bidirectional communication, respectively. Correspondingly, it affects the data IATs. Whereas, the number of restarts depends on power consumption and power harvested. Generally, when the harvesting power increases, the UE can perform more communication and thus loses more power. Therefore, the restart count increases with harvesting power, but at some higher optimal harvesting power point, the rate of decrease in capacitor voltage reduces and the UE can still communicate more without experiencing many restarts. At a TI of 1s for uni- and bidirectional communication, the tested optimal point is 30mW. Moreover, the solution also works for indoor natural light and the data IAT during the fall season is similar to the 4mW fixed harvesting power. It can be concluded that during the daytime and harvesting from natural lights, a batteryless NB-IoT UE can communicate data packets without being inactive if provided an opportunity to go into a PSM state.

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