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Developing Energy Autonomous and Cable-less Multi-gateway LoRa Networks

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Abstract—**Long Range (LoRa) networks are a reliable and efficient solution to serve Internet of Things (IoT) applications in a long range rural and forest areas. The capability of the gateways, both for wireless connection with the backbone network and be powered by renewable energy resources, makes possible the development of energy autonomous and without the need of cabling LoRa networks. This perspective greatly facilitates the network installation in hard-to-reach areas, as well as reducing their operating costs. An important obstacle, for the operation of energy autonomous LoRa networks, is the need for continuous operation of the gateways defined by the LoRaWAN protocol, leading to increased power consumption. For this reason, it is necessary the creation of a protocol that will reduce the energy consumption of the gateways, while maintaining the quality of the services provided in the IoT applications. In this paper we present a new hybrid protocol for energy autonomous and cable-less multi-gateway LoRa networks. The simulation results showed that the proposed protocol ensures a more than 50% reduced energy consumption for the gateways, as well as increased efficiency and reliability compared to the existing protocol, at the cost of slightly increased delay in data transmission.**

Keywords— energy efficiency, hybrid protocols, LoRa, wireless sensor networks

I. Introduction

Long Range (LoRa) networks offer significant advantages in supporting IoT applications deployed over long-range areas. The most important of these advantages are the use of the ISM unlicensed spectrum band [1], the low-cost hardware used [2], the resistance to propagation effects provided by the proprietary spread spectrum modulation scheme which ensures a propagation range of up to 15 kilometers [3], as well as the low energy consumption of End Devices (EDs) [4].

The operation of LoRa networks is defined by the Long Range Wide Area Network (LoRaWAN) open standard, which provides three different types of network devices. The operation of type A and B devices, which concerns the EDs of the network, ensures low energy consumption allowing them to be battery operated. On the contrary, type C devices that are the network gateways (GWs), require interconnections with both conventional energy supply networks, due to their continuous operation, and telecommunication backbone networks. These interconnection requirements, apart from the financial burden regarding installation and operating costs, are often difficult or even impossible to implement in a hard-to-access forest, mountain, and rural areas. Powering LoRa gateways through renewable energy resources (photovoltaic plant), as well as the use of a wireless connection (4G, 5G, satellite networks) with the network server, provide the possibility of creating energy autonomous LoRa networks which can operate without the need for wired support [5].

One of the most important problems facing LoRa networks is their reliability and scalability [6]. The deployment of multiple parallel operating GWs in a LoRa network has been studied in the literature as one of the most important solutions to the aforementioned problem. This solution achieves both an increase in reliability through the multiple receptions from the GWs of each transmission from the EDs, as well as a reduction in energy consumption for the EDs, due to their reduced distance from the GWs and consequently the possibility of using a more aggressive spreading factor (SF) [7], [8]. However, it has been considered that the parallel operation of multiple GWs, apart from increasing the networks installation and operation costs, creates a higher number of collisions due to the fact that most EDs use the same more aggressive SF due to their proximity to the GWs, thus increasing the interference between them [9].

In this paper we propose a hybrid protocol for energy autonomous LoRa networks (HPEAL), which is based on the round-robin operation of multiple GWs LoRa deployments and was designed to combine increased reliability with low energy consumption of both GWs and EDs. The operation defined by the HPEAL protocol achieves the partitioning of the LoRa network into subnets that use the available resources based on scheduling at specific time periods, which are centrally organized by the network server. The basic idea is to associate each ED to the nearest GW dividing this way the network into subnets. Each subnet, which is consisted of a single GW and its associated EDs, will exclusively own the spectral resources of the network in predetermined time intervals (timeslots), setting both GW and EDs in idle mode during the timeslots assigned to the rest of the subnets. To increase reliability, the protocol separates uplink and downlink transmissions, as well as making use of the Channel activity detection (CAD) mechanism. The operation of the protocol is hybrid since it combines the scheduling of uplink and downlink transmissions with the distributed operation of the EDs, since the medium is shared in the uplink.

The main novelty of our research work is the creation of a protocol for multi-GW LoRa networks, which, unlike corresponding protocols in the literature, defines the round robin and not parallel operation of the network GWs. The main advantages resulting from the operation of HPEAL are the following:

- Reduced energy consumption of the GWs due to their deactivation for most of the operating cycle.
- Reduced energy consumption of GWs due to the avoidance of forwarding duplicate packets to the server.
- Reduced energy consumption and increased reliability for EDs due to transmission protection, both through the use of the CAD mechanism and the separation of uplink and downlink transmissions, thus achieving a reduction in collisions.
- Adaptation of the protocol operation in cases of failure or low energy reserves in a GW.
- Dealing with the main problem of CAD application in LoRa networks which is the hidden node phenomenon. Since subnetting reduces the distance between EDs sharing available spectrum resources, greatly reducing this phenomenon.

The main disadvantages of the protocol compared to the existing LoRaWAN protocol are:

- Need of synchronization for the EDs.
- Increased latency in data transmission.

The rest of the paper includes Section II, which includes overviews related work, Section III, where the operation of the HPEAL is analyzed. Section IV describes the system model and presents the simulation results on the effectiveness of the proposed protocol. Finally, Section V concludes the paper and presents our plans for future work.

II. Related Work

The improvement of energy efficiency as well as the reduced reliability and scalability are among the most important open research topics concerning LoRa networks. In the literature there are many studies that examine and propose mechanisms and protocols that improve their performance. The solutions to improve the energy efficiency include the optimization of the transmission and modulation parameters [10], [11], the use of reinforcement learning mechanisms [12], the application of routing [13] and backoff algorithms [14], as well as the development of mesh topologies [15]. In all the aforementioned research works, only the improvement of EDs energy efficiency and not of the GWs is considered.

The development of multi-GW topologies to improve both the energy efficiency and scalability of dense LoRa networks has also been studied in the literature. The common conclusion drawn from the results in research works [7], [8], [16] and [17] is that GW densification improves both the energy consumption of the EDs, as well as the scalability and coverage in LoRa networks. The reasons for the improvement in performance are the robustness afforded by the multi-reception capability in the uplink transmissions, the possibility of more downlink transmissions due to per GW duty cycle limitations, as well as the use of more aggressive modulation characteristics by the EDs due to their proximity to the GWs [18]. However, the above performance improvements come at the cost of increased installation and operating expenses, as well as reduced reliability due to increased collisions, since the EDs use common aggressive modulation features.

The LoRaWAN protocol does not specify the procedure by which the network server selects the GW that will perform a frame transmission to an ED in multi-GW topologies. For this reason, the association between GWs and EDs has been studied in the literature. An algorithm has been proposed in [19] and a machine learning mechanism in [20] which, by calculating features such as link quality and duty cycle constraints, associate the GWs with the EDs in the downlink, thus achieving both the increase in network scalability and load balancing. In [21] the authors propose a corresponding uplink and downlink association protocol in a renewable energy powered GWs LoRa network, which considers the available energy resources of the GWs and adjusts the transmission parameters, achieving the reduction of the energy consumption of both the GWs and the EDs.

The LoRaWAN protocol defines Pure-Aloha as the default medium access mechanism, which due to its low complexity and low overhead offers low energy consumption and low complexity operation to EDs. However, when we have dense deployments and the offered load increases, collisions rise dramatically since transmissions are not protected, resulting in a degradation of the quality of service provided by the network. A large number of alternative medium access mechanisms have been proposed in the literature, which improve the rate of successful transmissions. A deterministic protocol has been proposed in [22] based on the centralized scheduling of transmissions through the time division multiple access mechanism, which ensures collision-free operation. A hybrid protocol based on Slotted-Aloha using the CAD mechanism b is presented in [23], the simulation results show an increase in reliability with a light burden on the EDs power consumption.

III. OPERATION OF THE HYBRID PROTOCOL FOR ENERGY AUTONOMOUS LORA NETWORKS

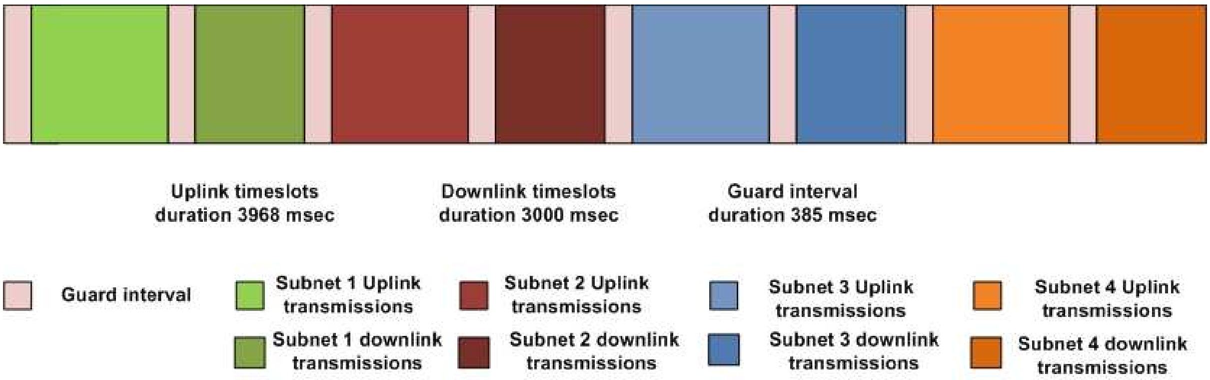

Figure 1.HPEAL operation cycle timing in a LoRa network consisted of four gateways.

The operation of the HPEAL protocol is based on the division of the network into subnets, in which we have exclusive allocation of the resources in a round-robin way. Each subnet consists of a single GW and its associated EDs, where we have temporal separation of uplink and downlink transmissions. Figure 1 shows an operating framework example of a four GWs LoRa network, which consists of timeslots that the protocol assigns to each subnet for uplink and downlink transmissions and the corresponding guard intervals between them. The assigned timeslots are repeated thus creating an operation cycle, the duration of which is proportional to the number of GWs. The operation of HPEAL aims to activate the GWs only during the time assigned to the subnet to which each one belongs, and to deactivate them for the rest of the operation cycle. The above approach has a double aim to reduce the energy consumption of the GWs. The first one is to suppress their operation time , while the second is to avoiding forwarding multiple copies of the same packet to the network server.

The proposed protocol is hybrid, since in the uplink timeslots the EDs share and compete for the access in the wireless medium. To reduce collisions, the CAD mechanism is used, which is within the functional capabilities of LoRa EDs. In the downlink the protocol is collision-free since the timeslot is used exclusively for GWs transmissions. The time duration of the uplink timeslots is determined by the maximum requirements that exist both for the duration of EDs transmission, as well as by the application of the CAD mechanisms used, so that even the longest in duration transmission can be fit in the timeslot. Thus the uplink timeslot duration is set to 3968 msec, and it results from the maximum transmission duration (3809 msec) provided for the European Union by LoRaWAN [24] (SF12, payload 59 bytes, Coding Rate 4/8, on a 125 KHz channel) , as well as from the maximum application duration of the CAD mechanism using SF12 (159 msec).

The downlink timeslot duration is set to 3000 msec in order to be compatible with LoRaWAN specifications and to be able to fit the entire procedure of downlink transmissions, which provides two reception windows for the EDs with a time distance of 1 sec between them. The operation of the protocol requires the synchronization of the EDs, where several synchronization mechanisms for LoRa networks have been proposed in the literature, which manage to provide a relatively high accuracy of the order of tens of msec with a minimum resynchronization requirement of 80 min [25]. The selected duration of guard interval between timeslots ensures the avoidance of collisions that may occur between uplink and downlink transmissions due to clock drift of the EDs.

The rest of this section describes the main functions operation that differentiate the HPEAL from the existing LoRaWAN protocol.

A. End devices join procedure

The process of associating an ED to the network contains the exchange of messages with the GWs. Upon completion of the process an ED is associated with the GW that has the best link quality. The main steps of this process are as follows:

- In the first step, when a GW receives the *join_request* message from an ED, it responds with a message specifying the time of a new transmission from the ED in the next subnet uplink timeslot of the responded GW
- In the specific timeslot of the new ED message, the network server instructs all GWs to activate their receivers, so that the received signals are compared and the ED is associated with the GW that has the best link quality.
- The selected gateway sends a message to the ED, which contains information about the allocated timeslot in which it will be able to transmit and open its receiver windows.

Based on the described process, each ED is associated with the GW that has the best link quality and transmits in a predetermined uplink timeslot, while opening the receiver in the corresponding downlink timeslot, resulting in the use of modulation characteristics that minimize energy consumption.

B. Uplink timeslot operation

In the uplink timeslot EDs belonging to the same subnet share the wireless medium. The duration of the uplink timeslot has been calculated so that it is possible to serve the most demanding transmissions, both in terms of time on air and the CAD implementation. The HPEAL protocol defines the following medium access rules to avoid collisions:

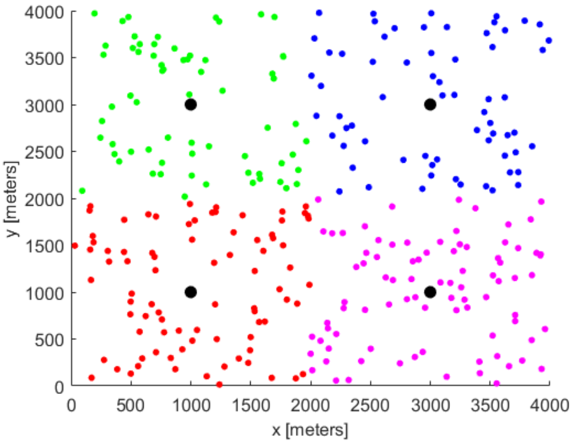

Figure 2. Network and subnets topology.

- When there is a packet arrival at an ED, the transmission process is initiated from the beginning of the next subnet uplink timeslot which is associated with.
- The exact application time of the carrier sense by the ED via CAD mechanism I_{CAD}, from the beginning of the uplink timeslot, is calculated in msec from a pseudorandom number in the interval:

$$I_{CAD} = rand\left(0, CAD_{margin}\right) \tag{1}$$

where CAD_{margin} is a time interval, which is determined by the transmission duration and the SF used, and is calculated as:

$$CAD_{margin} = T_{US} - (T_{CAD} + T_{TX}) \tag{2}$$

where T_{US} is the duration of the uplink timeslot, T_{CAD} the duration of the application of the CAD mechanism and T_{TX} the duration of the transmission. Using this technique, EDs transmission are spread over the entire timeslot duration, thus making efficient use of the medium.
- The ED applies the CAD mechanism, where in case of idle medium, it transmits the packet. In case of busy medium, it postpones the transmission and starts the transmission process from the beginning of the next subnet uplink timeslot.

Parameter	Value
Transmission power	14dBm LoRa, 23 dBm LTE
Transmitter antenna gain	3 dBi End device, 5dBi GW
Receiver antenna gain	6 dBi End device, 8 dBi GW
Number of end devices	300 (100 per channel)
Coding rate	4/5
Number of channels	3
Channel bandwidth LoRa	125 kHz
Application payload	12-250 bytes SF7 12-123 bytes SF9 12-59 bytes SF12 (uniformly distributed)
Simulation time	2 days
Mean packet time arrival	200-1800 sec (Poisson distribution)
Max number of retransmissions	7
Power consumption in listening mode for end device	50mW
Power consumption in transmission mode for end device	250mW
Power consumption in sleep mode for GW	1.8 Watts
Power consumption in listening mode for GW (LTE and LoRa)	6 Watts
Power consumption in transmission mode for GW	12 Watts (LoRa) 20 Watts (LTE)
LTE data rate	1 Mbps
Spreading factors used	SF7, SF9, SF12
Capture effect	Yes [27]
Propagation model	LoRa Path Loss Rural [26]
CAD implementation times	SF7 2.66 msec, SF9 19.14 msec SF12 158.79 msec

- In case of using confirmed transmission, the ED activates its receiver during its subnet downlink timeslot, where if the acknowledgment packet is not received, the packet retransmission process starts from the beginning of the next its subnet uplink timeslot .

C. *Downlink timeslot operation*

The downlink timeslot is collision-free, since the medium is used for transmissions exclusively by a single GW, while its duration is 3 sec so that there is sufficient time for the opening

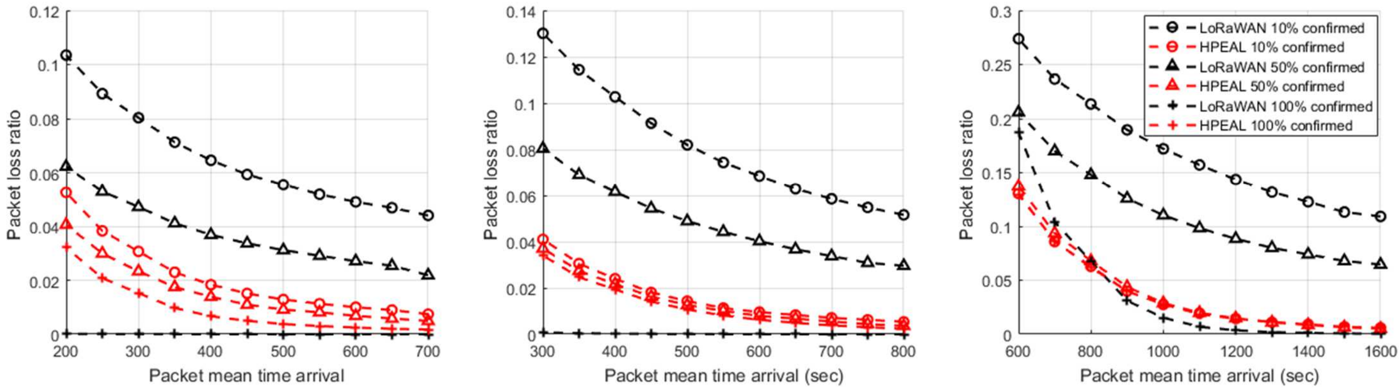

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Figure 3. Packet loss ratio using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

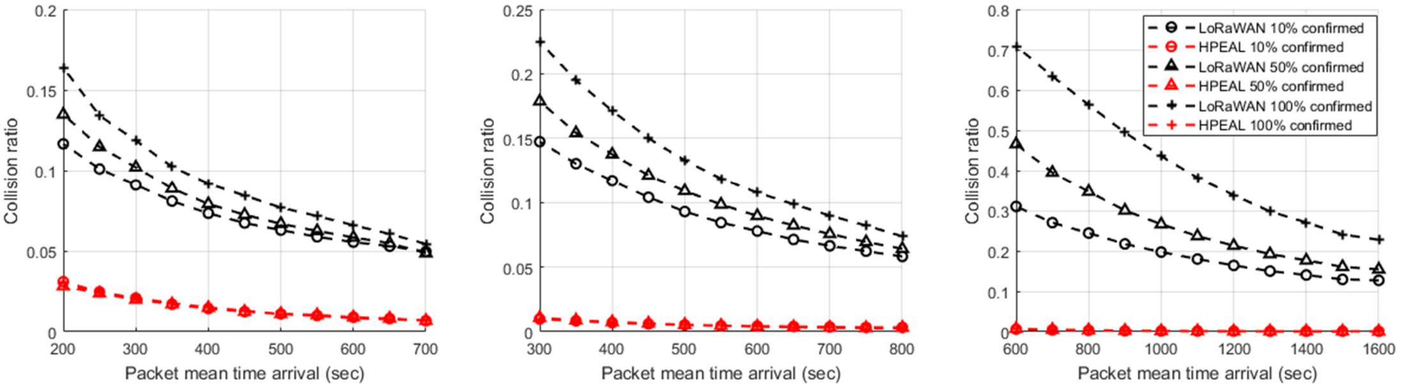

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Figure 4. Collision ratio using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

of the two receiving windows by the EDs. The exact times that the EDs will open the two receiving windows is determined by the time when their transmission will end in the uplink timeslot. Specifically, the first window will open at the first integer multiple in sec in which it will be contained in time in the immediately following downlink timeslot, while the second window will be 1 sec later. For example if the EDs transmission was completed 1950 msec from the start of the uplink time slot, the first receive window will not open at 2950 msec or 3950 msec, since those times are contained in the uplink timeslot, but at 4950 msec while the second window at 5950 msec after the beginning of the uplink timeslot, since this times contained in the downlink timeslot. In this way the downlink transmissions are scheduled and spread throughout the entire downlink timeslot, thus enabling multiple transmissions during a downlink timeslot from the GWs.

D. Adaptation of the protocol in cases of low energy reserves or failuree to a gateway

In the event that a GW has low energy reserves or has a failure, the network server activates the rest GWs for the timeslots of the respective subnet. For example, in the event that we have 4 GWs LoRa network and one of them is deactivated, we will again have energy savings since the rest GWs will be active in half of the operating cycle.

IV. SYSTEM MODEL AND SIMULATION RESULTS

A LoRa network simulator was developed at MATALB to evaluate the HPEAL protocol. The Lora network developed in the simulation covers a total area of 16 km^2 and includes 4 GWs and 300 EDs. The EDs were associated with the GW having better link quality according to the procedure described in section III A (Figure 2). Various simulation scenarios were performed which include variable offered load, three different percentages of confirmed transmissions from the EDs (10%, 50%, 100%), as well as operation of the EDs at three different SF. EDs has a buffer size for only one packet resulting that when a new packet is generated the older one is discarded and considered as lost. Other cases where the packet is considered lost are due to a collied unconfirmed transmission, and when confirmed transmissions reaches the upper limit of retransmissions.

In the simulation, the LoRa network devices use three frequency channels, while the offered load is adjusted through the mean packet arrival time at the EDs, which follows the poisson distribution. The models used, for path loss and capture effect, are those derived from the research works [26] and [27] respectively. The detailed parameters of the

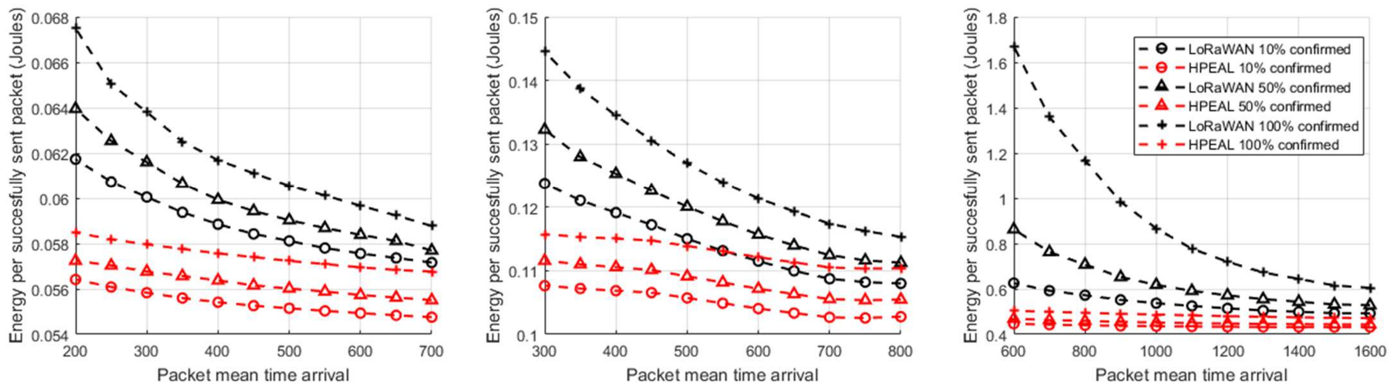

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Figure 5. End devices mean energy consumption per successful transmission using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

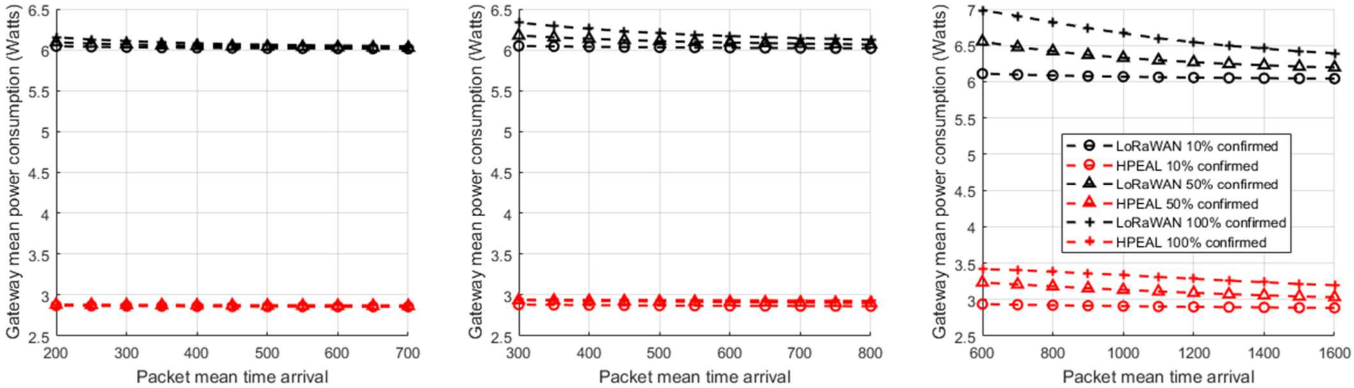

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Figure 6. Gateways mean energy consumption using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

simulation are presented in table I. In all simulation scenarios the HPEAL is compared with the existing LoRaWAN protocol The performance metrics used concern the energy consumption of both GWs and EDs, the percentage of lost packets, the percentage of collisions, the delay in data transmission, and finally the number of duplicate packets per successful transmission sent to the network server.

The first part of the simulation concerns the reliability evaluation of the protocols. In figure 3 we can see, as expected, that in both protocols as the percentage of confirmed transmissions increases, the percentage of lost packets decreases. In the cases of 10% and 50% confirmed transmissions, HPEAL outperforms LoRaWAN due to the transmission protection provided by both the CAD mechanism and the separation of uplink and downlink transmissions. In the scenario of 100% confirmed transmissions, LoRaWAN shows better results and achieves zero packet loss ratio in the scenarios with SF7 and SF9, while in the SF12 scenario, due to the long transmission time, it cannot achieve the same results. The reason why HPEAL cannot achieve the same zero packet loss ratio, in the 100% confirmed transmissions scenario, is due to the delay caused by both the CAD mechanism and the operation of the protocol, resulting in a new packet arriving without the previous one having been successfully transmitted. The next reliability metric of the protocols evaluation is the collision ratio, the results in figure 4 show that HPEAL has much less collisions in all scenarios due to the transmission protection it offers. Also in the results it can be seen that the superiority in the performance of the HPEAL increases as the used SF and the offered load increase

The next part of the simulation explores the energy efficiency of the protocols, both for the EDs and for the GWs. The mean energy consumption per successful transmission of the EDs is depicted in figure 5. As expected, energy consumption increases with the use of a higher percentage of confirmed transmissions. The results show that HPEAL offers reduced consumption in all scenarios. This is mainly due to reduced collisions and consequently to the need for fewer retransmissions compared to LoRaWAN, while the overhead of HPEAL from the CAD mechanism is compensated by the protection it offers to the transmissions. Figure 6 illustrates the average energy consumption of the GWs, the results show that in all scenarios HPEAL manages to reduce energy consumption by more than 50%. The reduced energy consumption is mainly due to the deactivation of the GWs during most of the operating cycle, as well as the reduced

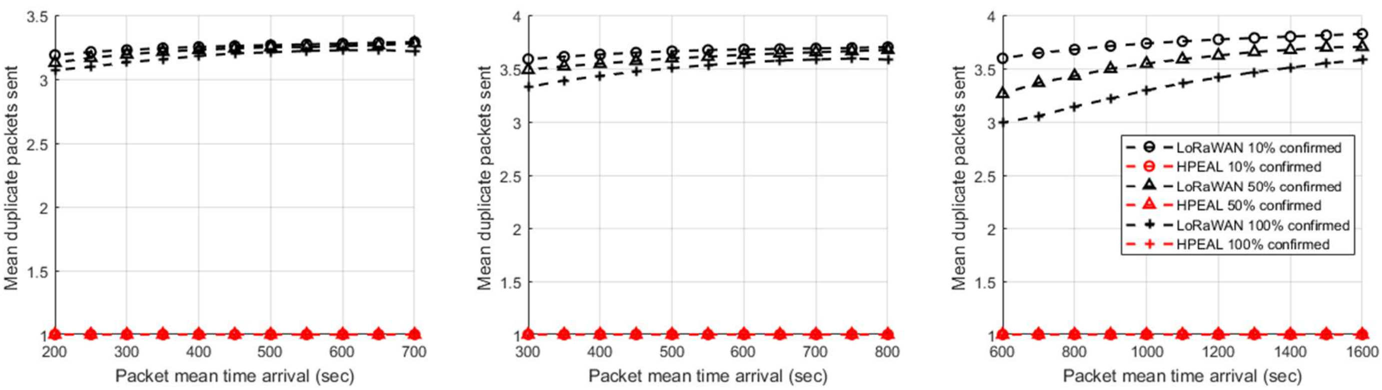

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Figure 7. Mean duplicate packets forwarding to network server using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

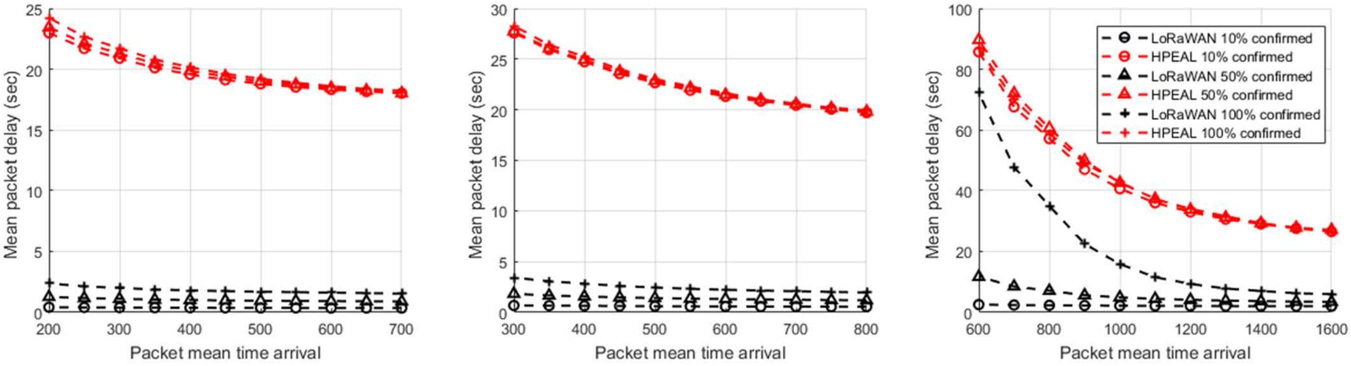

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Figure 8. Mean delay of packet transmission from end devices to network server using a. spreading factor 7 b. spreading factor 9 and c. spreading factor 12 as a function of a variable offered load.

transmissions to the 4G network due to the forwarding of a single copy of each packet to the network server.

The average number of copies of the same packet that the GWs forward to the server is shown in figure 7. The results show that in all scenarios we have more than 3 transmissions of the same packet from LoRaWAN, thus wasting energy. Finally, figure 8 shows the average delay of the packet from the EDs to the server. The results show that LoRaWAN achieves lower latency than HPEAL. This is expected due to both the use of the CAD mechanism and the round-robin operation implemented by the proposed protocol.

V. CONCLUSIONS

The development of energy autonomous LoRa networks, without the need for a cable connection with the conventional energy supply and telecommunication backbone networks, is an approach that reduces both the installation and operation costs of the network, as well as facilitating their installation in hard-to-reach rural and forest areas. The existing LoRaWAN protocol is designed so that the operation of the GWs requires continuous operation, resulting in the need to interconnect them with a conventional power supply network. The coverage of large areas by LoRa networks requires the development of multiple GWs for their smooth and efficient operation. The approach so far that exists in the literature, concerning the multi-GW LoRa networks, focuses on addressing two main issues they face, which are scalability and reliability. In all the corresponding research works, the parallel operation of the GWs is proposed, increasing the chances of reception and reducing their distance from the EDs, which implies the possibility of using a higher transmission rate. The main innovation in the proposed protocol is the round-robin operation of multiple gateways. As the simulation results showed, the proposed protocol manages to simultaneously achieve both the reduction of energy consumption for GWs and EDs, as well as the improvement of reliability at the cost of increased delay. Also, the division of the network into sub-nets manages to face two more other problems of LoRa networks, the first one is the reduction of interference between EDs, while the second is the limitation of the hidden node phenomenon by applying the CAD mechanism. The above advantages make HPEAL an effective solution for its application in energy autonomous LoRa networks powered by renewable energy resources. As a future work we intend to present a cost-saving and carbon footprint analysis offered by the proposed protocol in relation to LoRaWAN.

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