Enabling Green IoT: Energy-Aware Communication Protocols for Battery-less LoRaWAN Devices

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ABSTRACT

Many Internet of Things (IoT) scenarios, such as smart cities, wild life monitoring, or smart agriculture, involve thousands of battery-powered devices. The disposal and replacement of such batteries represent an important economical and environmental cost. To realize Green IoT solutions, it is therefore desirable to adopt battery-less energy-neutral devices that can harvest power from renewable sources, such as solar or wind energy and store it in much more sustainable capacitors. The limited and inconstant energy supply and the limited energy storage capacity of such devices, however, require special care in the design of communication and computational processes, which have a major impact on the energy consumption of the devices. In this work, we explore multiple elements that could affect the device energy and communication capabilities of LoRaWAN devices. We propose and compare different energy-aware packet scheduling algorithms, and test them in a scenario where values for the harvested power are collected from real testbeds. We show that the number of successfully transmitted packets can be doubled by using an energy-aware design approach.

CCS CONCEPTS

• **Networks** → **Network simulations**; • **Sensor Networks**;

KEYWORDS

Network simulations, ns-3, Internet of Things, Battery-less device, Capacitor, Energy Harvesting

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1 INTRODUCTION

In the last years, the rise of the Internet of Things (IoT) paradigm promoted the implementation of multiple services where many (smart) objects are connected to the Internet, realizing applications as smart cities (e.g., smart lighting systems, smart garbage collection, public transport monitoring), healthcare (e.g., wearable devices for human parameters monitoring), and smart agriculture (e.g., animal and soil monitoring). These scenarios differ from traditional network applications in many aspects, such as data traffic, which is expected to be sporadic but potentially generated by a very large number of sources, with limited computation and communication capabilities (sensor nodes). Also, the need to deploy such devices over wide areas (such as cities and large rural environments) requires to employ long-range wireless communication technologies as to minimize the infrastructure.

Low Power Wide Area Network (LPWAN) technologies have been recently proposed to address these specific requirements. Among LPWAN technologies, LoRaWAN is of particular interest, thanks to its flexibility and ease of deployment [7]. This technology, indeed, aims at providing wide coverage range with low power consumption, helping in reducing the costs of large deployments.

Therefore, LoRaWAN is a natural candidate to support communications in Green IoT, where the aim is to reduce the environmental footprint of IoT systems [1, 6]. In this perspective, it is fundamental to limit the use of batteries (both disposable or rechargeable) to power sensor devices, since their replacement is costly from a time, economic and environmental perspective, and motivates the migration towards greener solutions. An eco-friendly alternative to batteries is using energy harvesting techniques, where energy is derived from renewable sources (e.g., solar power, thermal/wind energy), and is stored in (super) capacitors to power the devices. Unfortunately, the variability of harvested energy and the small energy density of capacitors can potentially cause an intermittent behavior of the device, affecting its performance and capabilities, including communication.

In this paper, we consider energy-aware approaches that can work (and exploit) variable energy harvesting rates. We focus on a single-node scenario and analyze the impact of different parameters (i.e., capacitor size and packet size) on the device's performance. We compare different energy aware scheduling approaches where packet transmission is conditional on the energy level of the device, making the best use of the available energy resources.

The paper is structured as follows. Sec. 2 briefly describes the device's model, and the LoRaWAN technology. The methodology, simulation settings and results are discussed in Sec. 3, while final conclusions are drawn in Sec. 4.

2 MODELING OF A BATTERY-LESS LORAWAN DEVICE AND SCHEDULING APPROACHES

To evaluate the feasibility of such a battery-less LoRaWAN node with energy-harvesting, we leverage ns-3 simulations, with the implementation we previously described in [2]. In this section we briefly recall the model of a battery-less capacitor-equipped device, and the main features of the LoRaWAN technology. Finally, we introduce some scheduling algorithms that implement different energy-aware algorithms to determine when to transmit sensor data. Their performance will be evaluated in Sec. 3.

2.1 Battery-less IoT devices with energy harvesting

To model a battery-less IoT device, we consider the approach used in [2, 4]. The device is modeled as an equivalent electrical circuit with three parts: (i) the harvester, (ii) the capacitor, and (iii) the load. In the following, we will indicate with $P_h(t)$ the harvested power, whose value can change over time according to the environmental conditions. The resistence modeling the load takes different values according to the current consumption in each of the operational states of the LoRaWAN device. To be operational, real devices need a voltage above a certain threshold, that we define as V_{th_low}. When the capacitor's voltage drops below this value, the device switches off, and cannot perform any operation. In this state, the current consumption is minimal (5.5 μA, due to the circuitry [4]), and most of the harvested energy will hence be used to recharge the capacitor. When the stored energy exceeds the voltage threshold $V_{th\_high} > V_{th\_low}$, the device goes back to the active state (further details are provided in [2]).

2.2 LoRaWAN technology

LoRaWAN [5] is based on the proprietary LoRa modulation, which leverages the Chirp Spread Spectrum (CSS) modulation scheme. Its robustness can be tuned through the Spreading Factor (SF) parameter, which takes integer values from 7 to 12. Once fixed the bandwidth, the SF is inversely related to the data rate: higher SFs allow for more robust transmitted signals and longer coverage ranges, but at the price of a lower data rate and, thus, longer transmission times. The LoRaWAN standard also defines a star-of-stars network topology with three types of devices: (i) End Devices (EDs) are peripheral nodes, usually sensors or actuators, that communicate using the LoRa modulation; (ii) Gateways (GWs) are relay nodes that collect messages coming from the EDs through the LoRa interface, and forward them to the Network Server using a reliable IP connection, and vice-versa; (iii) the Network Server (NS) acts as a central network controller that manages the communication with the EDs through the GWs. The LoRaWAN specifications also define three classes of EDs, which differ in terms of energy saving capabilities and reception availability. In this work, we focus on Class A devices, which stay in sleep mode most of the time in order to minimize the energy consumption, transmit a packet whenever required by the application layer, and open at most two reception windows (first receive window (RX1) and second receive window (RX2)) after each transmission (RX2 is opened only if no downlink (DL) packet is received in RX1).

LoRaWAN operates in the unlicensed Industrial, Scientific, and Medical (ISM) frequency bands, using three 125 kHz wide channels for uplink (UL) communication which must collectively respect a 1% Duty Cycle (DC) constraint [3].

For Class A devices, the standard requires RX1 to be opened in the same frequency channel and with the same SF used for the UL communication. RX2, instead, is opened on the dedicated 869.525 MHz channel and with SF 12, by default, in order to maximize the robustness of the communication.

2.3 Packet scheduling approaches

To evaluate the feasibility of battery-less LoRaWAN devices powered with energy harvesting systems, we investigate the design of different packet scheduling approaches that take the device's energy level into account, and make the best use of the available energy resources. To this aim, we compare the following approaches, generating UL data packets in different ways.

- **Unaware Sender (US)**: it generates packets with a period I, independently of the device's energy level. This energy unaware approach will be used as baseline for comparison with energy aware approaches.
- **Energy Aware Sender with Fixed Threshold (FS)**: it generates packets when the voltage level of the capacitor is above a fixed threshold and at least I seconds have passed from the previous transmission.

We also consider other energy aware senders where the threshold voltage for generating packets corresponds to the minimum voltage needed to successfully complete the transmission cycle (from the UL transmission till the closing of RX2), preventing the device from switching off. This threshold is computed dynamically, taking into account the communication parameters: packet size, SF, and whether or not an Acknowledgment (ACK) is required. Furthermore, when computing the expected energy cost of the cycle, recharging of the capacitor during the cycle is also considered. In particular, the expected harvested power can be computed according to different algorithms that, in turn, determine the following sending algorithms:

- **Conservative Sender (CS)**: it computes the threshold considering no energy harvesting, i.e., conservatively assuming a worst case scenario.
- **Simple moving Average Sender (AS):** it considers that the harvesting during the cycle equals the mean harvested power in the last x seconds.
- **Optimal Sender (OS):** in this case, perfect knowledge of the harvested power during the whole cycle is considered.

While this assumption is not realistic, results obtained with this algorithm represent a performance upper bound for the considered harvesting scenario.

3 RESULTS

In this section, we describe the settings employed in our simulations and the performance metrics that we leverage to evaluate the different packet scheduling approaches. Then, we showcase and discuss the simulation results.

3.1 Simulation settings

For our simulations, we leverage the `lorawan` ns-3 module and the capacitor implementation described in [2], extended to evaluate different packet schedulers. We simulate a single-gateway single-ED network, with the ED transmitting packets with different data payloads (PL) using SF 7. Note that, since a single device is employed, the effect of using different SFs would only be on the transmission and RX1 durations.

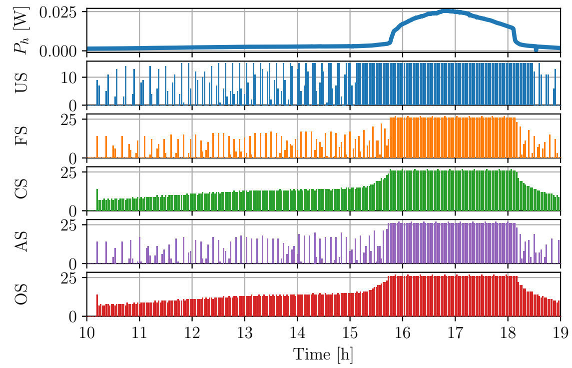
The ED is provided with an empty capacitor, which is charged by the harvesting process. The duration of the simulations was set to 9 hours. As energy source, we considered a self-collected trace of power harvested by a 6-cells mono-crystalline (4x2 cm^2) solar panel located in a west-facing windowsill in Antwerp (BE), during a sunny day in September. The average value of harvested power is 7.2 mW, with variability 8.2 mW: the high value of the variability is due to the high difference between the power harvested during the morning and the afternoon, where the device could benefit from direct sunlight.

The device switches off if the voltage falls below V_{th_low} = 1.8 V, value that is in line with off-the-shelf LoRaWAN devices [4], while the turn on threshold is set to V_{th_high} = 3 V. The current consumption considered in the different states of the devices is the same reported in [2]. The minimum interval between the generation of consecutive packets is set to I = 4 s, that yields a maximum transmission rate larger than what is actually allowed by the DC constraint for PL≥ 0 B, which hence sets an upper bound to the achievable throughput. In this way, we can better appreciate the effect of the different scheduling algorithms. In the results shown below, the voltage threshold for generating packets with the FS scheduling algorithm is set to 1.82 V, slightly above the V_{th_low} threshold.

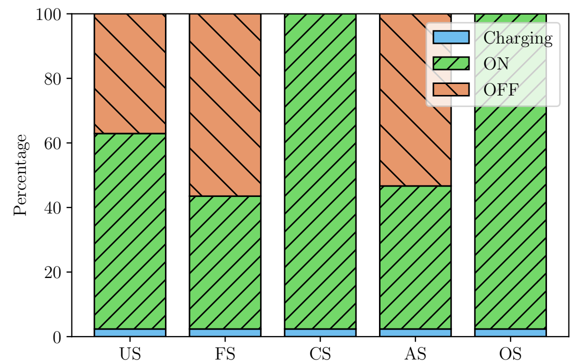
3.2 Performance metrics

To compare the different scheduling algorithms, we will employ the following metrics:

- Number of UL packets successfully transmitted by the ED. Note that it may be possible that a packet is successfully transmitted, but the ED is not able to complete the cycle because of a low voltage value. In this case, the packet transmission is successful, but the device will switch off, possibly preventing future transmission if not able to recharge on time.
- Since the capacitor is initially empty, during the simulation the device can be in operational state (ON) or not (OFF), or in the initial charging phase (Charging). We measure percentage of simulation time the ED spends in each of these states.



(a) Number of transmitted packets for different algorithms.



(b) Fraction of time spent in different states.

Figure 1: Comparison of scheduling behaviors for C=40 mF.

3.3 Results and discussion

3.3.1 Comparison of scheduling approaches. To compare the different scheduling approaches, in Fig. 1 we report the number of packets transmitted by the ED over time (upper plot), and the fraction of time the device spends in the ON/OFF states (lower plot). The transitory time needed to charge the capacitor, before the node becomes operational is considered separately and indicated as "Charging". More in detail, in Fig. 1a we show the evolution of the harvested power over time, and the number of packets sent by the device in this scenario, with each bar representing the aggregated number of packets sent during two-minute intervals for different schedulers and C = 40 mF. First, we can notice a correlation between the number of transmitted packets and the harvested power, with both of them increasing between 15:30 and 18:30, when the device was lighted by direct sunlight. Indeed, higher harvested power allows the ED to charge the capacitor faster, thus maintaining a voltage above the threshold set for transmissions (energy-aware approaches), or preventing the switch off. Secondly, we analyze the performance over time. As expected, during the initial part of the simulation the harvested energy is employed to charge the capacitor. Indeed, in Fig. 1a, for each scheduling algorithm, there is an initial part of the simulation where no packets are sent. Then, when the ED reaches V_{th_high}, there is a spike of sent packets, since

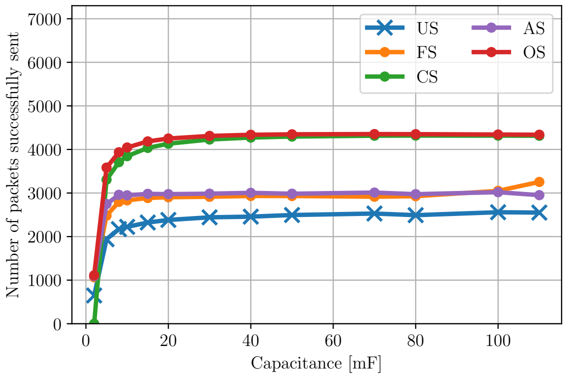


Figure 2: Comparison of scheduling behavior in terms of number of successfully sent packets, for different capacitances and PL=5 B.

the high voltage (3 V) reached is above the threshold set by the sender, and makes it possible to transmit more packets in a short time. After this initial transitory phase, we can see that CS and the optimal OS algorithms transmit packets rather homogeneously in time, while the other scheduling algorithms make the device switch off rather often, particularly when the energy harvesting rate is low. In particular, US yields periodic switching off of the device because it transmits regardless of the energy level. Similar considerations hold for FS and AS. Indeed, given the high variability of the energy harvested in time, the moving average estimate of the harvested power over a window of few seconds is not a good predictor of near future harvested power. As such, AS frequently overestimates the harvested power, causing the capacitor voltage to drop below the lower voltage threshold and thus making the device turn off. It is worth noting that, a more accurate prediction of harvesting power would provide some gain, but in these scenarios the CS approach is already so close to optimal that the possible gain when using other prediction techniques would be minimal.

3.3.2 Performance evaluation. In Fig. 2 we explore the impact of capacitor size on the number of packets successfully sent by the different packet scheduling approaches. First, we can notice that the number of sent packets increases with the capacitance up to values around 40 mF, though the absolute number of transmitted packets depends on the harvesting rate. Indeed, the considered harvesting trace had high variability, and it was observed (not showed here for space limitations) that periods with low P_h corresponded to a low amount of transmitted packets. From Fig. 2 we can also appreciate the difference between the scheduling approaches. US always performs the worst, transmitting about 40% less packets than the OS. The reason is twofold: on the one hand, the ED turns off more often; on the other hand, the scheduler drops packets that cannot be transmitted because of DC constraints, waiting I more seconds before generating a new packet, as will be better investigated below. CS, instead, is able to achieve a performance very close to the optimal because, due to the higher threshold value, the ED never turns off. Notice also that, for very small capacitors, no packets are transmitted because CS sets a higher voltage threshold, that is not achievable by a device equipped with only a small 2 mF capacitor assuming no harvesting during the cycle (as conservatively done by CS). The performance of FS and AS algorithms, instead, are similar, both transmitting between 70 and 80% of the packets with respect to OS. FS also transmits more packets for high capacitance values, due to the fact that, in that case, the capacitor will discharge slowly, staying above the 1.82 V level for a longer time and without falling below V_{th_low}. Other results, not reported here due to space constraints, also compared different versions of the AS approach, which considered different time-averaging intervals for the harvesting power prediction, i.e., 1, 5, 30 and 300 seconds, showing negligible difference in their performance. From these observations, it is interesting to observe that the CS approach, although its simple implementation not considering the energy harvesting capabilities, is the best among the tested solutions. Indeed, even if the set threshold is higher than the optimal one, thus preventing some packet transmissions, more gain is obtained by staying operational for all of the time.

4 CONCLUSIONS

In this work, we considered a battery-less energy-harvesting LoRaWAN node, and provided simulation results assessing the impact of some design choices (capacitor size, sender application) on the capability of the node to send packets. As expected, a major role on the performance is given by the availability of harvestable energy resources. Furthermore, we identified that, in this scenario, the best results could be obtained by employing a capacitor with minimal size of C=40 mF with the CS approach. Although its simplicity, the conservative sender reaches performance close to the optimal, thanks to the conservative assumption on the harvested power, preventing the ED from long silent period due to the switching off when the capacitor's voltage falls below the V_{th_low} threshold.

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