GreenLoRaWAN: An energy efficient and resilient LoRaWAN communication protocol

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***Abstract*— Long range wide area network (LoRaWAN) represents a promising low power wide area network (LPWAN) technology in the context of internet-of-things (IoT) that has recently attracted intense research interest. Due to the limited energy resources available on LoRaWAN constituent elements and intermittent power supply of gateways in harsh environments, an energy-efficient communication protocol is constituted of utmost importance in order to prolong network lifetime. Motivated by the aforementioned, this work presents a green, robust, and resilient communication protocol, namely GreenLoRaWAN, which increases energy efficiency, scalability and robustness of the LoRaWAN. The proposed protocol is evaluated by means of Monte Carlo simulations; Performance evaluation results acquired are very promising, revealing an important reduction in energy consumption and increase the duration of network lifetime.**

Keywords—communication protocol, energy efficiency, Internet of Things, long range wide area network, low power wide-area networks

I. Introduction

Novel information and communications technologies (ICTs), such as the Internet of Things (IoT) combined with wireless sensor networks (WSN), low power wide area networks (LPWANs), cloud and edge computing, data analytics, and artificial intelligence [1], [2], enable data collection, processing and analysis in real time, extracting knowledge and supporting informed decision making, providing solutions to complex problems. LPWAN technologies are increasingly gaining popularity due to the long transmission range, low energy consumption and low-cost deployment and maintenance achieved. Today, there are different LPWAN technologies including SigFox, narrow band (NB)-IoT and LoRaWAN. LoRaWAN is an open standard technology that constitutes one of the leading LPWAN technologies, due to its inherent connectivity support for a large number of IoT end-devices, the broad coverage achieved in non-urban environments, the easy, scalable and low-cost design and development of the network, its operation in the unlicensed radio frequency bands for industrial, scientific and medical purposes (ISM) zone and its low energy consumption.

In the light of the aforementioned, LoRaWAN is attracting intense research interest, addressing issues, like maximization of network throughput [3], capacity [4], [5], coverage range [6] as well as minimization of network delay [7] and energy consumption [8]. Due to the computational, communication and energy resources' limitations imposed on end-devices, data rate and energy efficiency should be carefully balanced in order to simultaneously maximize throughput and prolong the network lifetime. In general, the communication protocol selection constitutes a determinant factor of the network lifetime and the overall performance of LoRaWANs. LoRaWAN performance analysis, robustness and scalability issues raised in large scale networks have been also a focus of research [9]–[12].

Inspired by this a great amount of research effort was put on modeling and analyzing the energy consumption in LoRaWANs as well as presenting mechanisms that increase its energy efficiency [8], [13]–[18]. In more detail, in [13], the authors present detailed models for energy consumption and lifetime estimation of a LoRaWAN end-device, as well as energy cost of the delivered data, taking into account the energy efficiency in LoRaWAN, i.e., the energy consumed per unit of information transmitted. Acknowledged and unacknowledged transmission has been considered for Class A devices, taking into account both bit error rate (BER) and collisions impact on energy performance.

In [14], the authors present an extensive review of IoT technologies, including low power short area networks and LPWANs, in terms of energy efficiency and power consumption. Specifically, a categorization of metrics used is

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presented, as well as energy and consumption models. Energy efficiency techniques are categorized into a) algorithms for switching between sleep and wake-up states [15], b) data reduction techniques - to reduce the amount of transmitted data [8], c) network techniques (mainly referring to clustering and routing techniques that enhance robustness and network scalability and minimize system overhead and congestion [16], [17], and d) resource allocation techniques, reducing the required resource blocks and transmitted power [19]–[21].

An energy-saving practice discussed in [15] considers the dynamic state switching on wearable end-devices, depending on the needs and current situation of end-users as defined by analyzing data collected through heart rate sensors, magnetometer, microphone, and accelerometer/gyroscope, while proposed energy states are: a) Off, b) Hibernate, c) Normal and d) Emergency. In [8], an efficient technique is proposed, called Ambrosia, for reducing the data transmission from the sensors to the network server based on a simple window-based prediction scheme to decide which data samples need to be transmitted from the sensor node to the server. In [16], authors introduce a new LoRaWAN architecture and a new MAC protocol based on clustering. Cluster head is responsible for synchronizing end-devices to avoid collisions. In [17], an energy consumption comparison is made between networks with star and mesh topologies, with the mesh topology yielding better results in cases where the communication range exceeds 3 Km.

In long-range (LoRa), the adaptive data rate (ADR) algorithm is used in order to jointly determine the data rate so as to minimize the energy consumption of end-devices [18]. This algorithm determines the best combination of the physical layer transmission parameters (i.e., spreading factor (SF), bandwidth (BW) and transmission power (TP) of end-devices), considering the quality of the wireless link. Many research works of related research literature consider variants of ADR in order to minimize energy consumption of end-devices. For example, the AdapLoRa algorithm [19] performs dynamic resource adaptation related to transmission parameters, namely SF, TP, channel frequency, coding rate (CR), considering network lifetime. The Dylora algorithm [20] aims at energy efficiency maximization, considering packet delivery ratio (PDR) and energy consumed for transmission. In a multi-gateway scenario in order to improve the energy efficiency of the LoRa network [21], the authors present a new ADR algorithm which can rapidly determine the best LoRa transmission parameters (i.e., SF, TP, CR, and BW), using a few numbers of uplink transmissions.

In LoRaWAN star topology supports communication of the end-devices with the network gateway via a single hop, while the star-of-stars architecture [22] increases the reliability of the system, as it provides for the reception of packets from all network gateways within range of the final device. This, combined with the implementation of the p-ALOHA protocol on the wireless channel without prior coordination and transmission scheduling, creates a simple, easy-to-design and low-cost network deployment. However, it introduces system performance constraints, making robustness and scalability of the LoRaWAN a popular research issue, especially on large-scale LoRaWAN IoT systems. When the number of end-devices and potentially their transmission requirements increase significantly (i.e., more frequent transmissions with higher payloads resulting in higher medium occupation time), the network will be quickly saturated with a significant degradation of its performance.

Inspired by the gains that a suitable end-device to gateway association algorithm could bring, prior related research proposed an end-device association in the context of downlink traffic [12], [23], [24]. In [12], the authors propose gateway selection for the downlink transmission by selecting the smallest available SFs for end-devices, which are calculated according to the estimated signal-to-noise-ratio (SNR) performance metric, indicative of the quality of the wireless channel. Similarly, in [23], the best gateway for transmitting a downlink packet to an end-device is based on SNR, taking into account the information carried from multiple packets received to the network server by end-devices. The network server keeps only the packet with the highest SNR. Furthermore, in [24], the authors consider an urban LoRaWAN as a heterogeneous network (HetNet) and apply a load balancing scheme based on machine learning techniques that uses both unsupervised and supervised methods as well as Markov Decision Process (MDP) in order to select the base station (BS) that should transmit the downlink message to an end-device, in case an uplink message is received to the network server through more than one BS. An unsupervised technique (Principal Component Analysis – PCA) is employed in order to discover the hidden pattern behind selected features, a supervised probabilistic classifier in order to take advantage of historical labelled data and a MDP in order to make decisions on a BS – device association biasing scheme by contemplating metrics that are not directly related to signal strength. The proposed model learns to predict a device – BS association without considering signal-based measurements, but parameters such as frequency, data rate, latitude, longitude, time of the day, day of the week, as those describe the particular situation of a device at the moment that is successfully transmitting a packet to the BS.

The design and implementation of a green and resilient communication protocol is of paramount importance, considering the intermittent power supply of LoRaWAN gateways in harsh environments (such as fields in the context of precision agriculture). To fill this gap, we present a green, robust, and resilient communication protocol, increasing energy efficiency, scalability and robustness of the system, while also preventing system collapse due to depletion of the energy resources of network devices. The communication protocol can be used in any system without a continuous power supply from an electricity network. In contrast to the star-of-stars architecture of LoRaWAN technology [22] and prior related research [12], [24], [25], that propose an association of end-devices to gateways only for the downlink direction, GreenLoRaWAN communication protocol considers the association of end-devices to a single gateway at both uplink and downlink directions, taking into account the available energy resources of each gateway at the specific time. Additionally, efficient resource allocation is achieved, by defining proper values for LoRa transmission parameters, i.e., SF and TP, in order to minimize the energy consumption and maximize access network lifetime. The related problem is mathematically formulated, computationally efficiently solved by means of a heuristic algorithm, providing near-optimal solutions within acceptable time.

The rest of the paper is structured as follows. Section II summarizes key aspects of LoRaWAN technology. In Section III we present in detail the proposed GreenLoRaWAN communication protocol. Next, in Section IV we present initial experimental results acquired that display the efficiency of the proposed communication protocol. It should be noted that, the results are indicative of the performance that will exist in the full development of the protocol. Finally, in Section V concluding remarks are made and future work is highlighted.

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II. Background

A. LoRaWAN technology overview

LoRaWAN architecture consists of three levels, as illustrated in Fig. 1. Specifically, the lower level includes the IoT end-devices, which can be sensors or actuators. The intermediate level consists of concentrators or gateways, which allow and manage two-way communication between end-devices and the IoT platform, according to the rules imposed by the communication protocol. Finally, at the higher level, the network and application servers are located [26].

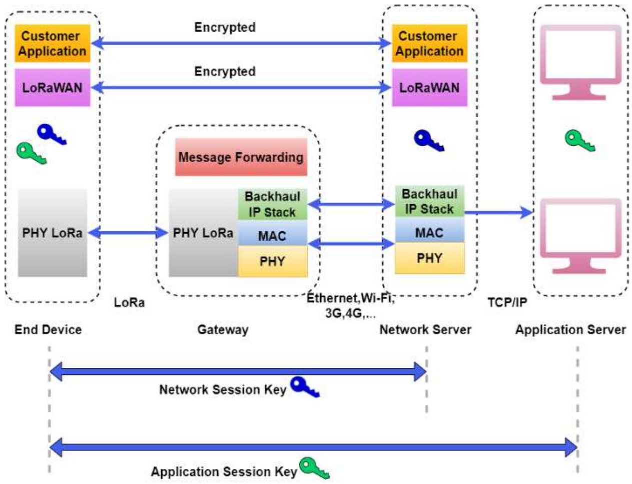

Figure 1: LoRaWAN protocol architecture

The communication between gateway and network server is enabled through the internet protocol (IP) stack. LoRaWAN provides end-to-end encryption and data integrity. The top-level payload is encrypted via an application session key to provide confidentiality and a network session key is used to provide data integrity [27].

LoRaWAN physical layer is based on chirp spectrum spreading modulation and is used to enable IoT devices to exchange messages with the gateway. SF determines the achievable data rate. Also, SF is inextricably related to energy consumption of the LoRa devices. LoRa employs 6 orthogonal SF from 7 to 12, with SF 7 being associated with higher sensitivity; thus, higher signal-to-noise-ratio (SNR) and shortest transmission range yield higher data rate through a lower SF value and vice versa. Note that assuming a higher value of SF increases dramatically the time on air (ToA); hence, the energy consumption per transmission [28]. Table I presents SF values against LoRa parameters at 125 kHz.

End-device access to LoRaWAN is based on pure-ALOHA, which is a multiple access protocol for data transmission through a common medium access control (MAC) layer, without any prior link coordination for scheduling transmissions or prior medium access control for other ongoing transmissions from IoT end-devices. Specifically, in LoRaWAN, packets are sent each time a device has data to transmit. This results to an increased number of packet collisions and subsequently packet loss, especially in large-scale networks. Several time division multiple access schemes [29]–[31] and carrier sense multiple access schemes have been proposed [32], [33] to avoid collisions. However, they lead to increased energy consumption [9], [32].

TABLE 1: LoRa values at 125 kHz [34]–[37]

SF	DR	Physical Bit rate (bps)	Sensitivity (dBm)	SNR (dB)	ToA for 11 bytes payload (ms)
7	5	5470	-123.0	-7.5	61
8	4	3125	-126.0	-10.0	113
9	3	1760	-129.0	-12.5	205
10	2	980	-132.0	-15.0	371
11	1	440	-134.5	-17.5	823
12	0	250	-137.0	-20.0	1482

In LoRaWAN, two frames collide when two or more packets overlap in time and use the same LoRa parameters, i.e., the same SF, BW and carrier frequency (CF). Adoption of the same configuration settings for a high number of end-devices increases the possibility of collisions and consequently decreases the packet delivery ratio. However, a packet received with a higher power level (at least 6 dB), can still be decoded during a collision [38]. Thus, both the selection of LoRa SF and TP will affect the total amount of packets collisions by effectively determining the coverage area that will set the final number of end-devices within the range of the deployed gateways.

LoRaWAN includes confirmed message transmission in order to improve transmission reliability by using acknowledgement messages (ACK) to guarantee data reception. Confirmed message transmission impose limitations to network capacity, constituting downlink communication efficiency and scalability an important need for LoRaWAN [38]. In [38], the authors perform an extensive evaluation of LoRaWAN performance in small and large-scale networks. The authors analyze several aspects, including coverage, traffic characteristics, packet loss, signal quality and LoRa parameter distributions. Deploying more gateways or using directional antennas at the device side can reduce the number of collisions. As collisions contribute significantly to packet loss, several mechanisms have been proposed in the literature for collision avoidance, including synchronization of end-nodes and scheduling techniques [39], as well as through monitoring of the medium access, following the listen-before-talk (LBT) concept [40].

B. LoRaWAN Energy Efficiency

Energy consumption is a determining factor in maximizing end-devices' and network's lifetime. To this respect, several mechanisms have been presented in the literature that aim at saving energy resources, through balancing between power consumption minimization, thus, prolonging network lifetime, while maximizing the achieved transmission rate/network throughput.

The LoRaWAN specification defines three classes of end-devices. In Class A, the end-devices are in sleep mode, except when transmitting data. The uplink transmissions are scheduled using ALOHA, followed by two receiving windows in order to allow end-devices to receive potential ACKs and/or commands from the network server. After the receive windows, the end-devices are set back to sleep mode to conserve energy. Class A is the end-device category yielding the lowest power consumption [41]. In Class B, the end-devices operate in a similar to Class A manner, but an extra receive window is introduced at pre-scheduled intervals, increasing, thus, the device's power consumption [42]. Finally, in Class C, the end-devices are continuously set to active mode; thus, they can accept messages from the server

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at any time, except their transmission periods. In Class C, end-devices increase further the induced power consumption compared to Class A and B [43].

III. GreenLoRaWAN Communication Protocol

A. Problem Formulation

GreenLoRaWAN protocol is designed for cases with intermittent power supply, aiming to support energy efficiency, robustness and scalability. Specifically, GreenLoRaWAN aims at maximizing access network lifetime, through minimization of energy consumption at the IoT end-devices and gateways, while also enhancing network robustness and scalability and avoiding network collapse events due to exhaustion of gateways' energy resources. GreenLoRaWAN introduces an IoT end-device to gateway association for both downlink and uplink directions, taking into consideration the available energy resources of LoRaWAN gateways.

GreenLoRaWAN communication protocol includes a robust resource allocation mechanism, yielding the optimal LoRa transmission parameters (SF, TP), while acquiring the association of IoT end-devices to LoRaWAN gateways minimizing energy consumption subject to the available gateways' energy resources. At the same time, the minimum required data rate of the end-devices is taken into account. This approach is expected to minimize **a)** the energy consumption of the access network (gateway and the end-devices), **b)** the data transmitted from gateways to the network server (and the respective cost involved in the transmission), and **c)** the computational cost of removing duplicate packets received from gateways at the LoRaWAN Network Server. This approach, besides increasing the resilience, also minimizes the operational costs of the IoT systems, considering the cost involved in the transmission of the collected data to the IoT platform (LoRaWAN network and application server and respective applications atop) through a mobile communication system (e.g., 4G).

The optimal assignment of IoT end-devices to gateways could be formulated according to the following optimization problem (1) that considers the minimization of the energy resources consumed at the gateways, under three constraints. The first constraint is related to the available energy resources at each gateway that should be satisfied by the provided assignment. The second constraint concerns the minimum data rate of the IoT end-devices that should be satisfied, while the third constraint is related to the protocol specification that each IoT end-device should be associated to only one gateway for both the uplink and downlink directions.

$$\min_{SF,TP,A} \sum_{i=1}^{N} E_{G_i}$$

$$C_1: \sum_{j=1}^{M} A_{ij} E_{G_{ij}} < E_{th_i} \quad \forall i \in [1, N] \qquad (1)$$

$$C_2: DR_j > DR_{th_{j_i}} \forall j \in [1, M]$$

$$C_3: \sum_{j=1}^{M} A_{ij} = 1 \quad \forall i \in [1, N]$$

where A is the association matrix, referring to the assignment of the j-th IoT end-device to the i-th gateway, while M and N refer to the number of IoT end-devices and gateways, respectively. Additionally, $E_{G_{ij}}$ and E_{th_i} are the energy consumed by the gateway due to its association with the j-th end-device and the available energy levels at the i-th gateway. Finally, DR_j and DR_{th_j} are the data rate of the j-th end-device and its minimum requested data rate, respectively.

B. Computationally Efficient Algorithm

In order to provide a near optimal solution in computationally efficient manner we propose a low complexity heuristic algorithm, GreenLoRaWAN, yielding an assignment of end-devices to gateways and the LoRa resource allocation of SF and TP to each IoT end-device.
Initially, the algorithm estimates the minimum acceptable TP and SF for each potential association of IoT end-devices to gateways. Specifically, based on the end-devices data rate requirement, the maximum allowable SF for the specific communication is found. Considering the sensitivity / SNR values given in Table I for each SF (starting with the lowest and up to the maximum allowable SF), the TP is computed based on the log distance path loss model, estimating the losses incurred during the transmission:

$$PL = PL_0 + 10\, n \log \frac{d}{d_0} + X_s \; (dB) \qquad (2)$$

where PL is the path loss, PL_0 is the path loss at the reference distance d_0, d is the length of the path, d_0 is the reference distance, n is the path loss exponent and X_s is a normal random variable reflecting the attenuation caused by flat fading.

We consider the receiver of the gateway as a sequence of a low noise amplifier (LNA), a receiver (RX) mixer, a RX cable and a digital software defined radio (SDR), as depicted in Fig. 2.

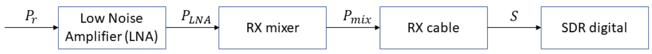

Figure 2: Structure of the receiver's gateway

The signal power S in the input of the SDR digital is:

$$S = P_r + G_{LNA} - L_{mix} - L_{misc} \; (dB) \qquad (3)$$

where P_r is the received signal power, G_{LNA} is the gain of the LNA, L_{mix} is the mixer losses and L_{misc} is the miscellaneous losses including the cable losses.

Also, the signal to noise ratio in the input of SDR is:

$$SNR = S - 10\log(kTB) - 10\log\left(\frac{10^{\frac{NF_{mix}}{10}} + 10^{\frac{NF_{LNA}}{10}} - 1}{10^{\frac{G_{LNA}}{10}}}\right) \qquad (4)$$

where k is the Boltzmann constant, T is the temperature, B is the bandwidth, NF_{mix} is the noise figure of the RX mixer and NF_{LNA} is the noise figure of the LNA.

It should be noted that some end-devices could have been deployed far away from any existing gateway, making it thus impossible to achieve the data rate requirements imposed; in the current version of the algorithm these end-devices will not be considered in the association. These constraints could be relaxed in a future version of this work.

As a next step, a distribution target value (DT) is estimated based on the available energy resources of all gateways, yielding the number of end-devices to be associated to each gateway. Specifically, the DT_k is computed in accordance with equation (5), where B_k is the battery level of the k-th gateway

$$DT_k = M \frac{B_k}{\sum_{i=1}^{N} B_i} \qquad (5)$$

The algorithm, having as a starting point the association of end-devices to their nearest gateways (A_{near}), yielding the

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lowest possible SF-TP values that satisfy also the minimum required data rate, a re-association is performed in order to succeed in providing an association in terms of the DT values estimated (A_{batt}), following the current available battery levels of each gateway. In order to succeed in maintaining low values for the TP, the algorithm considers the re-association of end-devices to the gateways with more residual energy closer to the end-devices, attempting to utilize the same SF. It is important to mention that in order not to increase the cumulative energy consumption, the algorithm will not re-associate an end-device, if it cannot find another gateway with which that device can communicate with the same SF.

In the current version of the algorithm, energy consumption is minimized as only the associated to the end-device gateway forwards the received packets to the network server. In order to evaluate the performance of the GreenLoRaWAN protocol, energy consumed during the transmission of packet from the gateway is estimated considering the usage of a LTE cellular network and adopting the formula proposed in [44], treating gateway as an LTE user device (6)-(7):

$$P_{tx} = P_{on} + P_{txBB}(R_{tx}) + P_{txRF}(S_{tx}) + \beta_{tx} \quad (6)$$

where P_{on} is the power consumption when the cellular subsystem is active, β_{tx} is the additional power consumption of the transmitter being active. Parameter P_{txRF} represents radio frequency (RF) block power consumption that is dependent on the transmission power S_{tx} and parameter P_{txBB} is the baseband power consumption.

$$P_{rxRF} = \begin{cases} 0.78 \times S_{tx} + 23.6, \quad S_{tx} \leq 0.2\ dBm \\ 17.0 \times S_{tx} + 45.4, 0.2\ dBm < S_{tx} \leq -11.4\ dBm \\ 5.90 \times S_{tx}^2 - 118 \times S_{tx} + 1195, 11.4\ dBm < S_{tx} \end{cases} \quad (7)$$

Sector antennas in the sensor nodes will be considered in a subsequent version of this study so as to minimize the number of collisions and the energy consumed at the gateways during the reception stage (i.e., each sensor will transmit towards the associated gateway, minimizing the number of packets received and the associated number of collisions at all gateways).

TABLE II: ALGORITHM NOTATIONS

Notation	Description
DR	data rate requirement of end-device
B	battery level of gateway
TP	transmission power of end-device
SF	spreading factor of end-device
A_{near}	association matrix according to the distance
A_{batt}	association matrix according to the battery level
DT	distribution target of gateways
E_{all}	energy consumption for forwarding all packets received
E_{near}	energy consumption resulting from packet forwarding, generated by associated end-devices according to A_{near} matrix
E_{batt}	energy consumption resulting from packet forwarding, generated by associated end-devices according to A_{batt} matrix

Algorithm 1 GreenLoRaWAN communication protocol

Input: *gateways, end-devices, DR, B*
for *every gateway*
  for *every end-device*
    compute TP and SF and check DR requirement using (2) - (4)
  end
end
for *every end-device*
  associate end-device to the nearest gateway and store to A_{near}
end
for *every gateway*
  compute E_{all} *forwarding all packets using (6) and (6)*
  compute E_{near} *forwarding only packets from its associated end-devices according to* A_{near} *using equations (6) and (7)*
end
for *every gateway*
  compute the distribution target DT according to B using (5)
end
while *end-devices are not distributed according to DT of gateways* **do**
  for *every gateway in descending order from gateway with the most associated end-devices to that with the least associated end-devices*
    associate end-devices to gateways with more residual energy B keeping the same SF for every end-device and store to A_{batt}
  end
end
for *every gateway*
  compute E_{batt} *while forwarding only packets from the associated end-devices according to* A_{batt} *using (6) and (7)*
end
Output: *TP, SF,* A_{near}, A_{batt}, E_{all}, E_{near}, E_{batt}

IV. Experimental Results

The algorithm was evaluated using Monte Carlo simulations. Table III depicts the parameter values considered in our simulation experiments. Specifically, the dimensions of the simulated network topology are 20 kilometers by 20 kilometers. Dense network topologies are considered with 5000 end-devices and 5 gateways, each equipped with a 90 Wh battery. These batteries operate at 12 Volts (V) and have a capacity of 7500 milliampere hours (mAh). Both gateways and end-devices are placed randomly in the topology so that performed simulations could reflect realistic scenarios. The gateways receive packets from end-devices over LoRa, which are subsequently forwarded to the network server over LTE. The simulated time is 1 day and the rate at which every end-device is sending packets is 1 packet per 15 minutes. The payload of each packet is ranging between 10 and 220 bytes. This payload is selected according to the SF, which limits the size of the maximum payload so as not to exceed the duty cycle limitation [45]. At this point, it is important to clarify that GreenLoRaWAN is designed to recalculates the results as the state of a network changes over time.

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TABLE III: SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
B	0% - 100%	DR	100-2500 bps
Transmission rate	1 packet / 15 minutes	Packet payload	10-220 bytes
Topology dimensions	20 km x 20 km	Battery capacity	90 Wh

Two different scenarios are explored in order to compare the performance of the GreenLoRaWAN algorithm. The first scenario considers that all gateways have fully charged batteries, (e.g., considering a newly deployed LoRa network). The second scenario considers that each gateway has different residual energy, assuming 62%, 47%, 60%, 39% and 72% battery levels, respectively (as illustrated in Fig. 3 and 4). In Fig. 3, the number of end-devices associated with each gateway are depicted for each association, namely, distance (starting point), equal (first scenario) and battery (second scenario) associations. It may be observed that the equal association is relatively uniform, while the battery association yields a distribution of end-devices to gateways relatively proportional to their battery level. Specifically, the associated end-devices of equal association are 1000 end-devices on each gateway and the associated end-devices of battery association are 1108, 840, 1072, 697 and 1283, respectively.

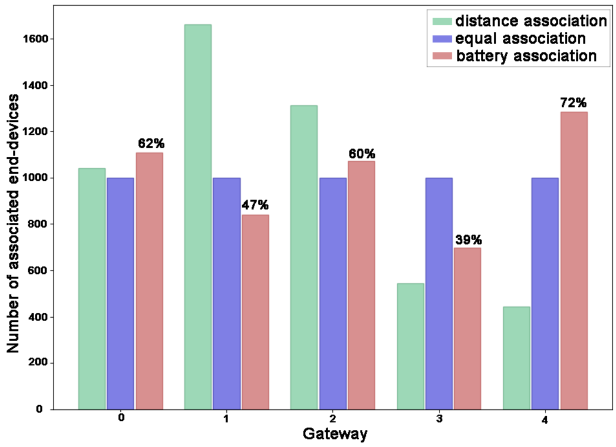

Figure 3. Number of end-devices associated to every gateway

In Fig. 4, the amount of energy consumed by each gateway forwarding packets to the network server over LTE is presented for each of the aforementioned scenarios where each gateway forwards packets received from their associated end-devices and the basic LoRaWAN technology forwarding all packets received by each gateway. As already mentioned, the energy consumption on gateways during the reception over LoRa is considered the same for each gateway and doesn't contribute to the presented results. It may be observed that the results on this figure are highly dependent on the results of Figure 3 as expected, because the number of associated devices is affecting the number of packets that are forwarded. The energy consumption of the gateways on the distance association (staring point) is reduced by 28% to 62% compared to the standard LoRa forwarding scheme. The energy consumption on the equal association (first scenario) is reduced by 37% to 60% compared to the standard LoRa forwarding scheme. And finally, on the battery association (second scenario), the energy consumption is reduced by 24% to 64% compared to the standard LoRa forwarding scheme.

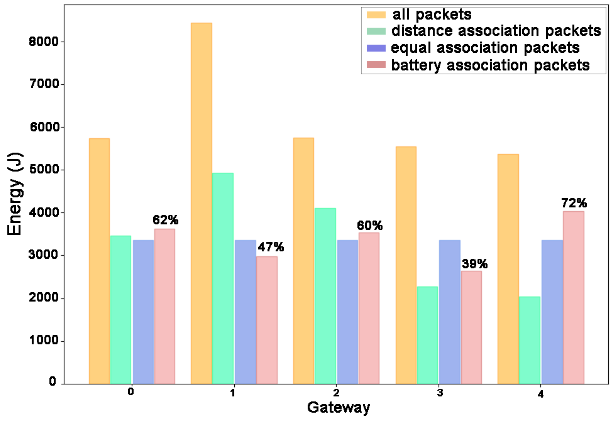

Figure 4. Energy consumption comparison between different associations

V. CONCLUSION & FUTURE WORK

In this work, an energy efficient and resilient LoRaWAN communication protocol, named GreenLoRaWAN, has been designed with the objective of prolonging network's lifetime, minimizing data transmitted from gateways and energy consumption in cases of intermittent power supply. GreenLoRaWAN, in contrast with other research works, uses in an efficient way the resources of end-devices and gateways both in uplink and downlink transmission. In future work we aim to enhance and further evaluate the performance of the proposed protocol. Our future plans involve usage of directional antennas on end-devices in order to minimize collisions, increase robustness and scalability and further improve on the gateways' energy consumption, minimizing the number of packets received. Furthermore, strict constraints on the transmission rate that each sensor must achieve could be relaxed in order to potentially increase the number of sensors that can be served by the system. Finally, considering energy harvesting models and exploiting machine learning techniques in order to estimate network's lifetime, new associations could be established in order to prolong gateways' (and therefore network's) lifetime and maximize robustness and resilience of the system. In such a context, sensors could be decided not to be served by the system or the periodicity of their transmissions could be adapted to prevent network's saturation.

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