2020 IEEE 21st International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)

Exploring the Use of Control Packets in LoRa Medium Access: a Scalability Analysis

Rui Fernandes*†, Rui Oliveira*†, Miguel Luís*‡, Susana Sargento*†
*Instituto de Telecomunicações, 3810-193 Aveiro, Portugal
†University of Aveiro, 3810-193 Aveiro, Portugal
‡ISEL - Instituto Superior de Engenharia de Lisboa, 1959-007 Lisboa, Portugal

***Abstract*—LoRa technology has been attesting itself as one of the most prominent and widely adopted low power wide area technologies. Highly compatible with Internet of Things (IoT) applications and urban environments, this technology enables large range communications although with small bandwidths and duty cycle restrictions. In this work, we propose a distinct way of dealing with the Medium Access Control (MAC) in LoRa, through the use of control packets to enhance the technology performance in urban city scenarios, where a large number of nodes is expected. The proposed protocol is asynchronous and takes into account the energy expenditure. We compare this scheme with the standard (LoRaWAN) by considering different network densities and packet sizes, and through different LoRa collision models. Performance results, such as network throughput and fairness index, show that, depending on the ratio between data and control packet lengths, it is possible to greatly improve the bit rate and overall network performance, even if increasing the duty-cycle restriction time due to the addition of overhead.**

***Index Terms*—IoT, LoRa, LoRaWAN, Channel Access, Performance Analysis**

I. INTRODUCTION

The concept behind the Internet of Things (IoT) alludes to a network in which all objects can exchange information actively. It aims to provide Machine-to-Machine and Machine-to-Person communications on a massive scale, and it is expected a significant increase in both the total number of devices connected and revenues [1]. The number of possibilities for IoT platforms' applications is enormous, with different areas having specific requirements and considerations [2].

A wide variety of technologies are considered for IoT, such as short-range passive and active radio frequency (RFID) systems, systems based on the family of IEEE 802.15.4 standards (ZigBee, 6LoWPAN), Bluetooth-based systems (including Bluetooth Low Energy (BLE)), systems based on IEEE 802.11/Wi-Fi and cellular networks. However, in order to achieve the long-range requirements, some of these technologies must recur to multi-hop techniques, which quickly increases the network cost.

Short-range, high cost and complexity are problems that can be solved by using Low Power Wide Area Networks (LPWANs). LoRa, Sigfox, Ingenu, Weightless, NB-IoT are some of the communication technologies supporting LPWANs, and they share a group of relevant characteristics for IoT, such as long-range, low-power, low deployment and operational cost, robustness and scalability, allowing for a high number of devices [3], [4].

The work here presented differentiates itself from the literature, since it presents the first study on the applicability of a simple control packet on the medium access control of LoRa duty-cycled networks. The evaluation is focused on the network throughput and channel access fairness, and considers two different LoRa collision models, with and without destructive communications. The results show that, depending on the network size and on the ratio between the length of the control and data packets, the proposed scheme generally outperforms LoRaWAN single channel, although at the cost of a shorter battery lifetime.

The remainder of this paper is organized as follows. Section II overviews the related work on medium access control protocols for LoRa networks. Section III is focused on the LoRa technology, its physical layer, the standard MAC protocol (LoRaWAN) and how the proposed MAC protocol works. Section IV details the simulations setup. Section V discusses the results, and finally, Section VI enumerates the conclusions and directions for future work.

II. RELATED WORK

Most of the research on medium access with LoRa has been focused on either improving or studying LoRaWAN. Meanwhile, other LoRA-based MAC layer protocols had far less scrutiny due to the limited research on using LoRa with MAC layer protocols other than LoRaWAN [5]. There are, however, some proposed alternatives.

Adelantado et. al [6] explored the limits of the LoRaWAN technology, providing an overview of its capabilities in aspects such as the number of nodes, network load, packet size and network delivery capacity. Oliveira et. al [7] proposed a MAC protocol based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), with Request to Send (RTS)/Clear to Send (CTS) message exchange to control the media access of the devices.

Bor et. al [8] proposed LoRaBlink, a MAC protocol that aims to enable high message delivery and low-latency, however assuming low traffic volume and a limited number of nodes, characteristics that we cannot expect. Hassan et. al [9] proposed MoT (MAC on Time), a protocol that focuses on the same purposes while supporting good scalability, with

978-1-7281-7374-0/20/$31.00 ©2020 IEEE
DOI 10.1109/WoWMoM49955.2020.00016

collisions being eliminated by precise time-scheduling and acknowledgement of all uplink messages. However, this will translate into large duty cycle constraints on the gateway's side.

Deng et. al [10] proposed ADC-MAC, a protocol that also takes into account the energy efficiency. The basic idea of ADC-MAC is to adjust the node duty-cycle dynamically. The duty-cycle selection is based on three indicators: *1) residual energy*, *2) node load* and *3) network congestion rate*. It was seen that, for small-scale networks the Packet Delivery Ratio was lower, when compared to the standard duty-cycle limitation. However, when increasing the size of the network, ADC-MAC gets better results.

The work here presented goes beyond the previous research in the literature through the introduction of a simple control packet on the medium access control of LoRa duty-cycled networks, evaluated in scenarios with both destructive and non-destructive communications, while keeping energy efficiency as a topic of analysis.

III. MEDIUM ACCESS CONTROL IN LORA NETWORKS

LoRa, which stands for Long Range, is a long-range wireless communications system that focuses on the support of long-live battery-powered devices. LoRa's physical layer uses a proprietary spread spectrum modulation scheme owned and patented by SemTech, derivative of the Chirp Spread Spectrum (CSS) modulation technique. Depending on the application, it is possible to optimize the LoRa modulation through customization of several parameters: Bandwidth (BW), Coding Rate (CR), which determines the rate of the FEC code, and Spreading Factor (SF), that expresses the ratio between symbol rate and chirp rate. Different combinations of these parameters provide different tradeoffs of throughput for coverage range, robustness or energy consumption. LoRa networks operate over ISM frequency bands, and therefore, under strict rules about the maximum transmission power and duty cycle operations.

The LoRa network architecture is typically laid out in a star-of-stars topology, ideal for preserving battery lifetime, where the end devices are connected via a single-hop wireless LoRa link to one or many gateways that, in turn, are connected to a common network server (NetServer) via standard Internet protocols [11]. Device-to-device communications are not allowed in LoRaWAN: packets can only be transmitted from an end-device to the network server, or vice-versa. If required, device-to-device communication must be sling-shot through the network server (and consequently, through two gateway transmissions).

A. LoRaWAN

The LoRaWAN medium access is based on a pure-ALOHA scheme, meaning that all devices can access the channel *whenever* they want. Its specification states that sub-GHz ISM frequency bands should be used with very stringent regulations regarding the maximum transmission power and duty-cycle. The latest corresponds to 1%, where a device will have to wait 99-times the duration of the last frame before transmitting in the same channel. Besides, an additional random backoff time is also calculated, so that packets that collided in the last transmission now have the chance to be delivered. Documentation on LoRaWAN does not specify a maximum backoff value, leaving it at the user's discretion[1].

Regarding battery lifetime, three different classes are provided (A, B and C), each with a different operating mode, allowing a trade-off between performance (*i.e.* throughput and latency) and energy consumption [12]:

- *Class A (for All):* Bi-directional end-devices with scheduled uplink transmissions. After each uplink transmission, the device opens up two short downlink windows. This class has the lowest power consumption but the highest latency, and the least flexibility on downlink transmission;
- *Class B (for Beacon)*: Bi-directional end-devices with scheduled receive slots. These extra receive windows reduce the downlink latency and increase the power consumption. Devices must receive a time-synchronized beacon from the gateway, allowing the server to know if the end-device is in the listening windows;
- *Class C (for Continuously listening):* Bi-directional end-devices with maximal receive slots. These devices have no energy restrictions, having almost continuous reception windows. Because of this, Class C has the highest power consumption and the lowest latency.

B. Reservation based MAC protocol

By assuming a typical LoRa network, with a single gateway and multiple end-nodes, we evaluate the impact of adding a simple control packet before every data message, with the purpose of notifying other possible transmitters - the active devices at the time - forcing them to readjust their access time windows. The method of operation of all end-devices would undergo changes, with all being unable to transmit data without previously sending a control message. Control packet collisions, although possible, are much less likely to happen due to a smaller packet size, and consequently with less channel occupation, having less impact in the duty cycle restriction.

The Ready-to-Send (RTS) message contains the following information: the sender node unique identifier, a type identifier that distinguishes control packets from data packets, and a data size field indicating the length of the data packet to be transmitted. The proposed scheme differs from CSMA since carrier sense is not applied, the device listens to the channel awaiting the reception of a message that can not only indicate channel occupation, but also allows calculating the time-on-air of the next data packet, using the length and current operation mode as inputs [13].

The protocol characteristics can be summarized as follows:

- End-nodes decide whether or not to send data based on the overheard RTS messages;

---

[1] https://lora-alliance.org/resource-hub/lorawantm-specification-v11 → Accessed: 26-01-2020

- Does not use burst transmissions, a single packet is sent at each instant;
- Acknowledgement packets are not used;
- Packet retransmissions are never used;
- RTS messages contain information regarding the size of the following data packet, allowing neighbours to calculate the minimum backoff time;
- Backoff time is composed of both sleeping periods and listening periods.

When not transmitting, devices are in one of two states: *Listening State*, so that it is possible to receive RTS messages coming from other nodes, and *Sleeping State*, for when the channel is known to be occupied or the end-node is forbidden to communicate for duty-cycle reasons. This is illustrated in Figure 1.

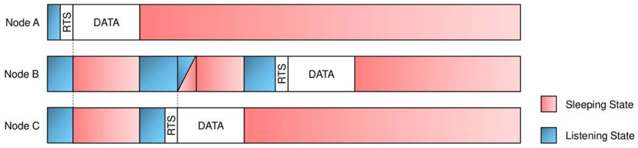

Fig. 1: Summarized functioning of RTS-LoRa protocol.

Upon hearing a RTS message, nodes can sleep for the duration of the following transmission. After listening to the medium and, if another RTS is received, the medium access window is adjusted as exemplified in Figure 1 in the case of node B, that abandons the *Listening State* earlier than expected and enters *Sleeping State*. Otherwise the node is allowed to communicate. This additional backoff time, in which nodes are obligated to listen to the medium, is slotted in order to minimize the probability of collisions, with each slot corresponding to the time-on-air of an RTS message.

C. Energy consumption comparison

The proposed scheme, hereinafter referred as RTS-LoRa, takes into account the energy expenditure of the end-nodes by allowing them to be in *Sleeping State* whenever possible. Even so, devices have a higher consumption than Class A LoRaWAN end-nodes - the least energy consuming class due to limited downlink windows - since they regularly need to listen to the channel, waiting to receive RTS messages. Therefore, a shorter battery lifetime is the price to pay for the introduction of the RTS packet.

However, it should be noted that this MAC protocol differs from LoRaWAN Class B, since gateway synchronization is not required. To operate successfully in Class B, a LoRaWAN end-device has to periodically receive a beacon for synchronization purposes, so that downlink windows between transmissions are open at precise instants. Depending on the frequency and duration of Class B downlink windows, the end-device can end up spending more time in receive mode between transmissions than when using RTS-LoRa, giving the latest an energy-saving advantage. With LoRaWAN Class C, the downlink window extends to the next uplink, causing this class to be used solely for applications in which battery saving is not a concern. For this reason, devices using RTS-LoRa are expected to have a significantly lower power consumption compared to the ones using LoRaWAN Class C.

IV. EVALUATION SETUP

To evaluate the MAC protocols in scenarios with a large number of end-devices, we developed a simulator in MATLAB that allows extensive testing. The two protocols implemented were: LoRaWAN Class A in single channel and RTS-LoRa in single channel. Regarding the LoRa physical layer, two distinct models are assumed: destructive collisions, when two or more packets transmitted simultaneously are always considered lost, and a probabilistic model obtained from real measurements, allowing the reception of one packet in the event of concurrent transmissions depending on the ratio of RSSI values between the colliding packets [14]. The destructive model, although proved to be unrealistic, is still considered in the evaluation process given its importance in the literature.

The following LoRa configuration was assumed: bandwidth of 125kHz, a coding rate of 4/5 and a spreading factor of 10, allowing a good tradeoff between time-on-air and sensitivity (-129 dBm). The work developed in [15] obtained a linear relation between the RSSI and distance between devices while using this configuration, for RSSI values between [-95, -120] dBm and distances between 572 and 5240 meters. Accordingly, regarding the end-nodes displacement, a concentric network layout was considered. The LoRa gateway was placed in the center of the network, and non-mobile IoT devices were equally distributed through 5 zones, with each zone representing a signal strength at the moment of the packet reception, as illustrated by Figure 2. The signal strength of a packet transmission is set to be related with the distance to the gateway as Table I indicates, based on the relation obtained in [15].

TABLE I: Range of RSSI values per zone.

Zone	Possible RSSI values
1	[-100,-95]
2	[-105,-100]
3	[-110,-105]
4	[-115,-110]
5	[-120,-115]

The end-node behaviour for both protocols is detailed in Figure 3, with the grey blocks corresponding to the changes made to a pure-ALOHA scheme to create RTS-LoRa: the four white blocks illustrate the LoRaWAN operation mode, while the RTS-LoRa is represented by the totality of the flowchart. The RTS packet contains all the fields detailed in the previous section, resulting in a packet length of 9 Bytes.

The calculated time-on-air upon reception of an RTS corresponds to the obligatory backoff period in which nodes

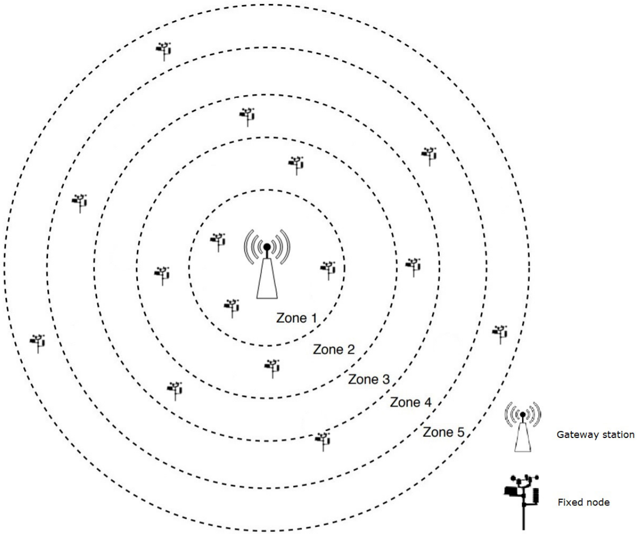

Fig. 2: Network layout.

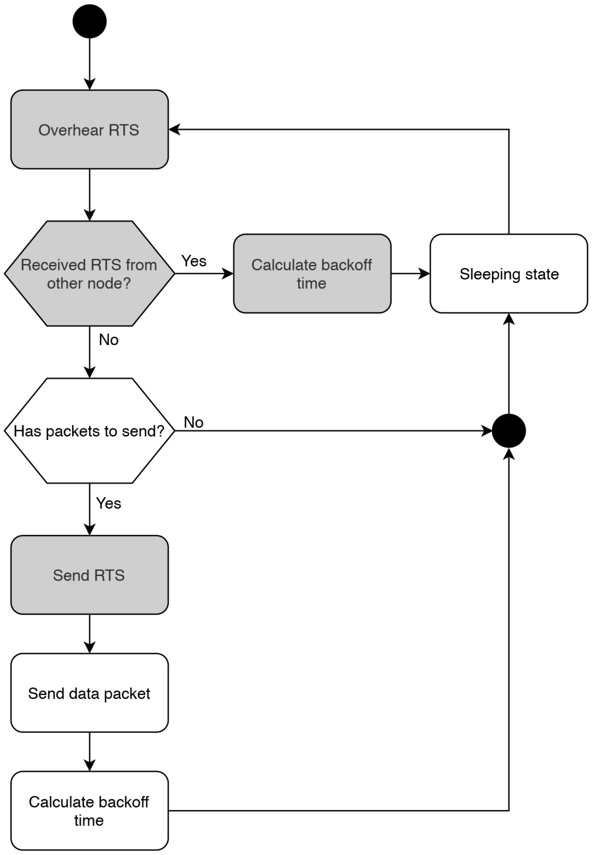

Fig. 3: MAC protocol flowchart for the end-nodes.

have no need to listen to the medium, and are allowed to sleep in order to save energy. When this time is fulfilled, the devices are obligated to switch to and remain in *Listening State* for a random amount of time. As referred, to maximize the probability of success this additional time is divided into n slots, with one slot corresponding to the time-on-air of a RTS message. In order to privilege high-scale networks, 50 slots are considered, leading to a maximum backoff time of $50 * RTS\_ToA$ which, for a control packet of 9 Bytes, results in 14.33 seconds. In the event of another RTS being heard while the node is in *Listening State*, the backoff time is adjusted accordingly. If nothing is received two things may occur: either the node accesses the medium, or if at the moment it has no information to send, goes into sleeping state. The amount of time spent sleeping is selected depending on the packet generation periodicity to maximize efficiency, but it is crucial that before it tries to access again some time is spent in *Listening State*, checking the channel availability.

The backoff time added for LoRaWAN devices after a transmission is a random value calculated between 1 and 15000 ms. In the evaluation process we have considered the following parameters: data sizes of {10, 25, 50, 75, 100 and 200} Bytes and network sizes of {5, 10, 15, 20, 30, 45, 60, 75, 100, 125, 150, 175, 200, 300, 400, 500, 750 and 1000} end-nodes. The simulation time is 10^{10} slots with 1 ms precision (slot length). Both protocols were evaluated under saturation conditions, meaning that every node has at least a packet to transmit at the end of the duty cycle constrained period. The selected metrics to evaluate the protocol performance were the network capacity, expressed in Bytes/hour, and the channel access fairness, represented by the Jain's Fairness Index [16], given by

$$J(x_1, x_2, ..., x_n) = \frac{(\sum_{n}^{i=1} x_i)^2}{n \sum_{n}^{i=1} x_i^2}, \tag{1}$$

where n is the number of end-devices and x_i is the throughput for the i'th connection. A completely fair network results in $JFI = 1$, while unfair networks result in $JFI < 1$. A situation with a total of N nodes where k users equally share the resource and the remaining $N - k$ are totally deprived of it, would result in $JFI = \frac{k}{N}$. Afterwards, an assessment of the energy consumption of both access schemes takes place.

V. RESULTS AND DISCUSSION

Let us now evaluate the scalability of LoRaWAN and RTS-LoRa, analysing the impact of different data packet sizes, network densities and physical layer models. This section also analyses the fairness and the energy cost of both LoRaWAN and RTS-LoRa.

A. *Network capacity*

The network capacity analysis is presented in Figure 4. As expected, it is immediately noticeable that, for all packet sizes and for both protocols, the probabilistic physical model results in a higher throughput, as it sometimes enables the reception of packets that overlap in time, unlike the destructive model. This discrepancy between the models is larger for LoRaWAN than for RTS-LoRa, because a pure-ALOHA scheme suffers more from collisions than a reservation based protocol.

It is true that both protocols achieve a higher data rate when the data packet is bigger, but RTS-LoRa gains more from using

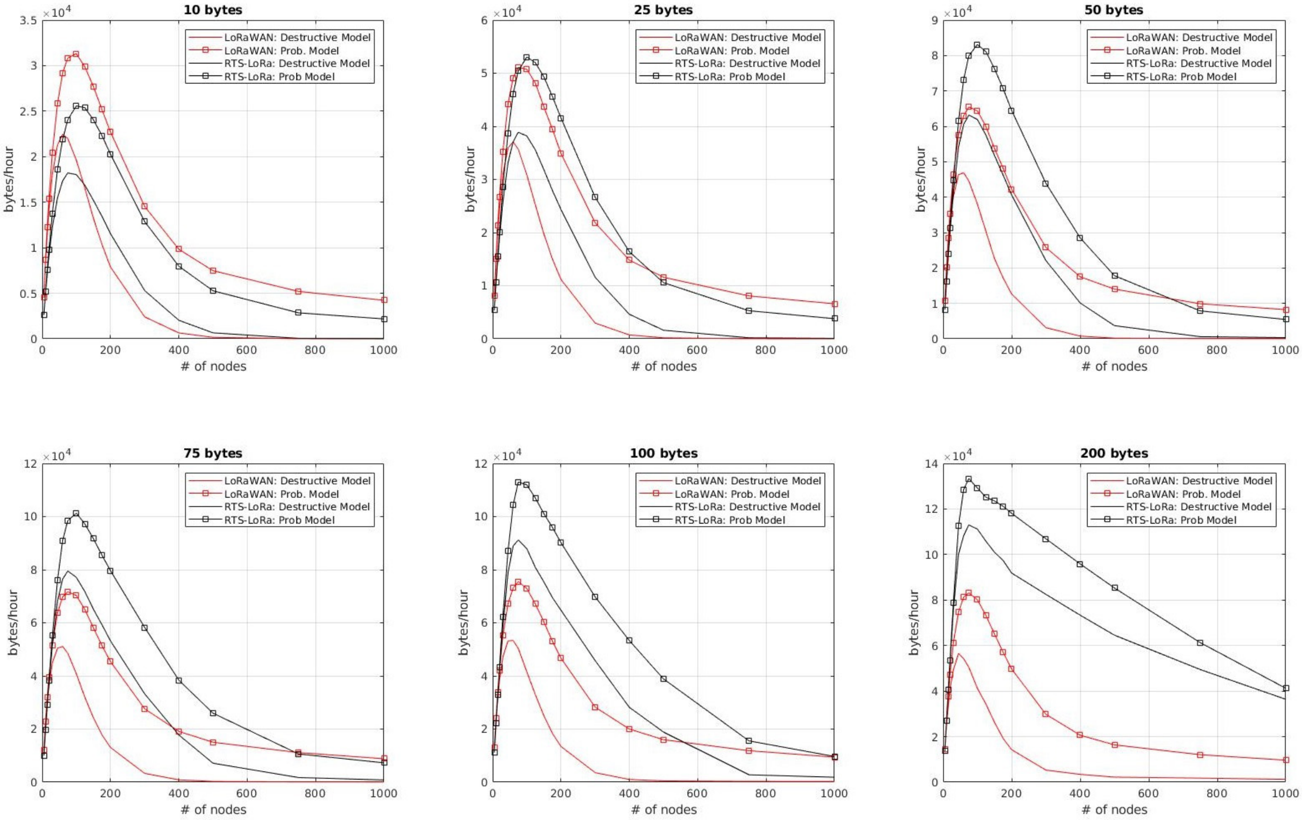

Fig. 4: LoRaWAN vs. RTS-LoRa: impact of data packet length on network capacity.

larger packets, since there is a higher ratio between the data size and the control message size. In general, we can verify that RTS-LoRa outperforms LoRaWAN, since the occurrence of collisions is alleviated by the inclusion of a control packet. The peak in terms of throughput is obtained for a higher amount of devices, around 100, proving that RTS-LoRa makes use of the duty cycle available to the technology in a more efficient way. However there is an important consideration to be taken from these results: even if RTS-LoRa peaks higher than LoRaWAN (with the exception of the 10-Byte packet situation), as the number of nodes increases and RTS collisions become more frequent, it is verified a steeper decline in terms of throughput. The data packets must be at least 100-Bytes long for RTS-LoRa to surpass LoRaWAN in networks with more than 1000 end-nodes.

B. Access fairness

Regarding the channel access fairness, under the destructive model, which has been shown to be unrealistic, all end-nodes would have the same channel access probability, resulting in $JFI = 1$. This being said, only the probabilistic model was considered for both MAC schemes. Three different packet sizes were considered: 50, 100 and 200 Bytes. After a long simulation period (10^{10} slots of $1ms$), the obtained results are shown in Figure 5.

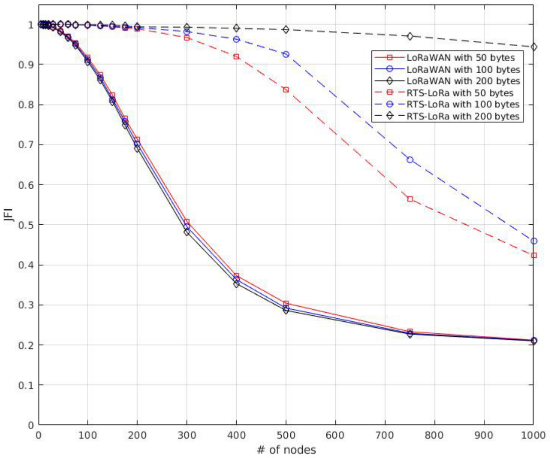

Fig. 5: LoRaWAN vs RTS-LoRa: fairness evaluation.

Due to the non-destructive property found in LoRa modulation, transmissions with higher RSSIs have a higher probability to be received, meaning that schemes with a high collision count will lead to unfair networks. This is illustrated by the

LoRaWAN curve, regardless of packet size. Moreover, with the increase in the total number of nodes, the JFI value starts do decrease, tending to 0.2, which corresponds to the amount of devices in the most privileged area (20% of devices in zone 1), located closer to the gateway. This corroborates the idea that, in very populated networks, nodes capable of maintaining a good connection to the gateway have a great advantage.

For the RTS-LoRa scheme the fairness indicator also decreases when the network size increases, however at a very slow pace. For example, we can see that JFI equals 0.999 for 75 in RTS-LoRa end-nodes, while the same value is obtained with 10 LoRaWAN end-nodes. Such behavior occurs because the proposed scheme effectively avoids a great amount of data collisions. Unlike in LoRaWAN, there is a large discrepancy in the fairness values depending on the packet size. This is justified due to the difference in the ratio between control packets and data packets. The long restriction periods inherent to large data packet transmissions allows for the nodes with less favorable conditions to have more access opportunities, increasing fairness. This shows that the fairness issue is in fact alleviated by the inclusion of a control packet in the medium access of an ALOHA scheme.

C. Energy cost

In both access schemes, three distinct phases have to be considered in terms of energy consumption: sleep periods, listening periods and transmitting periods. Based on the documentation [17], the current consumption considered is 0.1μA during sleep periods and 10.5mA when the device is in the listening state. The consumption during a transmission can vary between 18mA and 125mA depending on the transmission power selected, therefore an intermediate value is considered: 71.5mA.

Table II displays the average time spent by the end-devices, per hour, in each of the three phases referred, under saturation conditions. Three distinct packet sizes are considered: 50, 100 and 200 Bytes, implying a different transmission time-on-air.

TABLE II: Average time spent in each phase per hour.

		Transmission time	Listening time	Sleeping time
50 Bytes	LoRaWAN Class A	$32.6s$	$27.6s$	$58m58s$
	RTS-LoRa	$33.6s$	$242.3s$	$55m24s$
100 Bytes	LoRaWAN Class A	$33.9s$	$16.7s$	$59m09s$
	RTS-LoRa	$34.6s$	$163.6s$	$56m42s$
200 Bytes	LoRaWAN Class A	$34.8s$	$9.3s$	$59m16s$
	RTS-LoRa	$35.0s$	$99.2s$	$57m46s$

The listening period for RTS-LoRa is much higher than the one in LoRaWAN class A, since it was chosen a maximum additional backoff period (in which the end-nodes listens for possible RTS packets) of 14.33 seconds after each transmission. LoRaWAN Class A end-nodes open two short downlink windows after a packet transmission, whose length values must be at least the time required to effectively detect a downlink preamble [18], so it is chosen an interval of 300 ms for each window, sufficient for the reception of 10 Bytes with the used configuration.

Using the indicated current values and the times displayed in Table II, it is possible to estimate the battery consumption in Coulombs, over an hour, depending on the packet size considered, whose values are presented in Table III.

TABLE III: Average battery consumption per hour.

50 Bytes	LoRaWAN Class A	2.62C
	RTS-LoRa	4.95C
100 Bytes	LoRaWAN Class A	2.60C
	RTS-LoRa	4.18C
200 Bytes	LoRaWAN Class A	2.59C
	RTS-LoRa	3.55C

The long listening periods required by RTS-LoRa lead this protocol to have a higher energy consumption regardless of the packet size. However, it is noticeable that, as the payload size is increased, the discrepancy between access schemes is smaller, which is explained by the fact that the additional backoff period is always calculated the same way, causing a RTS-LoRa end-node to spend significantly less time per hour in the listening state when its data transmission time-on-air is longer. The analysis from Subsection V-A allowed to verify that RTS-LoRa generally surpasses LoRaWAN in network capacity, while the estimated energy consumption values show that LoRaWAN Class A has a battery lifetime advantage. For this reason, we decided to establish a relation between these two subjects by studying the delivery rate of a device per hour, per charge unit (1C). Table IV presents these values, for different packet sizes and network scales, namely with 45, 100 and 200 end-nodes.

TABLE IV: Average end-node throughput per hour, per Coulomb.

		45 end-nodes	100 end-nodes	200 end-nodes
50 Bytes	LoRaWAN Class A	487.9	245.6	10.7
	RTS-LoRa	276.0	167.9	7.2
100 Bytes	LoRaWAN Class A	573.2	280.1	12.3
	RTS-LoRa	462.6	268.0	18.6
200 Bytes	LoRaWAN Class A	592.2	284.5	14.8
	RTS-LoRa	705.6	364.2	48.1

In the 9 presented scenarios, the network capacity is always higher with RTS-LoRa. However, the results show that, with this parameterization, the increase in the throughput is not always justified from an energy consumption standpoint. The positive scenarios correspond to the ones in which LoRa-RTS has more advantage over LoRaWAN: bigger data packets and densely populated networks.

VI. CONCLUSIONS

In this work we evaluated the impact of a simple medium access strategy, such as the inclusion of a control packet in the channel access coordination, can have on the performance of LoRa networks. We addressed the effect of distinct parameters such as packet size, physical model and network size. Performance results, focused on the network capacity and channel access fairness, have shown that, even considering the duty cycle limitation associated with this technology, a simple control packet is able to greatly improve the network performance.

An analysis on the energy consumption of both protocols showed that this performance improvement comes at the cost of a shorter battery lifetime, since the modifications to the simple pure-ALOHA scheme imply longer periods of device activity. However, with scalability being a priority when it comes to LoRa networks, results show that this increase in energy consumption is easily justifiable in large scale networks, in scenarios where the performance of a pure-ALOHA scheme is unacceptable.

For future work we aim to explore the possibility of making use of the LoRa physical parameters in order to better deal with the duty-cycle regulations, by decreasing the time-on-air per transmission when possible. This would also be beneficial in terms of energy consumption, since shorter transmissions consume less energy.

ACKNOWLEDGMENTS

This work is supported by the European Regional Development Fund (FEDER), through the Regional Operational Programme of Lisbon (POR LISBOA 2020) and the Competitiveness and Internationalization Operational Programme (COMPETE 2020) of the Portugal 2020 framework [Project 5G with Nr. 024539 (POCI-01-0247-FEDER-024539)] and National Financial Support National (FCT/OE), through project MobiWise (POCI-01-0145-FEDER-016426).

REFERENCES

[1] Ericsson, “White paper: Cellular networks for massive IoT - enabling low power wide area applications,” 01 2016, accessed: 2019-02-05.

[2] U. Raza, P. Kulkarni, and M. Sooriyabandara, “Low power wide area networks: An overview,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 855–873, 2017.

[3] D. Ismail, M. Rahman, and A. Saifullah, “Low-power Wide-area Networks: Opportunities, Challenges, and Directions,” in *Proceedings of the Workshop Program of the 19th International Conference on Distributed Computing and Networking*. ACM, 2018.

[4] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, “Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios,” *IEEE Wireless Communications*, vol. 23, no. 5, pp. 60–67, 2016.

[5] G. Hassan, M. Elmaradny, M. Ibrahim, A. Rashwan, and H. Hassanein, “Energy efficiency analysis of centralized-synchronous lora-based mac protocols,” *International Wireless Communications & Mobile Computing Conference (IWCMC)*, vol. 14, pp. 999–1004, 2018.

[6] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, “Understanding the limits of lorawan,” *IEEE Communications Magazine*, vol. 55, no. 9, pp. 34–40, 2017.

[7] R. Oliveira, L. Guardalben, M. Luís, and S. Sargento, “Multi-Technology Data Collection: Short and Long Range Communications,” in *Vehicular Technology Conference (VTC-Fall), IEEE 86th*. IEEE, 2017, pp. 1–6.

[8] M. Bor, J. Vidler, and U. Roedig, “LoRa for the Internet of Things,” in *Proceedings of the 2016 International Conference on Embedded Wireless Systems and Networks*, ser. EWSN ’16. USA: Junction Publishing, 2016, pp. 361–366.

[9] G. Hassan and H. S. Hassanein, “MoT: A Deterministic Latency MAC Protocol for Mission-Critical IoT Applications.” *International Wireless Communications & Mobile Computing Conference (IWCMC)*, vol. 14, no. 2, pp. 588–593, 2018.

[10] T. Deng, J. Zhu, and Z. Nie, “”An Improved LoRaWAN protocol based on adaptive duty cycle”,” *IEEE Information Technology and Mechatronics Engineering Conference*, no. 3, Jan. 2017.

[11] L. Vangelista, A. Zanella, and M. Zorzi, “Long-range IoT technologies: The dawn of LoRa,” in *Future Access Enablers of Ubiquitous and Intelligent Infrastructures*. Springer, 2015, pp. 51–58.

[12] L. Alliance, “White paper: LoRaWAN: What is it? A technical overview of LoRa and LoRaWAN,” 2018, accessed: 2018-01-29.

[13] C. Pham, “QoS for Long-range wireless sensors under duty-cycle regulations with shared activity time usage,” *ACM Transactions on Sensor Networks*, vol. 12, no. 4, pp. 1–31, 2016.

[14] R. Fernandes, R. Oliveira, M. Lus, and S. Sargento, “On the Real Capacity of LoRa Networks: The Impact of Non-Destructive Communications,” *IEEE Communications Letters*, vol. 23, no. 12, pp. 2437–2441, 2019.

[15] R. Oliveira, L. Guardalben, M. Luis, and S. Sargento, “Long range communications in urban and rural environments,” *IEEE Symposium on Computers and Communications*, pp. 810–817, 2017.

[16] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, “A quantitative measure of fairness and discrimination,” *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, 1984.

[17] SemTech, https://www.mouser.com/datasheet/2/761/sx1272-1277619.pdf, accessed: 2020-01-09.

[18] L. Alliance, “Lorawan specification v1.1,” https://lora-alliance.org/resource-hub/lorawanr-specification-v11, accessed: 2020-01-10.