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***Abstract*—Long Range Wide Area Networks (LoRaWANs) have recently emerged as a hot research topic for their capability to collect sporadic data from a great number of widely spread low power devices. By enabling low-cost low-traffic wireless communications at large scale, such networks can be adopted in many application domains, including smart agriculture, logistics, and emergency detection among others. LoRaWAN employs a pure ALOHA default medium access scheme, that limits the maximum achievable throughput to 18%. Increasing the number of terminals would lead to more frame collisions, and eventually to network collapse. The easiest way to allow bigger network sizes is to synchronize devices, so that they can discretize time into slots, and use them to schedule frame transmissions. Herein, a Time Division Multiple Access (TDMA) scheme on the top of LoRaWANs is highly desired. However, since keeping synchronization can lead to heavy energy consumption, the design of such scheme should enforce energy-efficiency. This contribution describes the technical issues related to the implementation of such mechanism, that as a matter of fact represents the cornerstone on which more sophisticated random access protocols or even scheduling techniques can be designed. In dense networks, the proposed scheme combined with a very simple slotted ALOHA mechanism has also been shown to outperform the default LoRaWAN access protocol in terms of expected energy consumption.**

I. Introduction

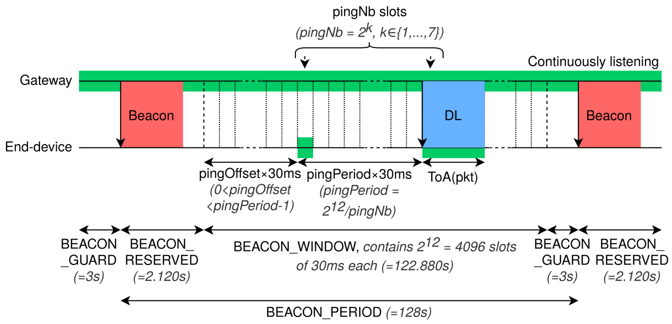
Low Power Wide Area Networks (LPWAN) have shown their capability to interconnect a huge number of battery-powered devices [1]. Such networks are tailored for large-scale sensing and actuating applications, with any device transmitting very small amounts of data per day. Among all the available LPWAN solutions, the Long Range (LoRa) [2] communication technology has triggered a major interest of the research and industrial communities for its inherent ability to exploit unlicensed ISM bands for featuring robust bidirectional low-power communications over very long ranges. The LoRa modulation is proprietary and owned by Semtech, while the LoRaWAN Medium Access Control (MAC) and its open development are supported by the LoRa Alliance. An important research challenge to be addressed is the enhancement of the scaling capabilities of LoRaWANs. Indeed, access to the radio medium follows a pure ALOHA scheme [3], with collisions naturally bounding the maximum achievable throughput to 18%. Therefore, when networks get denser, the increase of retransmission attempts leads to a significant waste of energy and eventually network collapse. Synchronization can be leveraged to alleviate this problem by allowing the use of Time Division Multiple Access (TDMA) and any contention-based (e.g., slotted ALOHA) or contention-free (e.g., resource scheduling) technique on the top of it to increase the network capacity. However, sharing a common time reference among all devices implies additional energy consumption. This paper defines a communication pattern, namely *Class S*, built on the top of the LoRaWAN *Class B*: this enhancement benefits from *Class B* beacons and the induced synchronization to define inter-beacon transmission timeslots. Their size is long enough to allow the transmission of the biggest frame size allowed by LoRaWAN. Such a design has been preliminary evaluated with a simple slotted ALOHA access scheme built on it through an *ad-hoc* simulator, LoRaWAN-sim. Results clearly show off two network behaviors. If the default LoRaWAN access scheme is sufficient to connect with a single gateway less than 2500 devices transmitting 1 frame per hour, the advantage of adopting a synchronized operation for higher densities is twofold. Indeed, further than the throughput increase achieved by switching from pure to slotted ALOHA access [4], *Class S* also makes the communication more energy-efficient, since it bounds the number of retransmission attempts. A threshold-based mechanism is then highly desirable to wisely switch between access techniques depending on the network load.

In order to give sufficient background on the technological landscape of the presented research, Sec. II overviews the LoRa modulation and LoRaWAN specification, as well as related research works on LoRa synchronization and scheduling. Then, Sec. III pictures the proposed synchronization and slotting scheme. Simulation results are presented in Sec. IV, and concluding remarks drawn in Sec. V.

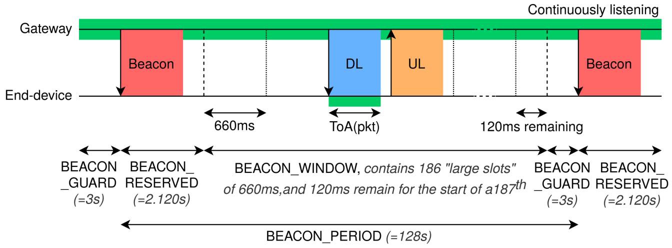
II. Overview and related works

LoRa is an LPWAN technology offering long range reliable communications with a large number of low power devices. While the LoRa modulation and physical layer are proprietary and owned by Semtech, the LoRaWAN specification [2], [5] is open and supported by the LoRa Alliance.

In details, the LoRa modulation relies on Chirp Spread Spectrum to reach long ranges at relatively low power, while being resilient to channel fading. Information is coded over linear frequency sweeps, chirps, over the whole bandwidth (BW) of the channel, and different symbols values are represented by different offsets on the start frequency [6]. One chirp carries one symbol, and the Spreading Factor (SF) is the number of bits encoded in one of these symbols. Increasing the SF lengthens the chirp Time-on-Air (ToA), thus improving the transmission range but lowering the data rate and increasing



(a) *Class B*.



(b) *Class S*.

Fig. 1: Usage of the `BEACON_WINDOW`.

energy consumption. Based on this, developers derived 7 Data Rates (DR), corresponding to 7 compromises between range, data rate and energy consumption. As LoRa operates over unlicensed ISM bands, it has to follow region-specific regulations (e.g., in Europe this is done by the European Telecommunications Standards Institute, ETSI), which mainly consist in duty-cycle and transmission (TX) power limitations.

LoRaWAN defines the MAC layer in details, as well as the server interfaces, security considerations and regional parameters. In LoRaWAN deployments, large numbers of end devices communicate via gateways using LoRa modulation. Gateways are in charge of forwarding the messages to the server through a TCP/IP ethernet or cellular backhaul. The LoRaWAN specification defines three main device classes.

Class A is the default operational mode that all LoRaWAN devices should implement. The radio medium is accessed by the device in a pure ALOHA fashion. Then, two receiving (RX) slots, `RX1` and `RX2`, are opened at fixed delays after the uplink transmission (1 and 2 seconds by default for Europe). `RX2` is only opened if nothing was received during `RX1`. In the case of a confirmed message, if no downlink acknowledgement was received during `RX1` or `RX2`, a collision must have occurred: the message will be retransmitted after a random delay. Receiving windows are sufficiently long to let the device detect a LoRa preamble (30ms). If a preamble is detected, then the window will be kept open to demodulate the whole message. A downlink generated by the server may only be transmitted synchronously with the `RX1` (or `RX2`) opened by the recipient end device after this latter has sent an uplink.

Class B devices still implement *Class A* for uplink communications but must open additional RX slots, namely *ping slots*, to enable server initiated exchanges, thus enhancing bidirectionality. Ping slots are 30ms long, as `RX1` and `RX2`, to correctly capture a LoRa preamble. Devices stay synchronized to the network by listening to periodic beacons broadcast by gateways. The opening of reception windows both for beacons and ping slots clearly implies an additional energy consumption for end devices. As shown in Fig. 1a, each beacon is sent at the beginning of a 128s long `BEACON_PERIOD` composed of: (i) a 2.120s-long `BEACON_RESERVED` interval, with the beacon being broadcast at the beginning of such an interval; (ii) a 122.880s long `BEACON_WINDOW` containing exactly 4096 ping slots; and (iii) a 3s `BEACON_GUARD` interval, permitting the transmission of the biggest frame started during the last ping slot of the `BEACON_WINDOW`. More specifically, a given device opens its first ping slot after `pingOffset` slots (randomly chosen), and then periodically after `pingPeriod` slots until the end of the beacon window. Fig. 1a pictures a device opening 2 ping slots, with a downlink received in the second one. All devices join a LoRaWAN using *Class A* and can switch to *Class B* after negotiation with the network server.

Finally, *Class C* devices are always listening when not transmitting. This allows to reduce processing delays to the minimum, but at the cost of a considerable energy consumption. In fact, *Class C* targets actuators or repeaters.

The LoRaWAN specification is quite recent and the networking research community is giving momentum to its development at large scale. In more details, several studies aiming at improving the capacity of LoRaWANs through synchronization and scheduling have been published in the last few years. In [7], Rizzi *et al.* propose a first attempt at using Time Slotted Channel Hopping (TSCH) within LoRaWAN, using very large slots encapsulating *Class A* operation to target soft real time industrial applications. However, no clear synchronization strategy is stated. The authors of [8] proposed to schedule large timeslots in which transmissions have similar Received Signal Strength and SF requirements in order to counter the capture effect. The possibility to use offline scheduling has also been investigated in [9] to reach real-time constraints with duty-cyle requirements, and in [10] by splitting the beacon window onto sub-periods with and without contention. In [11] and [12], Zorbas *et al.* explore the solutions in which data is stored within the nodes and then collected in bulk. Clock-based synchronization has also been studied in [13] and [14], which additionally features a full scheduling mechanism built on top of *Class A*. Yet, they do not rely on the use of *Class B* beacons. Finally, in [15], the possibility to use low-power wake-up receivers for synchronization has been investigated.

To the best of the authors' knowledge, this paper is the first work using *Class B* beacons to define timeslots that fit the biggest LoRaWAN frame size, and then uses this configuration to setup a slotted ALOHA access while thoroughly evaluating the impact of such a change on energy consumption.

III. Protocol Design

This proposal relies on the LoRaWAN *Class B* synchronization scheme to slice time into timeslots large enough to match the Time-on-Air (ToA) of the longest LoRa frame allowed. As the *Class B* access scheme enhances *Class A* to permit asynchronous downlink transmissions, the introduced *Class S* ("slotted") scheme is meant to enhance *Class B* to increase the uplink traffic throughput through TDMA. In that, the length of a *Class S* timeslot is set to be multiple of the 30ms duration of a *Class B* ping slot, that in turn is the time needed to detect a LoRa downlink preamble. Any *Class S* timeslot can be used for either uplink or downlink transmissions. As an example, Fig. 1b shows a downlink transmission happening within the second slot, and an uplink during the fourth.

The ToA of a frame [16] is computed as the number of preamble and payload symbols multiplied by the ToA of a symbol. The region specific number of preamble symbols s_{pb} is set to 12.25 in Europe, and the number of symbols in the payload s_{pl} is:

$$s_{pl} = 8 + max\left\{ \left\lceil \frac{8P - 4SF - 20H + 44}{4(SF - 2D)} \right\rceil (C+4), 0 \right\}, \quad (1)$$

with P the number of payload bytes, H being 0 or 1 whether a header is present, D being 0 or 1 whether the Adaptive Data Rate mechanism is enabled, and C the coding rate ranging from 1 to 4. Finally, the duration of a symbol is:

$$ToA_{symbol} = \frac{2^{SF}}{BW} \quad (2)$$

Then, the DR5 data rate configuration in Europe (SF7 with BW125) is chosen, since it offers the smallest energy consumption (Data Rate adaptation is disabled). All the parameter settings configuring the longest frame ToA are chosen. The maximum MAC payload length allowed for DR5 has been considered, i.e., 250 bytes [5], to which the 5 bytes of MAC header and Message Integrity Code (MIC) are added [2]. CR is set to 4, and explicit header is enabled.

All in all, the maximum frame ToA is 626.94ms. Hence, 21 ping slots would be needed to fit the corresponding transmission. For the sake of generality, using 22 ping slots to achieve 660ms long *Class S* timeslots would allow an end device to sense the radio medium for possible incoming downlinks before starting an uplink. Indeed, this feature can be safely exploited to design advanced scheduling techniques for dense networks. Following such design guidelines, 187 timeslots can be started during a `BEACON_WINDOW`, with the last one ending during `BEACON_GUARD` interval.

IV. Preliminary simulation results

The TDMA access scheme described above is general enough to be used by any scheduling mechanism. This paper describes a preliminary performance evaluation of such a strategy in the case of unconfirmed uplink communications randomly initiated at the beginning of any *Class S* timeslot. In this way, the resulting configured access scheme is of slotted ALOHA type.

In details, an *ad-hoc* simulation environment, LoRaWAN-sim, has been used to mimick single gateway scenarios. Networks operating in *Class A* are compared with ones using

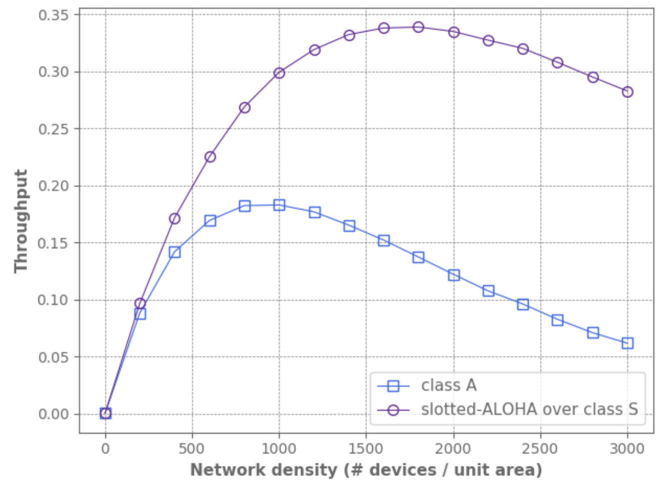


Fig. 2: Network throughput of *Class A* and *Class S* LoRaWAN deployments.

Class S. For these simulations, only one radio channel has been used and each deployment is evaluated for a 1 day duration. In compliance with European regulations, end devices and gateways are subject to duty-cycling limitations of 1 and 10% respectively. Each device pseudo-randomly generates Poisson traffic with an average of 1 frame per hour, matching typical LoRaWAN-based application requirements. Defining "unit area" as the squared surface having the coverage range as side, the density of end devices per unit area has been varied until 3000 (corresponding to $\sim$ 9420 end devices in the coverage area around a gateway). For each of the considered density values, 10 seeds have been used to feed the random number generator of the simulator, thus obtaining 10 different realizations of the same network configuration. The network throughput and the energy efficiency have been evaluated for each scenario, by averaging the results over those 10 realizations. Fig. 2 shows the throughput curves for *Class A* and *Class S*.

The energy efficiency index used is plot in Fig. 3, and it is defined as follows:

$$Energy\ efficiency = \frac{E_{useful}}{E_{all} + E_{synchro}}, \quad (3)$$

where E_{useful} is the per-device energy spent for successful transmissions, E_{all} is the per-device overall energy spent for any transmission attempt, and $E_{synchro}$ is the energy spent for keeping synchronization. It is important to specify that the energy consumed for a transmission attempt is evaluated as the product of the frame ToA, the current drawn by a typical SX1276 LoRa transceiver in TX mode [17], 20mA, and a typical battery voltage, 3.6V. Instead, the energy spent for synchronization is evaluated as the product of the total time a device keeps its radio on for listening to and receiving beacons, the typical current drawn by a SX1276 transceiver in RX mode, 10.8mA, and the same typical battery voltage mentioned before, 3.6V.

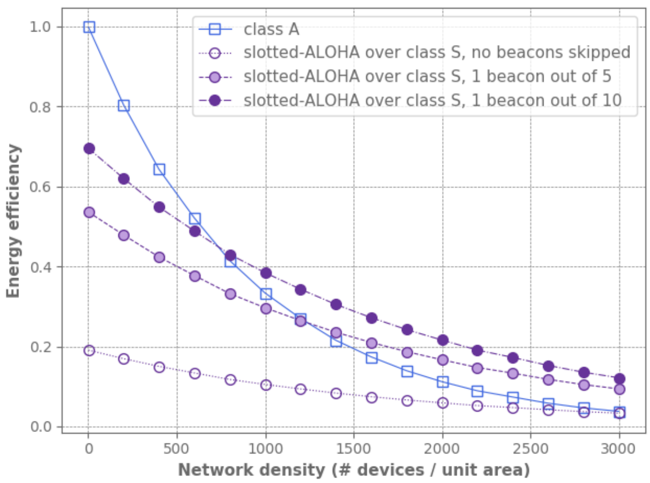


Fig. 3: Energy efficiency of devices using *Class A* and *Class S*.

Devices having a clock drift of $+/-30$ppm RTC XTAL will drift to a maximum of 4ms per beacon window. As specified in [2], end devices shall be able to maintain a beacon-less *Class-B* operation for 2 hours, i.e., without listening to 56 consecutive beacons. This specification detail can be wisely exploited on end devices to intentionally skip beacons, thus increasing their energy efficiency. For instance, listening to 1 out of 5 beacons bounds the drift to 20ms, which is reasonable for 660ms-wide *Class S* timeslots.

The maximum achievable throughput is 0.18 at a density of 800 per unit area for the pure ALOHA *Class A*. Instead, the slotted ALOHA access implemented on the top of *Class S* permits a maximum achievable throughput of ~ 0.34 at about 1600 devices per unit area. Such a value is lower than the theoretical $e^{-1} \approx 0.36$ for slotted ALOHA networks, because there are no uplink allowed during the `BEACON_RESERVED` and most of the `BEACON_GUARD` intervals. All in all, synchronization allows to increase network capacity by better exploiting the available bandwidth. Fig. 3 highlights that a beacon-skipping mechanism is crucial for energy efficiency. For low densities, *Class A* is more efficient as collisions are rare and spending energy for synchronization is energy-wasting. However, when 80% of the beacons are skipped (i.e., when 1 beacon out of 5 is still listened to by end devices) and the density of devices increases beyond 1200 per unit area, the TDMA access results more energy-efficient than the default *Class A* communication pattern. More interestingly, when end devices keep listening to beacons once every 10, and the density of end devices is the one that maximizes the throughput when they are operating in *Class A* (i.e., around 700 end devices per unit area, see Fig. 2), the TDMA-based *Class S* communication pattern outperforms *Class A* both in terms of throughput and energy-efficiency.

As matter of fact, the point where the *Class A* and *Class S* curves cross clearly shows the reason for which a mechanism to switch between communication patterns is extremely needed to build scalable and energy-efficient LoRaWANs.

V. Conclusions

In this paper, *Class S* has been introduced, featuring a novel synchronization and slotting scheme enabling TDMA access in LoRaWANs. Such a scheme is the milestone on which more complex medium access techniques will be designed. It has been shown through simulations that even a very simple slotted ALOHA access scheme outperforms *Class A* in dense deployments, improving the network capacity while being more energy efficient. Further than the impact of clock drift on synchronization, future works will tackle the design of smart threshold-based mechanism allowing a seamless switch between LoRaWAN classes depending on the network load. More interestingly, a thorough design of scheduling techniques will be done even for very complex scenarios, including multi-gateway LoRaWAN deployments. As a major achievement, the goodness of this design will be tested on real-world experimental setups as well.

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