2019 IEEE International Congress on Internet of Things (ICIOT)

# LoRa Network Planning: Gateway Placement and Device Configuration

Behnam Ousat and Majid Ghaderi
Department of Computer Science
University of Calgary

***Abstract*—LoRa is a leading Low-Power Wide-Area Network technology for IoT applications that require communication over long distances at low power. While there exist several studies on the performance, scalability and security of LoRa networks, the important problem of how to efficiently plan and deploy LoRa networks has not received much attention so far. In this work, we address this problem, which consists of the joint problems of gateway placement, spreading factor assignment, and power allocation. We formulate the problem as a mixed-integer non-linear optimization problem, which can be solved only for small networks. By systematically analyzing the structural properties of the optimal problem, specifically on regularly-structured networks, we develop an approximate algorithm for planning large-scale LoRa networks efficiently. Simulation results are provided to show the behavior and performance of our algorithm in different network scenarios. We have also compared our algorithm with the commonly used ADR algorithm, which shows 15% and 20% improvement in average throughput and energy efficiency of the network, respectively.**

## I. Introduction

### A. Background and Motivation

The Internet of Things (IoT) is an emerging paradigm in which everyday objects are equipped with Internet connectivity, enabling them to collect and exchange information. Currently, there are several Low-Power Wide-Area Network (LPWAN) technologies in the market, such as LoRa [1], Sigfox [2], RPMA [3], Telensa [4], and Weightless [5], that can be used to provide connectivity for IoT applications that require long-range communication and low power consumption. In this work, we focus on LoRa, a leading LPWAN technology that uses Chirp Spread Spectrum (CSS) [6] to achieve high levels of noise immunity, allowing for long-range communication. While there exist several works on the performance, scalability and security of LoRa networks, the important problem of how to efficiently plan and deploy large-scale LoRa networks has not received much attention so far. Our objective is to address this problem by jointly considering the problems of optimal gateway placement and end device configuration. Clearly, placing gateways optimally lowers the capital and operational costs of the network by allowing to install the minimum number of gateways, while optimal end device configuration results in an improved system performance in terms of throughput and energy efficiency.

### B. Related Works

This paper deals with two main problems: 1) gateway placement and 2) end device configuration. In the following, we review some representative works on each problem that are more relevant to our work.

**Gateway Placement.** Gateway placement along with coverage problems in wireless networks have been extensively studied in the literature and there exists a large body of works on such problems in different types of wireless networks and with different objectives [7]–[10]. For instance, in [11], a framework for access point placement in WiFi networks is proposed that aims to minimize the installation costs, while providing coverage for all users. The problem of gateway placement in wireless mesh networks with the objective of installing the minimum number of gateways is studied in [12], where it is shown that the problem is NP-Hard and an approximate algorithm is proposed to solve the problem efficiently. A greedy heuristic for base station placement in cellular networks is proposed in [13], where the objective is to maximize the energy efficiency of the network. The problem is solved by dividing the area into a grid, and selecting one candidate location in each grid, then installing base stations in candidate locations in a greedy manner.

A few works have recently considered gateway placement in IoT networks. For instance, gateway placement in IoT networks is considered in [9], where a multi-hop wireless network model is adopted, and subsequently an integer linear program is devised to decide on gateway locations while minimizing the installation costs subject to satisfying user demands. Considering interference cancellation, a greedy algorithm for gateway placement in LPWANs is proposed in [14], which tries to minimize the contention among end devices in the network.

However, none of these works can be applied to LoRa networks. What makes gateway placement in LoRa networks different from the placement problems in conventional wireless networks is the *association-less* nature of LoRa networks. Specifically, in LoRa networks, there is no notion of gateway-device association. Instead, end devices simply broadcast their messages. Any gateway that receives a message, forwards it to a so-called network server for processing. As such, as long as a message transmission is heard by any gateway in the network, that message is

978-1-7281-2714-9/19/$31.00 ©2019 IEEE
DOI 10.1109/ICIOT.2019.00017

considered to be received. In contrast, in cellular and WiFi networks, or traditional sensor networks based on Zigbee and Bluetooth, there is a well-defined notion of association with a gateway. In these networks, a gateway only serves (receives from or transmits to) those devices that are explicitly associated with it. As a result, placement solutions developed for such networks (*e.g.*, [9], [11]–[13]) cannot be applied to LoRa networks, as they are based on one-to-one association (*i.e.*, each device communicates with only one gateway) between devices and gateways as opposed to one-to-many association (*i.e.*, each device communicates with potentially many gateways) in LoRa networks.

**Device Configuration.** End device configuration in LoRa networks, which consists of spreading factor assignment and power allocation, has been recently considered in a few works [15]–[18]. The current end device configuration mechanism in LoRa is known as Adaptive Data Rate (ADR), which implements a simple distance-based approach. In ADR, the minimum possible spreading factor and transmission power that allow an end device to communicate with a gateway are assigned to it. As such, ADR does not always result in optimal network performance, but rather a basic configuration that only ensures end devices are *capable* of communicating with gateways. To achieve fairness in LoRa networks, [16] develops an algorithm for end device configuration by using guidelines that are extracted from a solution given by a genetic algorithm.The main idea in [17] is to provide fairness for devices that are very far from the gateway by devising an algorithm that balances devices' received power regardless of their distance from the gateway. In [18], a so-called ordered water filling approach is adopted to assign underused spreading factors to end devices, thus achieving higher levels of throughput. All these works, however, consider a network with a *single gateway*, and thus cannot be applied to large-scale LoRa networks that include multiple gateways. As mentioned earlier, in multi-gateway networks, end devices have the opportunity to communicate with multiple gateways, which is an important design aspect of LoRa networks. In our work, we explicitly take this into consideration when addressing the device configuration problem.

### C. Our Contributions

Our contributions in this paper can be summarized as follows:

- We formulate the problem of planning LoRa networks as a Mixed-Integer Non-Linear Program (MINLP), which is generally NP-Hard, and thus computationally intractable in large networks.
- We present an analysis of ALOHA-based networks with regular network structure and multiple gateway access. The analytical results are then used to simplify the original MINLP problem.
- We design a hybrid end device configuration strategy, which is partly based on an optimal solution to an unconstrained version of the problem and partly based on the ADR approach, thus achieving the benefits brought by both of these methods.
- We propose a planning algorithm, which in conjunction with our hybrid device configuration algorithm is shown to outperform the commonly used ADR algorithm in LoRa networks.

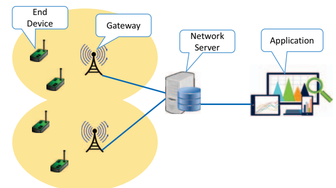


Fig. 1: A typical LoRa network architecture.

### D. Paper Organization

The paper is organized as follows. We provide a concise overview of LoRa networks in Section II. In Section III, the problem is formulated as a MINLP problem. The analysis of regularly-structured networks is presented in Section IV. An optimal end device configuration strategy along with a greedy algorithm are presented in Section V. Simulation results are presented in Section VI, while Section VII concludes the paper.

## II. LoRa Overview

### A. LoRa Networks

LoRa (Long Range) is an LPWAN technology developed by Semtech Corporation [19]. To keep the complexity of the network low, LoRa relies on a star topology in which end devices directly communicate with a few gateways in a single-hop manner. Gateways in turn forward data received from end devices to a central network server (see Fig. 1). Gateways and end devices communicate with each other using different data rates, where the selection of a particular data rate provides a trade-off between communication range and message duration.

In the PHY layer, LoRa implements Chirp Spread Spectrum (CSS) with integrated Forward Error Correction (FEC) [1]. Different data rates can be selected by changing the Spreading Factor (SF), which can be one of $\{7, 8, 9, 10\}$ in North American deployments. LoRa uses orthogonal SFs, which allows packets with different SFs to be transmitted concurrently without collisions. Using higher SFs results in higher noise immunity, thus longer communication range; however, it will result in longer packet air times, increasing the chance of collisions with other packets.

The link layer of LoRa networks is referred to as LoRaWAN. The channel access mechanism in LoRaWAN is pure ALOHA [20], in which end devices access the channel as soon as they have packets ready for transmission. LoRaWAN also defines the ADR mechanism used for end device configuration.

## B. LoRa Operations

In a LoRa network, end devices transmit their packets in a broadcast manner, while gateways listen for transmissions on all available channels and all possible SFs. An end device's transmission is received successfully at a gateway if the received signal power at the gateway is higher than a minimum required Received Signal Strength Indicator (RSSI). The minimum required RSSIs for successful reception at different SFs are provided in Table I. The gateways, in turn, send the decoded packets to a central network server using broadband Internet connections, where duplicate packets are detected and removed. An advantage of broadcast transmissions is that, while a packet might not be decoded successfully by one gateway, e.g. due to collisions, there is still a chance that it may be decoded by another gateway, resulting in more successful receptions. The number of gateways that can hear an end device's transmission depends on the communication range of the end device, which in turn is directly related to the transmission power and the SF used by the end device.

TABLE I: Minimum required RSSI for successful decoding with different SFs [21].

| SF | RSSI(dBm) |
|---|---|
| 7 | -123 |
| 8 | -126 |
| 9 | -129 |
| 10 | -132 |

# III. LoRa Network Planning

Planning a LoRa network consists of finding the optimal locations to install gateways and deciding on the SFs and transmission powers used by end devices in that network. In the following subsections, we present our network model and discuss how network planning can be formulated as an optimization problem by jointly considering gateway placement and device configuration.

## A. Network Model

We consider a network consisting of $N$ end devices (EDs) arbitrarily distributed in the network area. There are $M$ potential gateway locations in the area, where gateways can be installed. Each ED uses a particular SF and transmission power, and transmits a packet with fixed payload size $PL$ once every $T$ seconds. An ED is heard by a gateway if the corresponding received power at the gateway is above a threshold (as presented in Table I). An ED's packet is successfully received at the network server if it is decoded by at least one gateway.

At each gateway, EDs that use the same SF can collide with each other if their packet transmissions overlap in time. The ratio of an ED's packets that are successfully received at the network server over all packets transmitted by the ED is called its *Packet Delivery Ratio* (PDR). We use *Energy Efficiency* (EE) as the performance metric to optimize, since low energy consumption is one of the most important factors in designing LPWANs. Energy Efficiency of an ED is defined as the average number of packets transmitted successfully be the ED (*i.e.*, received at the network server) using 1 unit of transmission energy. While LoRa devices can transmit on one of the several frequency channels available in the unlicensed band, we restrict our analysis to only one such channel, since transmissions on different channels are orthogonal and do not affect each other in terms of interference and collisions.

## B. Optimization Problem

**Objective.** The goal is to maximize the average energy efficiency of the network by placing as few gateways as possible. Thus, the objective function $F$ to be maximized can be expressed as follows:

$$F = \frac{1}{N}\sum_{i=1}^{N}(EE_i) - \alpha\frac{1}{M}\sum_{j=1}^{M}y_j, \tag{1}$$

where, $EE_i$ denotes the energy efficiency of the $i$th ED, and is given by:

$$EE_i = \frac{\pi_i}{e_i}, \tag{2}$$

where, $\pi_i$ and $e_i$ are, respectively, the PDR and the per-packet energy consumption of the $i$th ED. The second term in (1) is used to impose a cost for using gateways. Without it, the optimal solution will have gateways installed in all potential locations. The binary variables $y_j$ indicate the location of installed gateways, *i.e.*, if a gateway is installed at location $1 \leq j \leq M$, then $y_j$ is set to 1, and 0 otherwise. The coefficient $\alpha$ is used to determine the trade-off between the number of installed gateways and the energy efficiency. It can be used to control the importance of energy efficiency over the cost of installing more gateways.

**Constraints.** The PDR of ED $i$ is given by the following expression:

$$\pi_i = 1 - \prod_{j=1}^{M}(1 - \pi_i^j), \tag{3}$$

where, $\pi_i^j$ is the probability that ED $i$ has a successful transmission to gateway $j$. The RHS of (3) is the probability of successfully transmitting to at least one gateway.

The energy consumed for transmitting one packet depends on the transmission power $p_i$ used by the ED, as well as its packet transmission time $t_i$:

$$e_i = p_i \times t_i\,. \tag{4}$$

In order for an ED to have a successful transmission to a gateway, two conditions must be satisfied: 1) the ED must be within the communication range of the gateway, and 2) there must not be any colliding packets at the gateway during its transmission. These conditions can be combined to calculate $\pi_i^j$ as:

$$\pi_i^j = C_i^j \times e^{-2\lambda_i^j}, \tag{5}$$

where, $C_i^j$ is a binary variable that specifies if ED $i$ is within the communication range of gateway $j$, and $\lambda_i^j$ is the traffic load on gateway $j$ that can cause collisions for ED $i$. The exponential term in this relation is the standard packet reception probability in ALOHA-based networks [22]. In the following, we will show how $C_i^j$ and $\lambda_i^j$ can be calculated.

In order to calculate $C_i^j$, we note that an ED is within the communication range of a gateway if the gateway is active and the ED's received power at the gateway is higher than the minimum required RSSI. Therefore, $C_i^j$ can be calculated as:

$$C_i^j = \begin{cases} 1, & \text{if } p_i y_j L_{ij} > \sum_{k=1}^{4} s_i^k \cdot RSSI_k \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where, $L_{ij}$ is the path loss between ED $i$ and gateway $j$, $s_i^k$s are binary decision variables that specify if ED $i$ uses the $k$th SF, and $RSSI_k$ is the minimum required received power at a gateway for successful decoding of a packet that uses SF $k$[1]. Since an ED can only use one SF, the following constraint needs to be added to the optimization problem:

$$\sum_{k=1}^{4} s_i^k = 1\,. \tag{7}$$

The traffic on gateway $j$ that causes collisions for ED $i$, denoted as $\lambda_i^j$, depends on the number of EDs transmitting to gateway $j$ that use the same SF as ED $i$. We denote this number by $N_i^j$. Then $\lambda_i^j$ can be calculated as:

$$\lambda_i^j = \frac{N_i^j t_i}{T}, \tag{8}$$

where, $t_i$ is the packet air time of ED $i$ and $T$ is the packet inter-arrival time. Note that $t_i$ is also equal to the packet air time of all EDs using the same SF as ED $i$. Consequently, $N_i^j$ can be computed as follows:

$$N_i^j = \sum_{l=1}^{N} C_l^j \sum_{k=1}^{4} s_i^k s_l^k\,. \tag{9}$$

In (9), we count the number of EDs that are connected to gateway $j$ and use the same SF as ED $i$, since only these EDs can cause collisions for ED $i$.

LoRa operates on ISM unlicensed band, which has strict restrictions on EDs' transmission power. These power restrictions are set by regional regulators. We assume a continuous power model, and require power levels to be below the maximum allowed power $P_{max}$:

$$0 < p_i < P_{max}, \qquad i = 1, \ldots, N\,. \tag{10}$$

**Optimization problem.** We can now write the planning problem as the following optimization problem:

$$\begin{aligned} \text{Maximize} \quad & F = \frac{1}{N}\sum_{i=1}^{N}(EE_i) - \alpha\frac{1}{M}\sum_{j=1}^{M} y_j \\ \text{s.t.} \quad & \sum_{k=1}^{4} s_i^k = 1 \\ & 0 < p_i < P_{max} \quad i = 1, \ldots, N \\ & s_i^k \in \{0,1\} \quad i = 1, \ldots, N; k = 1, \ldots, 4 \\ & y_j \in \{0,1\} \quad j = 1, \ldots, M \end{aligned} \tag{11}$$

where, $EE_i$'s are computed using (1) to (9). The above optimization problem belongs to the family of mixed-integer non-linear problems (MINLPs), which are generally NP-Hard to solve optimally. In the following sections, we use the structural properties of the network to design an approximate solution for the problem that can be applied to large-scale network.

## IV. Multiple Gateway ALOHA Network

Consider a regularly-structured linear network where gateways are placed at fixed distances from each other, and EDs are located uniformly on the line between gateways. This structure is quite simple yet allows us to analyze the effect of multiple gateway access in ALOHA-based networks. The network structure is depicted in Fig. 2. EDs broadcast their messages, and as long as at least one gateway receives a message then that message is considered successfully delivered. The goal is to study the effect of communicating with multiple gateways on the network performance. For simplicity of the analysis, we assume the network stretches to infinity on both sides. This assumption is valid when a large number of gateways and EDs are present in the network, which is typical in large-scale IoT deployments.



Fig. 2: A regularly-structured linear network. The red circles indicate the gateways.

In a single-gateway access mechanism, each ED only communicates with its closest gateway. As a result, the network can be seen as individual deployments of single gateways and their surrounding EDs, as in Fig. 3. In this scenario, the EDs are only connected to one gateway, which means that an ED experiences collisions only from other EDs connected to the same gateway.

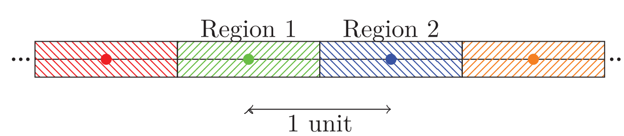



Fig. 3: Single-gateway access in the linear network. Regions indicate the EDs that communicate with the same gateway.

In this case, as the network has a repeated structure, the average PDR is equal to the PDR of each region. Since

[1] We use the mapping SF1 = 7, SF2 = 8, SF3 = 9, and SF4 = 10.

the EDs are assumed to follow an ALOHA channel access mechanism, the PDR in each region can be calculated as:

$$\Pi_s = e^{-2\lambda}, \quad (12)$$

where $\lambda$ is the packet load generated by EDs in a region with length 1 unit. The throughput of the system $\tau_s$, defined as the amount of traffic that is successfully received by the network server can then be calculated as

$$\tau_s = \lambda \cdot \Pi_s\,. \quad (13)$$

We now extend our analysis into a multiple-gateway access mechanism. In this scenario, the EDs increase their transmission power such that a fraction $\rho$ of them can be heard not only by their closest gateway, but also by the second closest gateway. This scenario is depicted in Fig. 4.

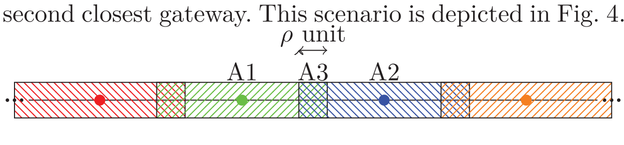



Fig. 4: Linear regular network with multiple-gateway access. The EDs in A1 and A2 are only heard by a single gateway, while EDs in A3 are heard by 2 gateways.

In the following, we show that in this scenario, the average PDR is given by,

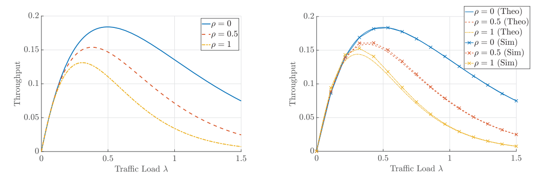
$$\Pi_m = (1+\rho)e^{-2(1+\rho)\lambda} - \rho e^{-2(2+\rho)\lambda}\,. \quad (14)$$

Since the network has a regular structure, it suffices to calculate the average PDR in one of the repeated sections. Consider the section made up of A1 and A3 regions. The PDR in A1 is $e^{-2(1+\rho)\lambda}$, since EDs in this region can only be heard by 1 gateway, and the load on this gateway is $(1+\rho)\lambda$. By applying the inclusion-exclusion principle, the PDR in A3 is equal to $2 \times e^{-2(1+\rho)\lambda} - e^{-2(1+2\rho)\lambda}$. Since $1-\rho$ fraction of EDs are in A1 and $\rho$ fraction of EDs are in A3, the average PDR will be $(1-\rho)e^{-2(1+\rho)\lambda} + \rho(2 \times e^{-2(1+\rho)\lambda} - e^{-2(1+2\rho)\lambda})$, which can be simplified to (14). The throughput of the system in this scenario, denoted by $\tau_m$, is then given by,

$$\tau_m = \lambda \times \Pi_m\,. \quad (15)$$

Note that for $\rho = 0$, the throughput in the multiple-gateway scenario is the same as that in the single-gateway scenario. The throughput of the system for different values of $\rho$ is shown in Fig. 5(a). It can be seen that the throughput keeps decreasing as more and more EDs attempt to access multiple gateways. The same behaviour is observed in a 2D regular network as well, where gateways are located on a 2D grid extending in both directions and end devices uniformly located in the area. Fig. 5(b) shows theoretical and simulation results for the case when the network extends in 2 dimensions. In this case, the PDR is theoretically calculated as:

$$\Pi_m^{2D} = (1+\rho)e^{-2(1+\rho)\lambda} - \rho e^{-2(2+1.5\rho)\lambda}\,. \quad (16)$$




(a) Linear repeated network. (b) 2D regular network.

Fig. 5: Throughput in regular networks with multiple gateway access.

The observations in this section shed light on a very important point: In a large-scale network where the distribution of EDs is uniform around gateways, having EDs attempt to communicate with multiple gateways only degrades the overall network performance. Hence, in an optimal planning solution, the EDs must be configured in such a way that they are able to communicate only with their closest gateway.

## V. Proposed Algorithm

In the previous section, we showed that for a regularly-structured network, the overall performance of the network degrades if some EDs attempt to communicate with multiple gateways by increasing their transmission power. In the context of our problem, recall that the transmission powers are the deciding factor that determine which gateways an ED can communicate with. This implies that, in an optimal solution, the transmission power of an ED depends only on its distance from its closest gateway and the SF used by it. This reduces the number of decision variables to only the gateway locations and the SF assignments for EDs.

We use the term *cell* to imply a set of EDs that are connected to the same gateway. In other words, each gateway in the network forms a cell in which all EDs are closer to that gateway than any other gateway. The problem now consists of two sub-problems: 1) finding a set of locations to install gateways 2) assigning SFs to all EDs in each resulting cell. In order to find the optimal solution, these two problems need to be solved jointly in a search space of size $2^M \times 4^N$. So, using an exhaustive search to find the globally optimum solution is not possible in reasonable time. Therefore, we rely on heuristics to find an approximate solution. First, we describe an approach for optimal SF assignment in an individual cell, then we apply a greedy approach to install gateways and configure EDs in the network.

### A. Spreading Factor Assignment

First, we describe how the ADR mechanism assigns SFs and transmission powers to EDs around a gateway, and then propose an unconstrained version of the problem for which we can find an optimal solution. Then we introduce a final strategy that tries to achieve close-to-optimal results by modifying the solution of the unconstrained problem.

**ADR**: In the ADR strategy, each ED uses the minimum possible SF and transmission power that allows it to communicate with the closest gateway without violating the power constraints. We assume if the gateway cannot be reached even with the highest SF, then the ED will transmit to the gateway by violating the maximum power constraint. As a result, all EDs that are located within a certain distance from a gateway will end up having similar SFs. The power constraint violations in this case will be minimal, since the EDs that violate the constraints are only those that are so far from the gateway that they cannot communicate with it even using the highest SF.

We now describe an SF assignment strategy that results in optimal performance in a single LoRa cell. The objective is to maximize the minimum PDR of EDs in the cell. Thus, the objective can be expressed as,

$$\text{Maximize } \min_{d}(\pi_d), \tag{17}$$

where $\pi_d$ denotes the PDR of ED $d$ inside the cell. Recall that only EDs with the same SF cause collisions for each other, therefore the PDR will be the same for all EDs that have similar SFs. As a result, the objective can be written as,

$$\text{Maximize } \min_{k}(\Pi_k), \tag{18}$$

where $\Pi_k$ denotes the PDR of EDs that use SF $k$. Subsequently, $\Pi_k$ can be calculated as:

$$\Pi_k = e^{-2\frac{N_k t_k}{T}}, \tag{19}$$

where $N_k$ is the number of EDs in the cell that use SF $k$, and $t_k$ is the air time of a packet when using SF $k$.

**Theorem 1.** *An optimal solution to* (18) *results in the same PDR value for all* $\Pi_k$*,* $k = 1, 2, 3, 4$*.*

*Proof.* By contradiction: Without loss of generality, assume that in the optimal solution, $\Pi_1$ has the lowest value and $\Pi_2$ has a higher value. Then we can increase $\Pi_1$ by reducing $N_1$ and increasing $N_2$, resulting in a higher objective value. So in an optimal solution, all $\Pi_k$s must have the same value. □

Based on (19), similar values for $\Pi_k$ can be achieved if $N_k t_k$ is the same for all $k$. In other words, the number of EDs that use SF $k$ must be proportional to the inverse of the packet air time $t_k$. If we denote by $N_c$ the number of EDs in the cell, we need to have:

$$N_k = \frac{N_c}{t_k \sum_{k=1}^{4} \frac{1}{t_k}}\,. \tag{20}$$

Therefore, to achieve an optimal SF assignment in each cell, the number of EDs that use each SF must be calculated from (20). In order to minimize the power consumption of EDs, the SFs are assigned based on the distance of EDs from the gateway, i.e. lower SFs are assigned to closer EDs, and further EDs end up with the higher SFs. We will denoted this SF assignment strategy as **EquiP**, as it results in equal PDRs for all EDs in a cell. While the EquiP strategy results in an optimal solution in terms of PDR, it does not take into account the constraints on transmission power, and is likely to result in a solution with more constraint violations than ADR.

In order to have a solution with minimal constraint violations, we propose a **Hybrid** strategy that works as follows: First, we start with the solution given by EquiP, then go through EDs that violate the power constraint and assign to them the minimum possible SF that resolves the violation. This approach takes advantage of EquiP's optimal configuration, and at the same time, resolves as many violations as possible, resulting in a violation level as low as that of ADR.

### B. Greedy Gateway Placement

Now that the optimal assignment of SFs inside a single cell is determined, we need to decide on the locations to install gateways such that maximum performance is achieved. While for small values of $M$ it might be feasible to check all possible combinations of gateway placement, the problem becomes intractable when $M$ becomes large. We propose to follow a greedy approach that iteratively installs gateways, choosing the location that results in the best performance in every iteration.

Algorithm 1 outlines the steps of this heuristic. We start with an empty set of installed gateways. Then, we hypothetically install gateways at available locations one at a time, and assigning SFs and transmission powers using the method described in Subsection V-A. Then we choose the location that results in the highest objective value and install a gateway there. This process is continued until all potential locations are filled. Finally, the desired number of gateways can be installed depending on the trade-off between cost and performance. The time complexity of the two nested loops is $O(M^2)$ and assigning SFs in each iteration takes at most $O(n \log n)$ for sorting the EDs by distance to gateways, resulting in a total time complexity of $O(m^2 n \log n)$ for the algorithm.

## VI. Performance Evaluation

In this section, we evaluate the performance of the algorithm proposed in Section V. We first demonstrate the SF assignment results achieved by each of the SF assignment strategies, showing how the Hybrid approach benefits from both ADR and EquiP strengths. Then, we compare several network performance metrics in different network scenarios when different configuration strategies are employed.

### A. Experiment Setup

A network of $N = 50000$ end devices is generated with an arbitrary distribution in an area of $50 \times 50\ km^2$. In order to mimic real-world scenarios, the concentration of end devices in the area is non-uniform, with some regions having a higher concentration of end devices than others. $M = 36$ potential gateway locations are distributed uniformly in

**Algorithm 1:** Greedy LoRa Planning

```
Input: M potential gateway locations, N ED locations
Output: Installed gateways = {}, SF assignments, power allocations
while there are empty locations do
    for j ← empty location indices do
        Add j to list of installed gateways.
        Assign SFs and powers and calculate the objective as F_new.
        if F_new ≥ F_old then
            next ← j
            F_old ← F_new
        Remove j from list of installed gateways.
    Add next to list of installed gateways.
    F_old = −∞
```

the area. For all end devices, the packet payload size is chosen as $PL = 50$ Bytes, resulting in different air times when different SFs are used (See Table II for packet air time values). A packet inter-arrival time of $T = 20$ minutes is used for all end devices. The propagation model is a log-distance path loss model with path loss exponent $\delta = 2.1$ and $P_{l0} = 130$ dB at the reference distance of $d_0 = 1000$ m, which is presented in [23]. Based on this propagation model, the transmission power of an end device $i$ that uses SF $k$ and located at distance $d_i$ from its closest gateway can be calculated as:

$$p_{i,dB} = RSSI_k + P_{l0} + 10\delta \log(\frac{d_i}{d_0}) \,. \tag{21}$$

The maximum coverage distances used in the ADR strategy for SF assignment can then be found as:

$$d_k^{MAX} = d_0 \times 10^{\frac{P_{Max,dB} - P_{l0} - RSSI_k}{10\delta}} , \tag{22}$$

where $d_k^{MAX}$ denotes the maximum distance where spreading factor $k$ can be used, $P_{Max,dB}$ is the maximum allowed transmission power, which is 23 dBm in North America, $RSSI_k$ is the minimum required RSSI level for decoding packets with SF $k$, and the rest of the variables are the propagation model parameters.

In our implementation, the minimum power level in the experiment is set to be 0 dBm. This will prevent end devices to show unusually high energy efficiency due to having very small transmission powers, caused by being very close to installed gateways.

TABLE II: Packet air times for different SFs.

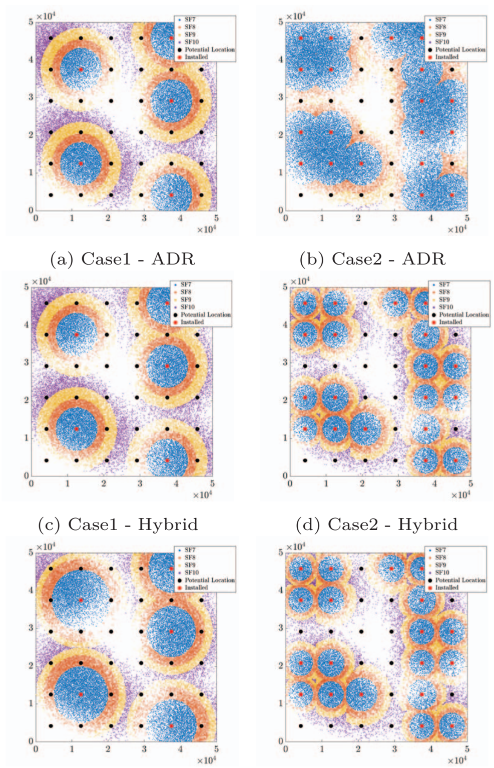
| SF | 7 | 8 | 9 | 10 |
|---|---|---|---|---|
| Air time (ms) | 98 | 175 | 329 | 616 |

### *B. Planning Results*

In order to demonstrate how the Hybrid approach tries to achieve the benefits of EquiP, while keeping the power constraint violations as low as when ADR is used, we will look at two cases that correspond to different iterations in the planning algorithm. In case 1, we consider the 5th iteration, where only 5 gateways are installed in the network, while in case 2, we look at the 20th iteration of the algorithm when many more gateways are installed. The planning results in these cases are shown in Fig. 6.

TABLE III: Parameters used in the experiment.

| Name | Value | Description |
|---|---|---|
| $N$ | 50000 | # of end devices |
| $L$ | 50 | Edge of analysis area (Km) |
| $M$ | 36 | # of potential locations |
| $PL$ | 50 | packet payload (Bytes) |
| $T$ | 1200 | inter-arrival time (s) |
| $\delta$ | 2.1 | path loss exponent |
| $L_0$ | 130 | reference path loss (dB) |
| $d_0$ | 1000 | reference distance (m) |
| $P_{Max,dB}$ | 23 | Maximum Power level (dBm) |



(a) Case1 - ADR (b) Case2 - ADR

(c) Case1 - Hybrid (d) Case2 - Hybrid

(e) Case1 - EquiP (f) Case2 - EquiP

Fig. 6: The planning results under different strategies with 5 and 20 installed gateways.

When only a few gateways are installed, as in case 1, EquiP causes a large fraction of end devices to violate the power constraint (note the large number of devices that are assigned the lowest SF in Fig 6(e), but are too far from their gateway). The ADR approach, on the other hand, results in a much lower number of violations. In this case, the solution achieved by the Hybrid approach is quite

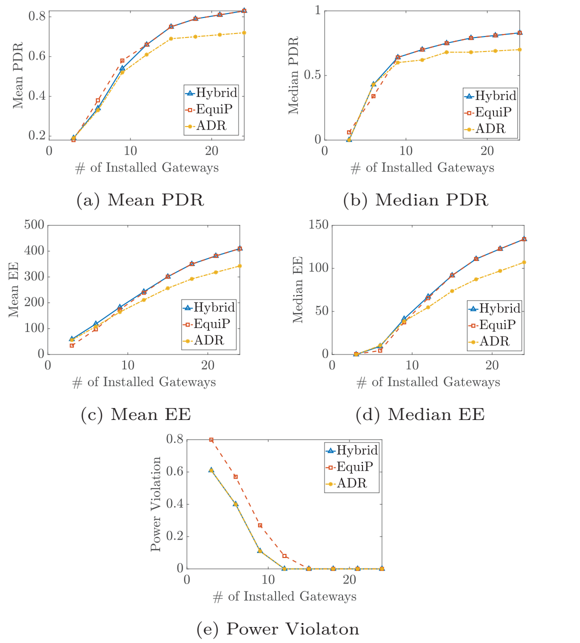



Fig. 7: Comparison of performance metrics achieved by the strategies with different number of installed gateways.

similar to that found by the ADR approach, with minimal constraint violations. When many gateways are installed, as in case 2, the ADR strategy will assign the same SF to a lot of end devices, which greatly reduces the PDR, as some SFs are overused, and some are underused (See Fig. 6(b)). The EquiP and Hybrid strategy, however, result in a solution with a higher PDR without violating any constraints. This analysis demonstrates how the Hybrid approach adapts to different situations and results in the benefits achieved by both strategies.

### *C. Performance Comparison*

We now consider different performance metrics of the network and track them in different iterations of the algorithm under different assignment strategies. The considered metrics are 1)Average energy efficiency, 2) Average PDR, 3)Median of energy efficiency, 4)Median of PDR, and 5)Power violation[2]. Fig. 7 presents a comparison of these performance metrics in different iterations of the algorithm if different strategies were to be used for end device configuration in that iteration. It can be seen that the Hybrid strategy outperforms the ADR strategy in all iterations, and shows a level of performance as high as the EquiP strategy in most iterations. For instance, when half of the gateways are installed, using the Hybrid approach increases the average PDR of the network by about 15%, and the average Energy Efficiency by about 20%. At the same time, the power violation in the Hybrid strategy is always as low as ADR, while the EquiP strategy always results in a higher power violation, which is at least 30%