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On the Optimization of LoRaWAN Gateway Placement in Wide Area Monitoring Systems

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Abstract. LoRaWAN-based wide area monitoring systems may use non-stationary LoRaWAN gateway devices to collect sensor data. In these cases, the most suitable locations for gateways must be found, while taking into account the scarcity of radio resources and energy consumption. In this paper an optimization model is proposed that aims to address this problem. The model ensures that power drain on the most critical devices is minimised fairly, considering an amount of packets to be delivered, and can be used to plan changes of gateway locations periodically, so that the network lifetime is extended. Results show that the optimization model and proposed pipeline are adequate for the planning of wide area monitoring where in the long-run different devices will be communicating in parallel, with the same gateway or different gateways, and sharing the spectrum. The approach can also be used to anticipate any gateway rearrangement need to ensure the extension of the lifetime of the network.

Keywords: Internet of Things · LoRaWAN · Energy saving.

1 Introduction

The Internet of Things (IoT) refers to the interconnection of smart devices, and low power wide area network (LPWAN) technologies are now considered a promising platform for the creation of large scale IoT applications (e.g., smart cities, smart agriculture), enabling low bit rate wireless connections covering long distances with minimum power consumption [10, 15]. One of these technology is LoRaWAN that operates in the unlicensed frequency band, so that end users are free to build LoRa-based architectures similar to house-owned WiFi routers. This freedom will certainly contribute to the emergence of new IoT applications.

The large-scale deployment of LPWAN for IoT brings many challenges because radio resources are scarce and their management becomes very challenging in practical networks. Therefore, procedures for an efficient and dynamic management of resources become necessary. In the case of LoRaWAN networks, an adaptive data rate (ADR) mechanism is available that dynamically assigns transmission parameters to the end nodes [8]. In general, the lifespan of the

battery and throughput depends on the time on air (ToA), which defines the time required for a packet to travel between an end-device and the gateway, and transmission power (TP). The transmission duty cycle (TDC), defined as the maximum time during which an end-device can access the channel per hour, is also a key constraint in such networks [2]. Such limitation applies also to gateways, and ends up limiting the number of updating packets a gateway can disseminate per hour. This means that a gateway can be prevented from updating all end devices, and global network optimizers should take this limitation into account. A gateway updating packet consumes 2-3 seconds.

LoRa-based wide area monitoring systems have been proposed in many fields (e.g., tree farms [16], [3]). In such deployments, coverage can be ensured by mobile LoRaWAN gateway devices that collect data from sensors located at longer distances, as in [7]. In these cases, an additional problem that needs to be solved is to find the most suitable locations for gateways, and determine when and how to move them for efficient data collection, given the energy consumption at the devices. Here in this article, the LoRa gateway placement problem is addressed and the goal is to assign gateways to places in a way that energy depletion at critical devices is fairly minimized. Although the developed optimization model is able to solve any instance of the problem, our final goal is to move to a real deployment (an orchard, more specifically). Therefore, all information required by the optimization model (in order to make its decisions) was extracted from a simulation developed in OMNet Flora, where the implemented environment conditions and device energy models are similar to the real deployment ones. This way gateway placement (and adequate number of gateways) can be decided before going into the field.

More clearly, the contributions of this article include:

- Mathematical optimization model of the LoRa gateway placement problem, having as goal the fair minimization of energy depletion at critical devices.
- Validation of the optimization model using realistic information extracted from a deployment simulation model developed in OMNet Flora.

The remainder of this article is organized as follows. Section 2 discusses work related with LoRa placement and applications similar to ours. Section 3 introduces some required definitions and formulates the gateway placement problem. Section 4 discusses the steps involved in obtaining the results, and performs an analysis of these. Section 5 draws conclusions and presents future work.

2 Related Work

Mobile LoRaWAN gateways are considered in applications like agriculture, wildlife monitoring and livestock applications where data has to be collected and/or productivity improved, as in [9, 7]. In these works in particular, a single mobile gateway is considered and the authors show that it can be a more cost effective

choice than using multiple static gateways. These studies do not address the gateway placement planning issue, and do not consider multiple gateways.

Regarding the data collection problem, in [18] it is assumed that gateways are not always available, so devices need to perform local data buffering. The problem of multiple devices having to deliver a larger number of packets, upon gateway availability, is addressed. To avoid bursts of collisions and expedite data collection, a time-slotted transmission scheduling mechanism is proposed. In [17], an offline heuristic approach is proposed to find time-slotted schedules. Information like the number of devices and their spreading factor (SF) is assumed to be known. In contrast to the just mentioned works, an online approach is proposed in [1] where partial knowledge is assumed. This allows the algorithm to adapt to dynamic changes, such as topology changes. This is achieved at the expense of higher energy consumption and longer data collection time than the offline approach. In [19, 4], the problem of collecting data using a single SF is addressed. The goal of the SF optimization problem is to maximize the success probability given an amount of data per node and a maximum data collection time window.

The gateway placement problem in LoRa networks was initially addressed in [12], where it is shown to be NP-Hard. The goal is to maximize the average energy efficiency of the network by placing as few gateways as possible. However, this approach does not consider the energy depletion at critical devices, and solutions lead to reduced network lifetime. A LoRaWAN gateway placement model for dynamic IoT scenarios is proposed in [11]. The approach is to group IoT devices when placing gateways, so that each gateway can serve a group of devices. The assessment of the most critical device among such devices, and therefore network lifetime extension is not addressed.

In this work the placement of gateways is done so that the energy depletion at the most critical devices (one per resulting gateway coverage) is fairly minimized. To the best of the authors' knowledge and bibliographic search this is being addressed for the first time.

3 Problem Statement

3.1 Definitions and Notation

Definition 1 (LoRa Bit Rate). *LoRa modulation uses chirp spread spectrum signals to modulate data. The spreading factor determines the number of chirps contained in each symbol, given by 2^{SF} . Therefore, $\frac{BW}{2^{SF}}$, where BW is the bandwidth, gives the symbol rate. Since the number of raw bits that can be encoded by a symbol is SF , and given a coding rate CR , the useful bit rate for a given SF will be $R_{SF} = SF \times \frac{BW}{2^{SF}} \times CR$.*

The bandwidth (BW) in LoRa can be 125kHz, 250kHz or 500kHz.

Definition 2 (Transmission Duty Cycle - TDC). *Ratio of the cumulated sum of transmission times per observation period. The maximum duty cycle ends*

up being the maximum percentage of time during which an end device can occupy a channel, per hour.

Definition 3 (Packet Reception Ratio - PRR). *Probability of correct package reception, at a gateway $g \in \mathcal{G}$, assuming an average signal to noise ratio (SNR) for a particular distance between a device $d \in \mathcal{D}$ and the gateway, and assuming a certain SF for transmission.*

Besides the PRR, a no collision probability is also considered by many authors, as in [14]. The traditional ALOHA is usually the underlying medium access protocol.

Definition 4 (Feasible Spreading Factors). *A spreading factor belongs to the set of feasible spreading factors of device $d \in \mathcal{D}$ for communication with location l , denoted by \mathcal{S}_d^l , if and only if it can be used for d to communicate with location $l \in \bigcup_{g \in \mathcal{G}} \mathcal{L}^g$.*

Definition 5 (Most Critical Device). *Assuming \mathcal{L}^g to be the set of possible locations for a gateway $g \in \mathcal{G}$, the most critical device in the coverage area of $g \in \mathcal{G}$, when placed in location $l \in \mathcal{L}^g$, is given by $\Delta_g^l = \arg \max_{d \in \mathcal{C}_g^l} \{B_d^l\}$, where B_d^l is the relative battery consumption of device $d \in \mathcal{D}$ when sending a packet to location l , and $\mathcal{C}_g^l = \{d \in \mathcal{D} : R_{d,s^*}^l \times PRR_{d,s^*}^l \times N_{d,s^*}^l \geq R_{d,s'^*}^l \times PRR_{d,s'^*}^l \times N_{d,s'^*}^l, \forall l' \neq l\}$ is the set of devices that are expected to adjust their SF to s^* (optimal SF) for communication with gateway g at location l .*

The R_{d,s^*}^l , PRR_{d,s^*}^l and N_{d,s^*}^l are the bit rate, PRR and the no-collision probability when device d is communicating to location l using SF s^* , the optimal SF assigned by the ADR mechanism.

Definition 6 (LoRa Gateway Placement Problem - LGP Problem). *Given a set of end node devices \mathcal{D} and a set of gateways \mathcal{G} , find the places for gateways that lead to a **fair minimization of energy depletion** in critical devices (considering a set of packets to be sent) while also ensuring that: i) all devices are covered and; ii) device transmission does not violate the TDC. More formally, let us assume that $\chi^U = \{\chi_1, \chi_2, \dots, \chi_{|\chi^U|}\}$ is the universe set of all feasible gateway-place assignments. Let us also consider a cost function $f : \chi^U \rightarrow \mathbb{R}^+$ defined by:*

$$f(\chi_i) = \arg \max_{\langle g, l \rangle \in \chi_i} \left\{ \frac{P_{\Delta_g^l} \times L_{\Delta_g^l}}{R_{\Delta_g^l, s^*}^l \times PRR_{\Delta_g^l, s^*}^l \times N_{\Delta_g^l, s^*}^l} \times B_d^l \right\} \quad (1)$$

where P_d is the number of packets per TDC to be sent by device d , L_d is the average packet length, and the device being considered is the most critical one. Then the most energetically fair gateway placement is given by:

$$\chi_i^* = \arg \min_{\chi_i \in \chi^U} \{f(\chi_i)\} \quad (2)$$

A gateway-place assignment is considered to be feasible if all devices are covered and no device transmission violates the TDC.

That is, from all possible gateway-place assignments, the one that provides the lowest upper bound on depletions at critical devices is the one that should be selected.

3.2 LGP Problem Formulation

Let us assume the following known information:

- \mathcal{D} Set of LoRa communicating devices, where $d \in \mathcal{D}$ denotes a specific device.
- \mathcal{G} Set of available LoRa gateways, where $g \in \mathcal{G}$ denotes a specific gateway.
- B_d^l Relative battery consumption of device $d \in \mathcal{D}$, when communicating with a gateway at location $l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g$, considering the time required for the transmission of all packets; $0 \leq B_d^l \leq 1$.
- \mathcal{S} Set of SF-CR configurations, where $s \in \mathcal{S}$ denotes a specific configuration.
- \mathcal{L}^g Set of possible locations for gateway $g \in \mathcal{G}$.
- \mathcal{C}_l Set of covered devices when location $l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g$ is in use.
- \mathcal{S}_d^l Set of SFs that can be used for device $d \in \mathcal{D}$ to communicate with a gateway in location $l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g$, $\mathcal{S}_d^l \subseteq \mathcal{S}$.

Let us also consider the following variables:

- σ_d^l One if device $d \in \mathcal{D}$ is communicating with location $l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g$; zero otherwise.
- $\varphi_d^{g,l}$ One if $d \in \mathcal{D}$ is the most critical device, from all devices covered by gateway $g \in \mathcal{G}$ placed at location $l \in \mathcal{L}^g$; zero otherwise.
- $\phi^{g,l}$ One if gateway $g \in \mathcal{G}$ is to be placed at location $l \in \mathcal{L}^g$; zero otherwise.
- Π Most difficult transmission conditions among all critical devices (upper bound).

The LGP problem can be solved using the following objective function:

– Objective function:

$$\text{Minimize } \Pi \quad (3)$$

The following set of constraints must be fulfilled:

– Allocation of gateways to places and covering of all devices:

$$\sum_{\{l \in \mathcal{L}^g\}} \phi^{g,l} = 1, \forall g \in \mathcal{G} \quad (4)$$

$$\sum_{\{g \in \mathcal{G}\}} \sum_{\{l \in \mathcal{L}^g : d \in \mathcal{C}_l\}} \sigma_d^l = 1, \forall d \in \mathcal{D} \quad (5)$$

$$\sigma_d^l \leq \sum_{\{g \in \mathcal{G} : l \in \mathcal{L}^g\}} \phi^{g,l}, \forall d \in \mathcal{D}, \forall l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g : d \in \mathcal{C}_l \quad (6)$$

$$\begin{aligned} & (R_{d,s^*}^l \times PRR_{d,s^*}^l \times N_{d,s^*}^l) \times \sigma_d^l \geq \\ & \geq (R_{d,s'^*}^{l'} \times PRR_{d,s'^*}^{l'} \times N_{d,s'^*}^{l'}) - \Theta \times (1 - \sigma_d^l), \\ & , \forall d \in \mathcal{D}, \forall l, l' \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g : d \in \mathcal{C}_l \wedge d \in \mathcal{C}_{l'} \end{aligned} \quad (7)$$

where Θ is a big value, required for constraints to hold true regardless of the gateway location a device is communicating with. Constraints (4) place gateways at one of the allowed locations, Constraints (5) ensure that all devices are covered. Constraints (6) ensures that communication with a location occurs only if there is a gateway placed in there. Constraints (7) ensure that devices communicate with the gateway location providing the best conditions.

– Most critical device depletion:

$$\sum_{\{d \in \mathcal{D} : d \in \mathcal{C}_l\}} \varphi_d^{g,l} = \phi^{g,l}, \forall g \in \mathcal{G}, \forall l \in \mathcal{L}^g \quad (8)$$

$$\varphi_d^{g,l} \leq \sigma_d^l, \forall g \in \mathcal{G}, \forall l \in \mathcal{L}^g, \forall d \in \mathcal{D} \quad (9)$$

$$\begin{aligned} B_d^l \times \varphi_d^{g,l} & \geq B_{d'}^{l'} \times \sigma_{d'}^{l'} - \Theta \times (1 - \varphi_d^{g,l}), \\ & , \forall g \in \mathcal{G}, l \in \mathcal{L}^g, \forall d, d' \in \mathcal{C}_l \end{aligned} \quad (10)$$

where Θ is a big value, required for constraints to hold true regardless of a node being considered critical or not, which must hold in mathematical optimization models. Constraints (8) and (9) determine the critical device per gateway cover, while Constraints (10) ensure that it is the one with higher relative energy consumption.

$$\begin{aligned} \Pi & \geq \varphi_d^{g,l} \times \frac{P_d \times L_d}{R_{d,s^*}^l \times PRR_{d,s^*}^l \times N_{d,s^*}^l} \times B_d^l, \\ & , \forall g \in \mathcal{G}, l \in \mathcal{L}^g, \forall d \in \mathcal{D} \end{aligned} \quad (11)$$

Constraints (11) determine the most difficult transmission conditions among all critical devices.

- Non-negativity assignment to variables:

$$\varphi_d^{g,l}, \phi^{g,l}, \sigma_d^l \in \{0, 1\}; \Pi \in \mathbb{R}^+. \quad (12)$$

This optimization model can be solved using packages like CPLEX or Gurobi, [5, 6], which find the optimal solution given an instance of the problem. Other approaches, such as genetic algorithms and meta-heuristic algorithms, do not guarantee that the optimal solution is obtained, although they are faster to execute. Since the LGP can be planned offline, and since there is no strict time frame for completion, an optimisation model ensuring an optimal solution is preferred.

4 Analysis of Results

The architecture implemented follows the one proposed by the LoRa Alliance. The network has a star-of-stars topology where gateways work as intermediary points between devices and the central network server, allowing for bidirectional communication between these end points. The real deployment is an orchard (Figure 1) with the following characteristics:

- Orange grove of 45.6-hectares of square-shaped field with 25 sensing devices;
- Orange trees are equally spaced, each having off-the-shelf temperature and luminosity sensors, mounted inside the tree’s canopy, to evaluate de impact of local conditions on fruit development;
- Each device is 150m horizontally and 190m vertically away from each other

The simulation model developed in OMNet Flora, for the just mentioned real deployment, consideres:

- 2 gateways and 5 different feasible locations for both gateways.
- Oulu path loss model, using $n = 2.32$, $B = 128.95$, $\sigma = 7.8$ and antenna gain of -4.15dB, similarly to [13].
- ADR algorithm for SF optimization;
- Energy model provided by Flora, following values in Table 1.

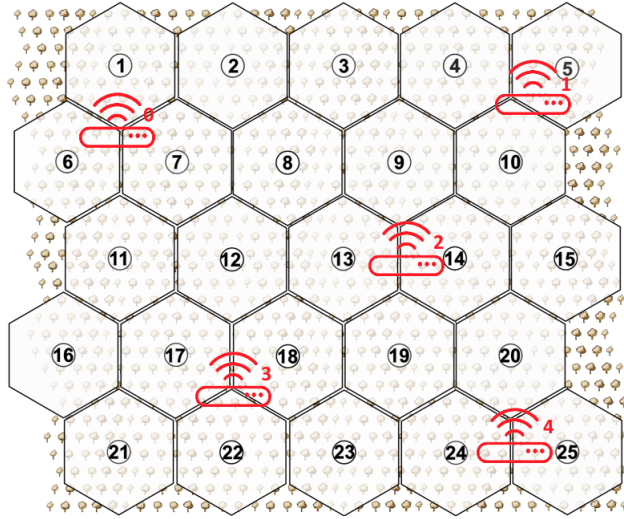
The first step is to use the simulation model to collect R_{d,s^*}^l , PRR_{d,s^*}^l and N_{d,s^*}^l , which depend on path loss conditions, and B_d^l , resulting from the energy model in use, $\forall l \in \bigcup_{\{g \in \mathcal{G}\}} \mathcal{L}^g$ and $\forall d \in \mathcal{D}$. This is input information to the

optimization model. Such characterization of transmission conditions and energy consumption, from every device towards every possible gateway location, is done considering the transmission of 10000 packets per device.

The next stage is to determine the optimal gateway placement given by the mathematical optimization model, and then run the simulation considering the

Table 1. Flora Energy Consumption Model.

Mode	Power Consumption (W)
Off	0
Sleep	0.001
Switching	0.002
Receiver, idle	0.002
Receiver, busy	0.005
Receiver, receiving	0.01
Receiver, receiving preamble	0.01
Receiver, receiving header	0.01
Receiver, receiving data	0.01
Transmitter, idle	0.002
Transmitter, transmitting	0.1
Transmitter, transmitting preamble	0.1
Transmitter, transmitting header	0.1
Transmitter, transmitting data	0.1

Fig. 1. Schematic representation of the gateways and end node locations.

placement of gateways found by the optimization model. Results are compared against other placements. Table 2 summarizes the obtained results, where the placement resulting from the optimization model (and impact of that choice) is displayed in bold. Results were similar for a coverage cutoff of 0% (all devices covered by all gateway locations, when in use) and 10% (a device not able to transmit at least 10% of its packets, towards a given gateway location, is considered uncovered).

Devices end up transmitting a different amount of packets, and for this reason we cannot look at energy consumption in an isolated way. For this reason the

Table 2. Energy Consumption per Packet (2 GWs).

Gateways positions	Energy Consumption Packet Data Rate			
	Average	Standard Deviation	Lowest	Largest
0 1	0,41	0,23	0,073	0,86
0 2	0,25	0,12	0,07	0,62
0 3	0,28	0,13	0,08	0,53
0 4	0,29	0,13	0,08	0,56
1 2	0,29	0,16	0,07	0,70
1 3	0,27	0,14	0,07	0,53
1 4	0,39	0,20	0,07	0,73
2 3	0,28	0,17	0,07	0,66
2 4	0,36	0,21	0,07	0,87
3 4	0,40	0,25	0,08	0,96

results regarding energy consumption per packet are the ones included in Table 2. Results show that the optimization model ends up being capable of finding the best places for gateways, when compared with other possible locations. This is because it was able to select one of the gateway positioning combinations presenting the lowest value in the “Largest” column, meaning that the worst energy consumption per packet is minimized. This solution is one of the fairest solutions because minimizing such upper bound (worst energy consumption) ends up balancing energy consumption among devices, extending network lifetime. The average energy consumption per packet is also one of the lowest, ensuring energy saving in general.

These results allow us to conclude that basing the decision on the most critical nodes, one per covered range, and make placements that lead to the minimization of the most difficult transmission conditions among critical devices, is adequate for such kind of deployment where in the long-run different devices will be communicating in parallel, with the same gateway or different gateways, and sharing the spectrum. Any attempt to minimize the sum of device’s energy consumption, or maximize the overall throughput, would not be appropriate in this context.

5 Conclusions and Future Work

In this article the LoRa gateway placement problem is addressed and an optimization model is developed that assigns gateways to places in a way that energy depletion at critical devices is fairly minimized. Results show that the optimization model and proposed pipeline are adequate for the planning of LoRaWANs, in particular for wide area monitoring systems requiring multiple gateways, which is a step that should precede any deployment. Planning is done offline, for any real scenario, and applied when appropriate, allowing prior validation of gateway placement. Such pipeline can also be used to anticipate any gateway rearrangement need to ensure the extension of the lifetime of the network, being only

required to change the input information. Future work will address the scheduling of gateway rearrangements. More specifically, given an existing deployment, determining when it becomes necessary to carry out a new gateway rearrangement and how to do it without service disruption is an issue that needs to be addressed.

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