



Synchronizing or not? Selecting the most energy efficient access scheme for LoRaWAN monitoring

Laurent Chasserat, Nicola Accettura, Balakrishna Prabhu, Pascal Berthou

► To cite this version:

Laurent Chasserat, Nicola Accettura, Balakrishna Prabhu, Pascal Berthou. Synchronizing or not? Selecting the most energy efficient access scheme for LoRaWAN monitoring. 2020. hal-02998586v1

HAL Id: hal-02998586

<https://laas.hal.science/hal-02998586v1>

Preprint submitted on 10 Nov 2020 (v1), last revised 30 Apr 2021 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Synchronizing or not? Selecting the most energy efficient access scheme for LoRaWAN monitoring

Laurent Chasserat, Nicola Accettura, Balakrishna Prabhu and Pascal Berthou

LAAS-CNRS, Université de Toulouse, CNRS, UPS, Toulouse, France

Email: {firstname.lastname}@laas.fr

Abstract—The emerging LoRa technology is quickly becoming the *de facto* standard for Low Power Wide Area Networks. Herein, the LoRaWAN medium access sets up a lightweight network architecture able to connect very low power devices to the Internet. Several periodic reporting applications conveyed by LoRa require the collection of an increased amount of sensor information during the daylight hours, *e.g.* monitoring air pollution or sun intensity. However, the expected increase in the network throughput is currently limited by the default LoRaWAN Pure ALOHA access scheme. In such a context, even a time synchronized Slotted ALOHA access would double the achievable throughput. On the other hand, the power consumption would be increased for synchronization duties. The goal of this paper is to leverage Slotted ALOHA to increase the data collection rate range of such applications and to determine which access scheme maximizes their energy efficiency for a given frame periodicity. Results show that a proper skip of synchronization beacons is crucial to handle efficient and scalable LoRaWANs.

I. INTRODUCTION

The last decade was marked by relevant technological progresses in radio communications and miniaturization of electronic components that altogether have unveiled the possibility to monitor many physical phenomena at large scale [1]. Low power wireless devices have been leveraged to deploy widely spread radio networks. Battery replacement is costly, so maximizing their lifetime is a top priority. To address this issue, the Low Power Wide Area Network (LPWAN) architecture has been widely adopted for large scale low throughput data collection under energy constraints. Several LPWAN technologies have emerged from the industrial community, including Long Range (LoRa) networks. They are promoted by the LoRa Alliance, that gathers more than 500 companies to drive the open development of the LoRa Wide Area Network (LoRaWAN) specification [2]. LoRa deployments display many interesting features such as bidirectionality or end-to-end encryption, making them suitable for a large variety of applications. Moreover, LoRaWANs are built upon unlicensed Industrial, Scientific, Medical (ISM) radio bands enabling easy prototyping and deployment. All in all, the technology proves to be an interesting subject of study for LPWAN research.

The LoRaWAN Medium Access Control (MAC) uplink scheme was designed as Pure ALOHA [3], trading-off a low throughput for a low power consumption. Indeed, devices operating under such protocol do not require synchronization, so power is saved and circuitry is kept simple. However, this scheme suffers from high collision rates that naturally limit

the channel throughput to 18%. Several works in the literature have proposed channel access improvements to increase the scaling capabilities of LoRa, many of them based on synchronization and the consequent possibility to slice time into slots. Such enhancement allows to increase the maximum throughput, but it was shown in a previous contribution [4] that the additional energy consumption induced by the process only makes it beneficial for high traffic situations in which pure ALOHA does not suffice.

This knowledge can be used when monitoring physical phenomena featured by non-constant variation rates. For instance, one of the many LoRaWAN applications is pollution tracking. Interestingly, the air quality in a city varies much more during the day than during the night [5]. Efficient monitoring of this phenomenon would thus require a variable number of measures depending on the time of the day. In such network, switching between Pure ALOHA and a synchronized access would allow to increase the maximum measuring rate, but also minimize the power consumption during night hours. In this context, this paper timely provides a simulation-based performance evaluation of a large scale monitoring network, with variable data collection rates and operating over Pure or Slotted ALOHA. Intermediary states where both access schemes coexist are also considered. Indeed, Slotted ALOHA is leveraged to reach higher traffic rates that cannot be handled with default LoRaWAN. However, this synchronized access consumes more energy than Pure ALOHA in low throughput network conditions. Energy efficiency has consequently been chosen as the decision criterion to select the most suitable access scheme. Results show that Slotted ALOHA devices spend a considerable amount of energy listening to synchronization beacons. Therefore, a mechanism allowing devices to skip an adequate number of these broadcasts is highly desired to reduce the rate at which the slotted access becomes beneficial.

The rest of this paper is organized as follows. Sec. II and III give an overview of LoRaWAN and highlight other significant contributions proposing enhancements for these networks. In sec. IV the simulation environment is described in details, and the results are analyzed in sec. V. Finally sec. VI concludes this contribution and provides work perspectives.

II. BACKGROUND ON LORA

The LoRa LPWAN technology is well known for its capability to gather data from a large number of widely-spread sensors. The term LoRa specifically designates the physical

layer technology, while LoRaWAN is the MAC layer. The proprietary LoRa modulation, owned by Semtech, relies on a Chirp Spread Spectrum (CSS) technique, resilient to multi-path interference and channel fading [6]. It allows transmissions to reach up to 10 km ranges under certain conditions [7], with a relatively low power operation. The main parameter of this technique is the Spreading Factor (SF), that can be associated to the time a chirp takes to sweep over the available bandwidth [8]. Increasing the SF lengthens the transmission (TX) range, but also increases the frame Time on Air (ToA), inducing a lower data rate and a higher energy consumption.

Even though the LoRa modulation is proprietary, the upper layers are open and well documented. The LoRa Alliance regroups many industrials and facilitates the interoperability of LoRa networks, especially through the development of the LoRaWAN specification [2] which provides a common view on the MAC layer implementation. It defines a 2-tier topology, in which nodes communicate with gateways via LoRa communications, and gateways interact with servers using IP. The standard also specifies device sub-classes and their detailed implementation, as well as parameter guidelines such as several Data Rates (DR) derived from the SFs.

A notable LoRaWAN feature is the use of the Industrial, Scientific and Medical (ISM) license-free radio spectrum, which facilitates the prototyping and deployment of distributed applications. However, these public frequency bands are subject to Duty Cycle (DC) limitations. This means that any device transmitting a message for a given duration must then remain silent for a certain time. These rules are region-specific, in Europe they are determined by the European Telecommunications Standards Institute (ETSI). The LoRaWAN specification thus provides channel access rules in their regional parameters document [9] to ensure legal compliance.

LoRaWAN defines several device classes with specific communication modes able to fit different types of applications. *Class A* is the default scheme that all devices must implement. In this mode, the uplink (device to server) transmissions are carried-out in a Pure ALOHA manner, and followed by two 30 ms reception slots, providing the server with an opportunity to return a downlink message. In other words, if the server has a pending message for a given node, it will wait for an indeterminate time before having a transmission opening. *Class B* was then introduced to reduce the downlink delay. *Class B* devices operate as *Class A* ones for uplink transmissions, but they also periodically open additional reception slots, offering frequent downlink opportunities. To do so, they need to synchronize to the network by listening to beacons broadcast by the gateways. Finally, *Class C* devices must continuously be listening for possible incoming frames when they are not transmitting, which consumes a significant amount of power and should be reserved for certain critical actuators.

III. RELATED WORKS

Many contributions have proposed MAC layer enhancements to go beyond the default Pure ALOHA scheme. If some Carrier Sense strategies have been explored [10], most

of the novel protocols somehow rely on synchronization and the induced possibility to slice time into transmission slots. A first work in this direction has been provided by Rizzi *et al.* in [11], where class A transactions are placed within a Time Slotted Channel Hopping scheme to reach real-time requirements. However, the timeslot size is not tailored to maximize the throughput and there is no explanation on how to achieve synchronization.

There are several ways to give all devices a common time reference, and they can be used to discriminate some of the proposed protocols. For instance in [12] and [13], respectively proposing a Slotted ALOHA and a scheduling scheme over LoRaWAN, acknowledgements are used to synchronize the devices. This option has not been chosen here because the gateway DC limitations and collisions induce a poor downlink reliability [14], which may lead to synchronization difficulties when increasing the network load. The authors of [15] proposed to use low-power wake-up receivers to setup an on-demand Time Division Multiple Access (TDMA) that completely avoids frame collisions. This scheme is similar to the strategy proposed by Zorbas *et al.* in [16], where nodes buffer all generated data and a scheduling algorithm is used to collect it all in a burst. The main drawback of this approach is that it requires storing data into the nodes while waiting for the burst collection, so the information is no longer available in real time. In [17], the synchronization strategy relies on leveraging the LoRaWAN beaconing to provide a contention-free access during a sub-portion of the period. Yet, the goal here is to reserve channel resources to critical traffic, not to increase the overall network capacity. In [4], *Class S* was introduced as an extension of *Class B*. It relies on beacon synchronization to slice time into slots fitting the longest frame ToA of the network. This is the option that has been chosen as a basis for the Slotted ALOHA scheme used in this contribution, as it requires very little changes to the legacy protocol and keeps the node complexity low.

The variety of access schemes flourishing in the literature triggered higher level analyses such as the one led by Beltramelli *et al.* [18], where a model is proposed to compare LoRa network MAC layers. This shows the clear interest of the research community in testing new LoRaWAN access schemes. Interestingly, a recent contribution [19] proposed adapt the protocol to ease firmware updates. This is a first example showing how the LoRa access scheme can be temporarily changed to suit the network state.

To the best of the author's knowledge, this paper is the first performance evaluation aiming at choosing between Pure and Slotted ALOHA access depending on the desired data collection rate.

IV. SIMULATION ENVIRONMENT

The deployment studied in this contribution fits a large-scale monitoring LoRa network that may for instance be used to gather air pollution data. Its performances are evaluated with an *ad-hoc* event-based simulator and several metrics detailed hereafter. In order to best resemble a real-world deployment,

the traffic shape and device parameters have been implemented as faithfully as possible.

A. Traffic shape

IoT traffic cannot be simulated with the same tools as standard Internet traffic. From this observation, the Third Generation Partnership Project (3GPP) proposed a first model to reproduce it accurately [20], and subsequent works have proposed improvements [21] and comparisons [22], [23]. It may follow three typical shapes: (i) Periodic Update, mostly used for monitoring purposes, (ii) Event Driven, where traffic may be randomly triggered by external events (*e.g.* emergency detection systems), and (iii) Payload Exchange, when transmitting large files such as pictures or firmware updates [24]. The aggregated outcome may be modeled by a combination of these patterns, and adapted to the applications using the network [25].

The LoRa network considered in this paper has a periodic monitoring purpose, and thus a traffic fitting the Periodic Update shape that knows no spatial nor temporal correlation. Devices in the simulation are started with a uniform random offset to mimick a network that has been running for some time by evenly spreading the transmissions. They generate packets periodically, but a small random time delta is added to prevent successive frame collisions between two devices.

B. Simulation parameters

The network features have been set to resemble a large scale single-gateway monitoring deployment. The data collection rates match realistic values for real-world use-cases and the number of devices has been set sufficiently high to test the maximum network capacity. Exact details about the network settings are listed in Table I.

TABLE I: Simulation parameters

Parameter	Value
Number of devices	2000
Simulation duration	12 hours
Frame ToA	626.94 ms
Beacon ToA	173.06 ms
Timeslot size	660 ms
Data rate	DR5 (SF7 with bandwidth 125 kHz)
Interarrival time	Varies from 14580 to 466 seconds
Channels	868.1, 868.3 and 868.5 MHz
Uplink Duty Cycle	1%
Downlinks/Acks/Retransmissions	Disabled
Sensor voltage	3.3 V
Sensor current intensity	20 mA TX, 10.8 mA RX [26]

The periodic monitoring scenario considered here calls for a traffic with uplink communications only, thus the downlink frames have been disabled along with acknowledgements and re-transmissions. Only the three mandatory LoRaWAN channels are implemented, which are subject to a Duty Cycle of 1%. In order to follow the day and night variation rates, interarrival times vary from 14580 (~ 1 frame every 4 hours) to 466 s (~ 1 frame every 7 – 8 minutes).

Only the smaller LoRaWAN SF (SF7, corresponding to DR5) is used because it results in the lowest frame ToA, which

is beneficial because it reduces the collision rate and consumes less energy on the device side. This work can however safely be extended to the other orthogonal SFs by following a similar reasoning.

The simulated devices may follow a Pure or Slotted ALOHA access, respectively implemented as the LoRaWAN *Class A* and the *Class S* presented in [4]. In order to give a lower bound of the network capacity, the worst case scenario is considered regarding the frame ToA. Indeed, all frames are considered to be sized according to the maximum MAC payload allowed (250 bytes), with the Coding Rate set to 4, and explicit header and Message Integrity Code are enabled. This all in all results in a ToA of 626.94 ms for data frames and 173.06 ms for beacons [27]. The *Class S* timeslot size is set to 660 ms in order to comfortably fit this packet size. In facts, this value is a multiple of the 30 ms LoRaWAN receive window, so that hardware implementations will require minimal modifications to the firmware. The reception slots of slotted devices occur at the beginning of the second and fourth slot after the one used for the transmission. They will not be used in this scenario, but are still implemented to account their contribution to the device power consumption.

The portion of beacons that devices choose to skip is an important parameter to consider when evaluating the energy efficiency. It is clear that this skipping helps in reducing the energy consumption of slotted-ALOHA devices, but it may also increase the chances of losing synchronization. For the following analysis, the parameter n_{skip} is thus introduced to represent the number of beacons that a device skips between two beacons that it actually receives. The LoRaWAN specification states that nodes should be able to maintain beacon-less synchronization during at least two hours, and the inter-beacon time is 128 seconds so n_{skip} is subject to range from 0 to 56.

C. Metrics

In order to understand which access scheme is suitable for different data collection rates, the scenario presented above will be tested with different proportions of slotted devices in the network. The overall network throughput T and energy efficiency E will be analyzed to grasp the limits of the network and find the conditions that will maximize the lifetimes of the device batteries. The limited channel resources will naturally induce a raise of the frame loss percentage when increasing the data collection rate. This value will be derived for the most energy efficient configuration in order to give insights on the reliability that can be expected for several data collection rates. The simulated throughput, expressed in bytes per second, is computed as such:

$$T = \frac{t_{ok}}{d} \cdot \frac{B}{ToA} \quad (1)$$

With t_{ok} the overall successful transmission time, d the duration of the simulation, B the size of a frame in bytes, and ToA the associated frame Time on Air. In order to evaluate the network energy efficiency, bytes per joule [28] will be used, computed as:

$$E = \frac{T \cdot d}{P_{TX} \cdot t_{TX} + P_{RX} \cdot t_{RX}} \quad (2)$$

With t_{TX} , t_{RX} the overall time spend by devices in TX and (RX/listening) states, and P_{TX} , P_{RX} the power a Semtech SX1276 chip consumes in TX and (RX/listening) states under a typical LoRa battery voltage, 3.3V [26].

V. PERFORMANCE EVALUATION

The network throughput T has been plot in figure 1 for several data collection periodicities. At low rates, the benefits of using Slotted ALOHA are negligible. However, when the number of generated packets increases, the 100% Pure ALOHA curve reaches its maximum quickly while the slotted scenario scales more easily, showing that the slotted access gives access to data rates that were unreachable in legacy LoRa networks. This is due to the fact that the use of timeslots reduces the frame collision window to half its Pure ALOHA size.

Remarkably, the advantage of a slotted access is substantial only when a significant portion of devices are using it. Indeed, the curve associated with 50% of slotted devices peaks at 250 bytes per second, displaying a raise of only 13% compared to the maximum of the 100% pure curve. On the other hand, the scenario with 75% of slotted devices allows a 36% increase, and when all devices are synchronized the network capacity is almost doubled.

Figure 2 displays the network energy efficiency, the most energy efficient access scheme and the associated frame loss percentage for different data collection rates and different values of n_{skip} . The energy efficiency E has been plot in figures 2a, 2c and 2e. There, it is clear that the channel is used less efficiently when the number of generated frames increases. The pure-ALOHA energy efficiency starts much higher but drops much faster than the slotted one. This highlights the existence of a given rate at which Slotted ALOHA becomes more efficient than Pure. It is also interesting to note that at all rates, the maximum energy efficiency is always obtained by the 100% Pure or the 100% Slotted ALOHA scheme, showing that intermediary states should be avoided. The analysis remains relevant to evaluate performances of a network gradually switching to a synchronized access, or if some devices in the deployment do not implement *Class S*.

By looking at which curve is associated with the highest E for the different rates, the preferable portion of slotted devices is identified and forms the curve with squared markers in figures 2b, 2d and 2f. The curve with circle markers corresponds to the frame loss percentage experienced when using this same portion. These figures allow to clearly distinguish the threshold at which devices should change their access scheme, as well as the drop in performance that should be expected when increasing the data collection rate. When looking at the results produced by different values of n_{skip} , it is clear that this parameter has a strong impact on the value of the tipping point where the slotted access becomes preferable. The more beacons are skipped, the more the rate at which curves

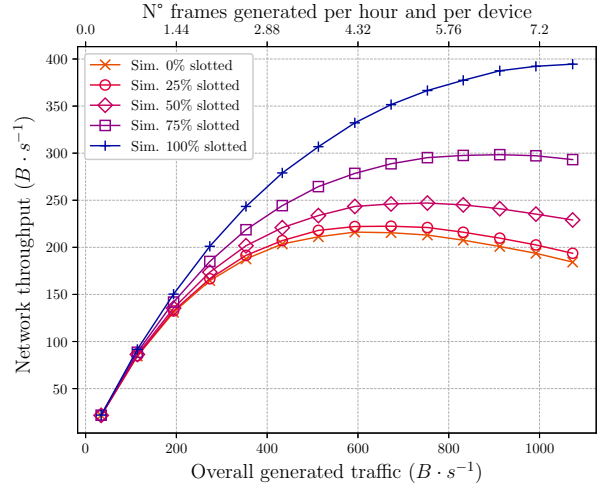


Fig. 1: Throughput.

cross is shifted to the right. This makes perfect sense because setting slotted devices to use higher values of n_{skip} will cause a reduction of t_{RX} , and therefore increase E .

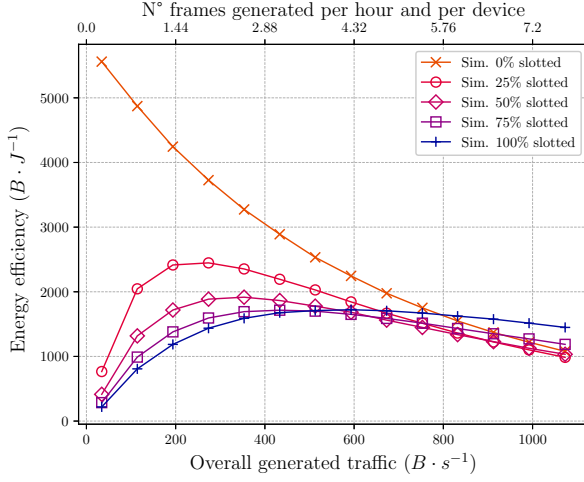
The frame loss percentage naturally increases with the generation rate. The curve only displays a drop when going from Pure to Slotted ALOHA, because such change reduces the probability that two transmissions collide. It is interesting to notice that skipping an adequate number of beacons allows to make the synchronization worth at smaller rates, and thus to provide a better frame delivery ratio in these conditions. Indeed, when devices generate 5 frames per hour, if $n_{skip} = 0$ Pure ALOHA is preferred and 70% of frames collide. However, with the higher values of n_{skip} the network would rather operate with a Slotted ALOHA access, and the collision probability would drop to 50%.

In order to quantify the impact of n_{skip} on the rate at which Slotted ALOHA becomes more efficient, the percentage difference between the 100% slotted scheme over the 100% pure one is plotted in fig. 3 for several frame generation rates.

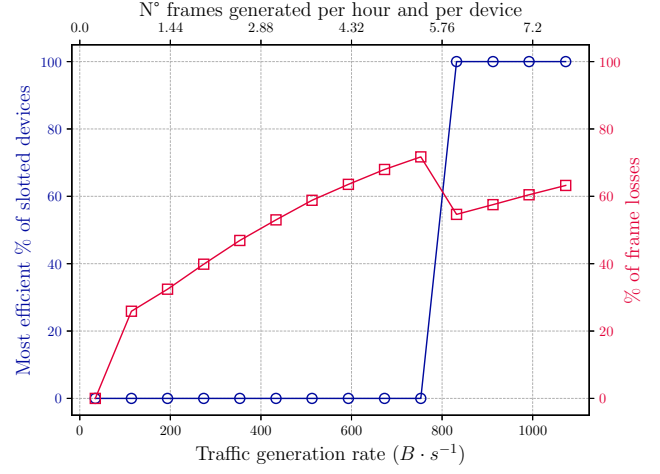
In the case where one frame is transmitted every 4 hours, this percentage difference is always negative, meaning that Pure ALOHA is always preferable energy-wise. However, with 2 frames per hour, Slotted ALOHA may be a better solution if it is possible to skip 10 beacons between each reception. Then, when the rate increases this crossing point occurs at smaller and smaller n_{skip} values, until finally slotted-ALOHA becomes always preferable for high generation rates such as 1 frame every 10 minutes.

VI. CONCLUSIONS AND FUTURE WORKS

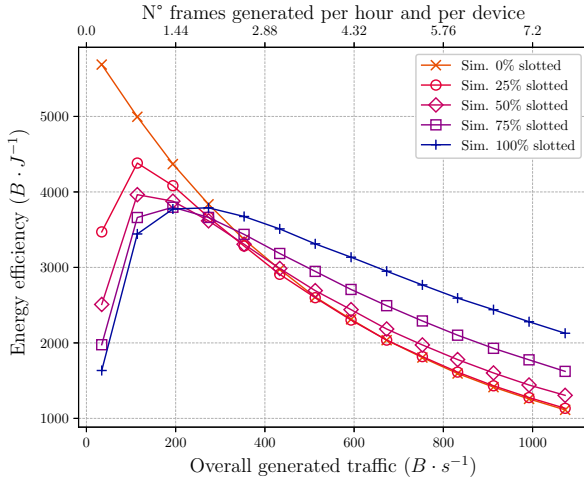
This contribution presented a simulation-based performance evaluation of a large scale LoRa network used for periodic reporting. Pure ALOHA, Slotted ALOHA and different degrees of coexistence between the two schemes have been compared and tested for a wide range of data collection rates. Results show how to adapt the access scheme to maximize energy efficiency, and provide insight on the expected frame loss



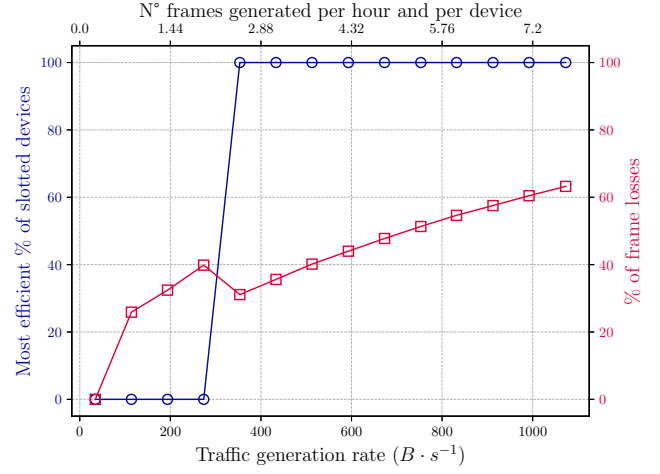
(a) Network energy efficiency ($n_{skip} = 0$).



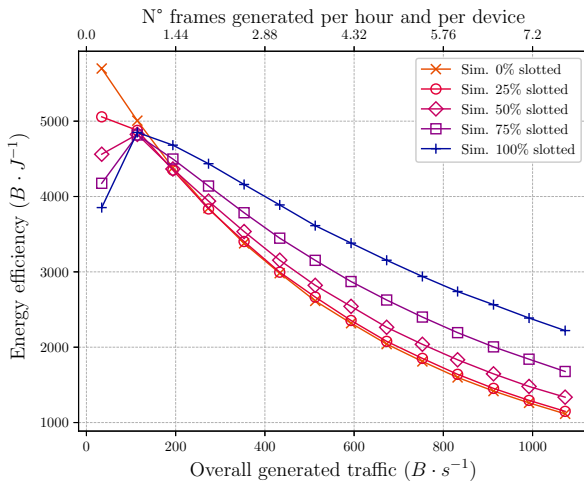
(b) Most energy efficient access scheme and corresponding frame loss percentage ($n_{skip} = 0$).



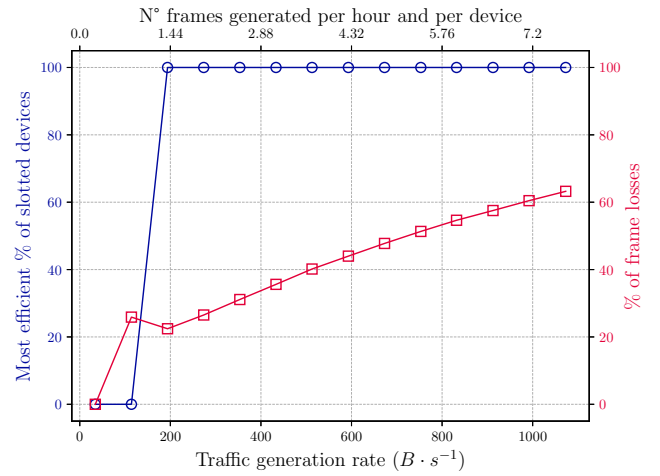
(c) Network energy efficiency ($n_{skip} = 9$).



(d) Most energy efficient access scheme and corresponding frame loss percentage ($n_{skip} = 9$).



(e) Network energy efficiency ($n_{skip} = 49$).



(f) Most energy efficient access scheme and corresponding frame loss percentage ($n_{skip} = 49$).

Fig. 2: Energy efficiency and switching thresholds with different degrees of beacon skipping.

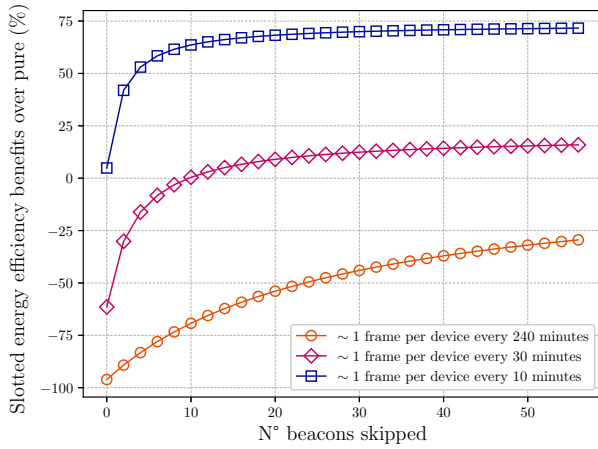


Fig. 3: Percentage difference of slotted-ALOHA energy efficiency over pure-ALOHA.

rates. This allows to increase the data collection periodicity compared to legacy LoRa deployments, or conversely to save energy on the nodes when little data is needed. This paves the way to more adaptive sensor networks, in which the channel access scheme will follow the variations of the monitored phenomenon. It has been found that a beacon skipping mechanism was crucial to take full benefit of the slotted devices while still maximizing the energy efficiency. This calls for a study linking n_{skip} to the clock drifting of wireless devices, and consequently the investigation of the impact of synchronization losses on energy efficiency. The transient states studied in this contribution will also be leveraged in subsequent contributions to analyze the convergence times needed to switch from a pure to slotted access. Future works will also tackle the design of a scheduling algorithm over LoRaWAN to increase the channel capacity even further, also considering slot placements in multi-gateway deployments.

REFERENCES

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, Mar. 2002. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1389128601003024>
- [2] LoRa Alliance, "LoRaWAN® Specification v1.1," 2017.
- [3] N. Abramson, "THE ALOHA SYSTEM: another alternative for computer communications," in *Proc. of AFIPS '70 (Fall)*, ser. AFIPS '70 (Fall). Houston, Texas: ACM, Nov. 1970, pp. 281–285.
- [4] L. Chasserat, N. Accettura, and P. Berthou, "Short: Achieving energy efficiency in dense LoRaWANs through TDMA," in *IEEE International Symposium On a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Cork, Ireland, Aug. 2020. [Online]. Available: <https://hal.laas.fr/hal-02551973>
- [5] P. I. Jalava, Q. Wang, K. Kuusalo, J. Ruusunen, L. Hao, D. Fang, O. Väisänen, A. Ruuskanen, O. Sippula, M. S. Happonen, O. Uski, S. Kasurinen, T. Torvela, H. Koponen, K. E. J. Lehtinen, M. Komppula, C. Gu, J. Jokiniemi, and M. R. Hirvonen, "Day and night variation in chemical composition and toxicological responses of size segregated urban air PM samples in a high air pollution situation," *Atmospheric Environment*, vol. 120, pp. 427–437, Nov. 2015. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1352231015303332>
- [6] S. El-Khamy, S. Shaaban, and E. Thabet, "Frequency-hopped multi-user chirp modulation (FH/M-CM) for multipath fading channels," in *Proceedings of the Sixteenth National Radio Science Conference. NRSC'99 (IEEE Cat. No.99EX249)*, Feb. 1999.
- [7] K. Mikhaylov, J. Petäjäjärvi, and T. Haenninen, "Analysis of capacity and scalability of the lora low power wide area network technology," in *European Wireless 2016; 22th European Wireless Conference*, ser. Proceedings of EW '16, Oulu, Finland, May 2016, pp. 1–6.
- [8] M. Knight and B. Seeber, "Decoding LoRa: Realizing a Modern LPWAN with SDR," *Proc. of the GNU Radio Conference*, vol. 1, no. 1, Sep. 2016.
- [9] LoRa Alliance, "LoRaWAN Regional parameters v1.1," 2017.
- [10] C. Pham, "Robust CSMA for long-range LoRa transmissions with image sensing devices," in *2018 Wireless Days (WD)*, Apr. 2018, pp. 116–122.
- [11] M. Rizzi, P. Ferrari, A. Flammini, E. Sisinni, and M. Gidlund, "Using LoRa for industrial wireless networks," in *2017 IEEE 13th WFCs*, May 2017, pp. 1–4.
- [12] T. Polonelli, D. Brunelli, A. Marzocchi, and L. Benini, "Slotted ALOHA on LoRaWAN-Design, Analysis, and Deployment," *Sensors*, vol. 19, no. 4, p. 838, Jan. 2019.
- [13] J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Low Overhead Scheduling of LoRa Transmissions for Improved Scalability," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3097–3109, Apr. 2019.
- [14] A.-I. Pop, U. Raza, P. Kulkarni, and M. Sooriyabandara, "Does Bidirectional Traffic Do More Harm Than Good in LoRaWAN Based LPWA Networks?" *arXiv:1704.04174 [cs]*, Dec. 2017, arXiv: 1704.04174. [Online]. Available: <http://arxiv.org/abs/1704.04174>
- [15] R. Piyare, A. L. Murphy, M. Magno, and L. Benini, "On-Demand TDMA for Energy Efficient Data Collection with LoRa and Wake-up Receiver," in *2018 14th WiMob*, Oct. 2018, pp. 1–4.
- [16] D. Zorbas, K. Q. Abdelfadeel, V. Cionca, D. Pesch, and B. O'Flynn, "Offline scheduling algorithms for time-slotted lora-based bulk data transmission," in *2019 IEEE 5th WF-IoT*, April 2019, pp. 949–954.
- [17] L. Leonardi, F. Battaglia, G. Patti, and L. L. Bello, "Industrial LoRa: A Novel Medium Access Strategy for LoRa in Industry 4.0 Applications," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2018, pp. 4141–4146.
- [18] L. Beltramelli, A. Mahmood, P. Osterberg, and M. Gidlund, "Lora beyond aloha: An investigation of alternative random access protocols," *IEEE Transactions on Industrial Informatics*, pp. 1–1, 2020.
- [19] K. Abdelfadeel, T. Farrell, D. McDonald, and D. Pesch, "How to make Firmware Updates over LoRaWAN Possible," *arXiv:2002.08735 [cs]*, Feb. 2020, arXiv: 2002.08735. [Online]. Available: <http://arxiv.org/abs/2002.08735>
- [20] 3GPP, "3GPP Study on RAN Improvements for Machine-Type Communications," 3GPP, Technical Report TR 37.868, 2012.
- [21] M. Laner, P. Svoboda, N. Nikaein, and M. Rupp, "Traffic models for machine type communications," in *ISWCS 2013; The Tenth International Symposium on Wireless Communication Systems*, Aug. 2013, pp. 1–5.
- [22] K. Smiljkovic, V. Atanasovski, and L. Gavrilovska, "Machine-to-Machine traffic characterization: Models and case study on integration in LTE," in *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace Electronic Systems (VITAE)*, May 2014, pp. 1–5.
- [23] M. Zarrini and A. Ghasemi, "Loss and delay analysis of non-Poisson M2M traffic over LTE networks," *Transactions on Emerging Telecommunications Technologies*, vol. 29, no. 2, p. e3273, 2018. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ett.3273>
- [24] N. Nikaein, M. Laner, K. Zhou, P. Svoboda, D. Draic, M. Popovic, and S. Krcic, "Simple Traffic Modeling Framework for Machine Type Communication," in *ISWCS 2013; The Tenth International Symposium on Wireless Communication Systems*, Aug. 2013, pp. 1–5.
- [25] M. O. Farooq and D. Pesch, "Evaluation of Multi-Gateway LoRaWAN with Different Data Traffic Models," in *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*, Oct. 2018, pp. 279–282, iSSN: 0742-1303.
- [26] Semtech Corporation, "SX1276/77/78/79 datasheet," Jan. 2019.
- [27] —, "AN1200.13 SX1272/3/6/7/8: LoRaModemDesigner'sGuide," 2013.
- [28] E. Björnson and E. G. Larsson, "How energy-efficient can a wireless communication system become?" in *2018 52nd Asilomar Conference on Signals, Systems, and Computers*, 2018, pp. 1252–1256.