Graph-Based Gateway Placement for Better Performance in LoRaWAN Deployments

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***Abstract*—Low Power Wide Area Networks with Long Range Wide Area Networks (LoRaWANs) as one of their most prominent representatives are very promising solutions for future Internet of Things deployments. The technology is characterized by low energy requirements leading to long battery lifetimes. However, the drawback is very limited throughput rates. However, the unreliable nature of the LoRa technology is hindering the adoption. Especially its random channel access approach leads to significant message collisions and thus, data loss in larger deployments.**

From a network planning point of view, one possibility to deal with collisions is the reduction of potentially colliding messages at the frequency bands in combination with limiting the transmission duration of messages. For that reason, we present a novel graph-based gateway placement approach. The main focus is collision probability reduction, which directly increases reliability in LoRaWAN deployments. We show that our approach performs similar to state-of-the-art related work in the worst case and reduces the required number of gateways by up to 40 % while reducing the collision probability by up to 70 %. Furthermore, we discuss the scalability of our approach to cover arbitrarily large networks with gateways and only little overhead by splitting the problem into smaller sub-problems.

***Index Terms*—Gateway Placement, Collision Probability, LoRaWAN, IoT**

I. INTRODUCTION

The increasing requirement for automation and data fosters the current development of Internet of Things (IoT) solutions. However, IoT is not only based on connecting sensors using existing WiFi or mobile communication solutions or by the sole usage of future 5G networks. In recent years, many other IoT access network technologies arose with different characteristics, advantages, but also challenges compared to already available networks. In particular, one interesting technology is the family of Low Power Wide Area Networks (LPWANs) with Long Range Wide Area Network (LoRaWAN) as one of their most prominent and fastest growing representatives.

The current LPWAN market size is assumed to be $ 12.81 B [1] with LoRaWAN making 36 % [2]. Especially in the smart metering segment, LPWANs have many use cases according to IoT analytics [2] and adoption is rapidly increasing. This leads to an expected annual growth for LPWAN solutions of 65 % and a projected market size of more than $ 650 B by 2028 [1]. Thus, it is important to study the potential of LoRaWAN and demonstrate current challenges. For that reason, many studies already discuss improvement potential compared to current deployments, guidelines, and standardization in literature.

LoRaWAN has advantages like low energy requirements, long possible transmission distances, and an in general robust communication against interference due to its exceptionally robust physical layer [3]. Nevertheless, it has one major challenge and drawback compared to traditional mobile communication: no guaranteed reliability in the network. The reason is a large potential for message collision and data loss because of the random frequency channel access for transmissions. In addition, to operate sensors several years without battery changes, the goal is to minimize the power consumption in LoRaWAN. For that reason, frequent retransmissions, message acknowledgments, or additional communication between sensors and gateways is limited.

However, from a network operator's point of view, it is important to deal with these limitations and guarantee specific service level agreements for customers. For that reason, different channel access strategies, parameter adjustments at the sensor level, or network planning ideas are currently investigated. The goal is to find possibilities to deal with message collisions. In particular, one idea is to use the collision probability in the complete LoRaWAN as one quality metric in the network planning and gateway placement phase [4].

In this work, we present a novel gateway placement approach for LoRaWANs based on a graph-based solution to provide full sensor coverage. We further discuss several placement constraints like the maximal distance between gateways and connected sensors or the maximal number of sensors connecting to a single gateway. We compare the expected collision probability achieved with our placement to related literature with a large simulation study for different scenarios. Furthermore, we study future network and placement scaling and gateway placement for increasingly large problem instances.

Thus, the contribution is the answers to the following three research questions: (1) does a graph-based gateway placement approach perform good results for LoRaWAN, which graph metrics are important, and which constraints during graph creation influence the overall collision probability in the network most, (2) is the graph-based approach generalizable for a multitude of different networks and is it possible to compete with state-of-the-art literature, and (3) what are the limits from a computational but also LoRaWAN technology perspective and is it possible to overcome these limits?

The remainder of this work is structured as follows. Section II presents fundamental background information on LoRa and LoRaWAN. Afterwards, in Section III related work is presented, followed by the methodology for graph creation, gateway placement, and the scenario overview in Section IV. In Section V the presented scenarios are evaluated and the research questions are answered. Finally, Section VI concludes this work.

II. BACKGROUND

This section presents fundamental background information, required to understand this work. Details about Long Range (LoRa) and LoRaWAN are given first, followed by important considerations regarding the quality of a LoRaWAN.

A. LoRa and LoRaWAN

The LPWAN modulation technique LoRa is based on the chirp spread spectrum and was developed by Cycleo, later acquired by Semtech in 2012 [5]. The key characteristics of LoRa include long transmission ranges of 2 km - 15 km, a battery lifetime of up to 10 years for sensor nodes, and low data rates [6]. This physical layer transmission technique is used by the LoRaWAN medium access control protocol. It operates at the license free 868 MHz frequencies in Europe. Although the simple and free to use idea of LoRaWAN has many advantages, one major drawback is the constant risk of message collision because of the random channel access scheme that is currently used [7]. In general, the maximal utilization in an ALOHA-like random channel access environment is 18.4 % [8]. However, the actual utilization is higher due to the robust physical layer [3].

A different approach to increase the channel utilization and, in particular, decrease the collision probability, is an intelligent channel management [9]. However, the collision probability, and thus data loss probability in LoRaWAN is directly correlated with the transmission duration of messages and the number of transmitted messages per time frame.

The transmission duration can be computed based on the total message length in symbols and time required to transmit a single symbol. Details about the message size, message creation, and influence of the payload on the overall message is given by many research groups in literature [10], [7], [11]. Thus, this is not presented in detail here.

The time to transmit a single symbol T_s is determined by $T_s = 2^{\mathrm{SF}}/\mathrm{BW}$ with SF as the Spreading Factor in the range of 7 - 12 and the bandwidth BW, typically 125 kHz in Europe. The collision probability for the same channel access methodology is in general increasing with more and longer messages on the channel. Furthermore, longer messages are generally achieved with more payload or larger SF values.

B. LoRaWAN Quality Metrics

Based on this consideration, different quality metrics for LoRaWAN can be inferred. The goal in this work is to optimize these metrics. Naturally, some goals may oppose each other, e.g. coverage and the required number of gateways. In this case, it is important to identify a suitable trade-off that enables reliable system operation.

Coverage: First and most important, coverage must be guaranteed to provide a high Quality of Service. There are two major ways to increase coverage in a LoRaWAN deployment: increase the possible transmission distance between sensors and gateways, or place additional gateways. The possible transmission distance of LoRa sensors is influenced by the sending strength and the used SF at the sensor side, the interference during transmission, and the antenna gain. The sending strength is highly correlated with sensor quality, battery lifetime, and other factors that can not be influenced by a LoRaWAN provider. Since the interference during transmission is influenced by, among others, location and existing development, only the SF can be actively adjusted and is thus of major interest. Here, the general idea is that larger SFs are more robust against interference and allow transmission across longer distances with the drawback of longer channel occupancy times. Thus, a trade-off between transmission distance and channel occupancy time must be determined.

Number of Gateways: Another parameter is the number of placed gateways as well as the quality of placement decisions. We show in [4] that increasing the number of gateways in combination with a good gateway placement can increase the potential number of sensors by a factor of 5 with an increase of gateways by a factor of 2.5 without increasing the collision probability. Thus, besides the cost aspect of additional gateways, the collision probability in growing networks must be taken into account. Furthermore, a more dense gateway placement makes LoRaWANs more robust against future load increase [4].

Collision Probability: Finally, the collision probability is a crucial quality factor in LoRaWAN. The collision probability depends on the number of sensors in one LoRaWAN cell, meaning the number of sensors transmitting to a single gateway and their transmission behavior by means of message sending rate, required time on air for messages, and transmission distance, and thus interference distance. Since the general transmission behavior of a single sensor is dependent on, among others, the specific sensor type, the use case, and configuration, it can not be modified in many situations. Thus, the collision probability can only be affected if the LoRaWAN cell size is changed. The cell size can be decreased with more gateways and vice versa. In addition, smaller cell sizes with more gateways have another positive effect. On average, it reduces the distance between gateways and sensors, which leads to a smaller required SF. Thus, the average message in a LoRaWAN requires less time on air which reduces the collision probability.

III. RELATED WORK

This work deals with network planing of LoRaWAN in general and gateway placement in particular. Specifically, we focus on reducing the collision probability. Thus, this section summarizes related literature with focus on these topics.

An early collision study with LoRa messages was done in 2017 [3]. The authors show that the robust physical layer of LoRa can reduce the collision probability compared to pure ALOHA. Further works study collisions and packet loss in more detail [12], use different channels and the quasi-orthogonality of different SFs [13], or develop mechanisms to decode multiple LoRa messages transmitted in parallel [14]. Others reduce the collision potential by different channel access mechanisms like Listen Before Talk [15], Slotted ALOHA [16] or scheduled MAC [10]. These approaches can perform well if the number of sensors transmitting to a single gateway is limited. This can be regulated by an appropriate gateway placement that limits the geographical area one gateway has to handle, as we discuss in this work.

The idea of demand based gateway placement dates back to mobile network studies in 1998 [17]. Since then, many researchers have studied placement approaches based on network load (e.g., [18], [19]). However, these approaches could only steer available load. In contrast, our approach directly influences the network load by adjustments on the average distance between sensors and gateways. Because of the adaptive data rate used in LoRaWAN, these distance changes directly influence the SF and thus, the transmission duration of LoRa messages.

In contrast, available LoRaWAN gateway placement approaches in literature follow in general the goal of gateway reduction for a given area or network. Matni uses k-

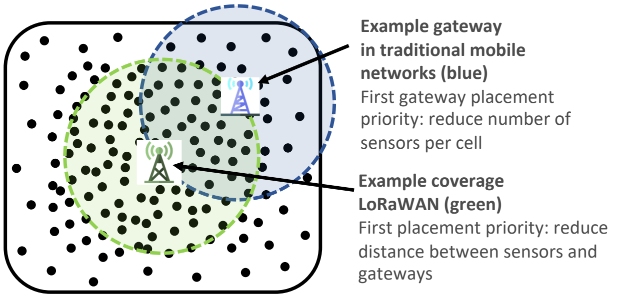

Figure 1: Comparison of placement decision effect in mobile networks and LoRaWAN

means and c-means approaches [20] while other clustering approaches are studied in [21]. Mnguni et al. study LoRaWAN gateway placement by simulating a network with FLoRa simulator [22]. They show a coverage potential of two gateways for a 10 km dense urban area. A comprehensive survey of this research area is conducted by Mnguni in [23]. A general tool to evaluate gateway placement in LoRaWAN is presented in [24]. Another approach is the usage of mixed-integer non-linear optimization by Ousat [25]. However, their approach only works for small networks.

The drawback of all LoRaWAN gateway placement approaches in literature is the focus on minimizing the number of gateways only. However, without taking the collision probability into consideration, a general high quality LoRaWAN can not be guaranteed. We overcome this limitation in [4], where we add the number of sensors per gateway and the maximal possible distance between sensor and gateway as constraints. Thus, we can reduce the collision probability in the network significantly. However, due to the used random gateway positioning behavior in the approach, there is still potential for placing a gateway at the edge of the network or a different number of gateways for different runs on the same network. Furthermore, long runtimes for the suggested ILP are not feasible for large network deployments and the ILP only provides optimal results based on the input constraints.

We solve these issues in this work by combining the benefits of a clustering and graph based approach, where gateways are placed in network centers, with high sensor density and further limit the placement with additional constraints to keep the expected collision probability in the network low.

IV. METHODOLOGY

In this section, the general methodology is discussed by introducing the placement idea first. Afterwards, all steps for describing a LoRaWAN as a graph are introduced, the usage of different constraints is highlighted, and the actual placement approach is presented. At the end, a simulation study on the collision probability in the resulting network is presented, and a scenario overview is given to compare different placements.

A. Placement Idea

In current LoRaWAN, each sensor is transmitting data using random channel access. Thus, the number of sensors in one cell and the channel occupancy time for each sensor are the most dominant factors influencing the collision probability, and thus the transmission quality. But the number of sensors and the transmitted payload are out of the control for network operators. The only possibility to reduce the collision probability is to manage the channel occupancy time via, for example, intelligent gateway placement. In traditional mobile networks, in current 4G networks, and also in current and future 5G deployments, a single transmission with the same payload of the same sensor located in a specific cell requires in general the same channel occupancy time. Specifically, this is independent on the distance to the gateway if the propagation delay is neglected. Thus, the number of sensors that can be covered by a single gateway is limited by available frequencies and the transmission behavior and rate of sensors. To visualize this behavior for a network with increasing traffic load, where a single gateway is not enough to cover all sensors, Figure 1 shows an example coverage for a gateway in a traditional mobile network in blue and LoRaWAN in green. All sensors are symbolized by black dots with more sensors to cover in the center of the network and less at the edge.

In a traditional network, it might be better to place a gateway at the edge of an area with many sensors and cover that dense area with multiple gateways around it. Additional gateways could be placed at the other edges of this example area. However, the situation is fundamentally different in LoRaWAN. Despite the available frequencies and the sensors' transmission behavior, the SF is influencing the required channel resources. Sensors transmitting with larger SFs can transmit across longer distances with the acceptance of a longer time on air for messages, and thus longer channel occupancy per transmission. For that reason, it is possible to reduce the required channel resources by reducing the average SF, and thus, the distance between senors and gateway for transmission.

Thus, it is better to place a gateway in the middle of a dense network part and avoid splitting these parts in separate cells, as indicated by the green circle in the figure. This reduces the average distance between sensor and gateway in the network and the average required SF. Therefore, our idea for an efficient gateway placement is the identification of dense parts in a LoRaWAN first, and place the gateways at suitable locations in these dense areas afterwards.

B. LoRaWAN Network Creation and Gateway Placement

The network creation and gateway placement approach in this work contains five steps. It is introduced in the following, starting with the establishment of sensor locations and ending with the fully planned LoRaWAN, including gateway locations. A step by step visualization of this approach is presented in Figure 2. The source code for all scenarios is available at Github[1]

Step 1: Sensor Locations*:* To represent a real world LoRaWAN, possible locations for sensors in the network must be determined. Therefore, we derive the centroids of buildings of different real cities from OpenStreetMap similarly to [4]. For each building, we obtain an x- and y-coordinate, augment it with an ID, and use the resulting object to represent a single sensor. Each sensor is a potential gateway during the following gateway placement.

This approach has two benefits to display more realistic scenarios. First, more dense populated regions receive more

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[1] https://github.com/lsinfo3/lora_graph_gw

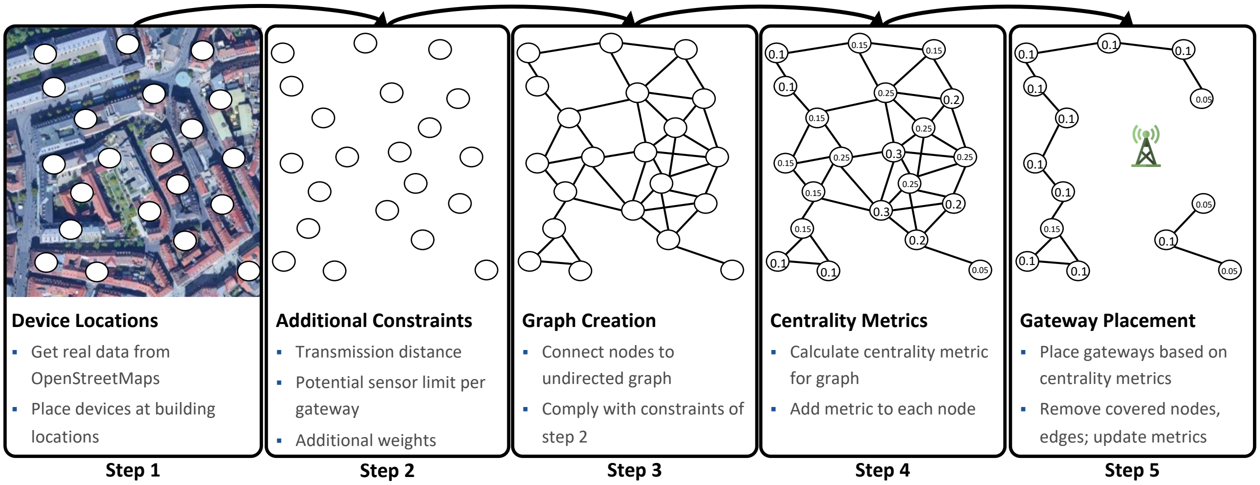

Figure 2: Overview of graph creation and gateway placement process

sensors and second, the placement is not optimized for synthetic, evenly distributed scenarios but for different real city deployments. However, please note that a mapping of sensors to other entities like trees, specific buildings, or other infrastructure is also possible.

Step 2: Placement Constraints: Placement constraints are important to first, achieve a valid placement and second, improve the achieved result. Therefore, we define three constraint classes: class 1 must be satisfied. The only class 1 constraint in this work is coverage of all sensors. Class 2 constraints are variable parameters in this work with the goal of reducing the collision probability in the LoRaWAN with the minimum possible number of gateways. Class 2 constraints are the gateway range and the number of sensors a gateway can process. Last, class 3 constraints are additional information in the network like transmission characteristics of specific sensors, sensor importance, or message importance. These constraints and their influence on the overall results are briefly presented and discussed at the end of the evaluation.

The gateway range is influencing the used SF and is one of the most important constraints in this work. For that reason, it is described in detail in the following. It is achieved by calculating the possible transmission distance of sensors.

Possible Transmission Distance: In particular, the possible transmission distance is, due to the technical relation of transmission distance and SF, a major contributor to the collision probability. In this work, we determine the possible transmission distance d of a gateway with the urban version of the Hata propagation model [26], [27]. Hence, we compute the transmission distance as

$$d = 10^{\frac{(-(69.55+26.16log_{10}(f)-13.82\cdot\log_{10}(h_G)-a(h_{\mathrm{T}})-\mathrm{PL})}{(44.9-6.55\cdot\log_{10}(h_G))}} \tag{1}$$

for f =868 MHz with

$$a(h_{\mathrm{T}}) = 3.2\cdot(log_{10}(11.75\cdot h_D)^2) - 4.97 \tag{2}$$

and h_G as gateway height, h_D as sensor height, and PL as maximum tolerable path loss for the connection. Thus, since larger SFs tolerate higher path loss, or in particular require a lower Received Signal Strength Indication (RSSI) limitation according to Table I, longer transmission distances are possible. The tolerable path loss is further dependent on the sensor sending strength and the antenna sensitivity. For our study, we use a SX1276 sensor [28] as reference with an antenna gain of +8 dBm that can generally be achieved by many common gateways [29]. The gateway height is set to 15 m and the sensor height to 1 m.

Table I: RSSI and transmission distance for different SFs

SF	RSSI	Distance	SF	RSSI	Distance
SF 7	-131 dBm	973.63 m	SF 10	-140 dBm	1,699.62 m
SF 8	-134 dBm	1,172.32 m	SF 11	-141 dBm	1,808.16 m
SF 9	-137 dBm	1,411.56 m	SF 12	-144 dBm	2,177.15 m

Step 3: LoRaWAN Graph Creation: In the graph creation procedure, the first step is to express all sensors and gateways as nodes N_i while the complete set of nodes in the LoRaWAN is expressed as N_{all}. Each node $N_i \in N_{\mathrm{all}}$ has an x- and y-coordinate to determine its location. Afterwards, for all pairs of nodes $(N_i, N_j) \in N_{\mathrm{all}} \times N_{\mathrm{all}}$, an edge E_{ij} connecting N_i and N_j is added if N_i is within reach of a LoRa transmission from N_j and vice versa. Thus, we can express the LoRaWAN as an undirected, unweighted or weighted graph. The requirement of an undirected graph is important to ensure the possibility of bidirectional transmissions. The graph can be unweighted if each sensor has the same behavior, importance, or transmission characteristics or weighted if additional characteristics are included in the gateway placement decisions.

Step 4: Graph Centrality Calculation: The result of the graph creation is not necessarily a connected graph, for example if at least one sensor that is out of range of all other sensors exists. Next, it is important to determine good locations to place gateways. As discussed in Section IV-A, for LoRaWAN specifically, dense network parts should be preferred to place gateways if other placement constraints can be met.

Therefore, we calculate the degree centrality $C_D(N_i)$ for all nodes $N_i \in N_{\mathrm{all}}$ with

$$C_D(N_i) = \frac{Deg(N_i)}{N_{\mathrm{all}} - 1} \tag{3}$$

according to [30]. The betweenness centrality $C_B(N_i)$ for node N_i refers to the contribution of a node $N_i \in N_{\mathrm{all}}$ to all shortest paths from node $N_s \in N_{\text{all}}$ to node $N_t \in N_{\text{all}}$ in the entire network [31]. It is achieved by

$$C_B(N_i) = \sum_{N_s \neq N_i \neq N_t} \frac{\sigma_{N_s} N_t(N_i)}{\sigma_{N_s} N_t} \tag{4}$$

The term $\sigma_{N_s} N_t$ refers to the total number of shortest paths between node N_s and node N_t and $\sigma_{N_s} N_t(N_i)$ as the number of shortest paths between node N_s and node N_t containing node N_i.

Both, the degree centrality and the betweenness centrality show good results to describe node centrality in literature [30] and are therefore considered as gateway placement metrics.

Step 5: LoRaWAN Gateway Placement: The input for gateway placement is a LoRaWAN in graph representation as defined in step 3 and the calculated graph metrics from step 4.

Gateway Selection: The node with the highest metric is selected as next gateway. If several nodes have the same maximal remaining weight, the node with the lowest ID is chosen. However, we observed that random selection does not change result quality. Furthermore, choosing the first node makes the algorithm repeatable and reproducible.

Graph Update: Afterwards, the gateway node and all sensor nodes that are covered by this new gateway based on the constraints defined in step 2 as well as all edges that connect to at least one of these nodes are removed from the graph.

Metric Update: When all covered nodes are removed and no more nodes are available, the algorithm terminates with a valid placement. Otherwise, the graph metrics of the remaining graph are updated and the placement algorithm continues with the next gateway selection.

C. Scenario Definition

In the scenario definition, a general assessment of both graph metrics usable for the placement is done first. Afterwards, detailed scenarios with different constraints are defined to optimize and study gateway placement decisions based on the presented graph creation. The quality of the achieved placement is determined by the achieved collision probability in the network and the number of required gateways. Therefore, we describe the required parameters in this work in the following, starting with the used sensor locations.

Sensor Locations: Different sensor location sets in different cities are chosen for the gateway placement. First, 10,000 sensors in Würzburg, Germany are selected randomly from a set of 28,000 sensors as presented in [4] as baseline. It is used to study the general performance of different graph metrics and parameters. We see, similar to the reference work, that the randomness of sensor selection has no influence on the result. Thus, it is not studied hereafter.

In addition, seven sensor sets for different global cities are studied to analyze the usability of the approach in other, differently urbanized areas. An overview of all cities is given in Table II. Furthermore, different city sizes, districts, and urbanization is chosen during city selection. Please note that for Bangkok and Manhattan, only 50 % of the available buildings are randomly used as sensor locations and for San Francisco, only 33 % of all buildings are used to limit the size of the networks and study differently sized large deployments.

Table II: Device locations

City	**Country**	**District**	**Number sensors**	**Nodes per km^2**
Würzburg	Germany	complete city	10,000	114
London	UK	City of London	1,959	412
Munich	Germany	Schwabing-West	3,094	489
Shanghai	China	Pudong	17,210	5.8
Sydney	Australia	City of Sydney	1,058	193.1
Bangkok	Thailand	complete city	14,443	4.7
New York City	USA	Manhattan	11,521	46.2
San Francisco	USA	complete city	20,048	19.2

Parameter Overview: The used simulation parameters are in accordance with default LoRaWAN parameters from standardization. In addition, the following parameter settings are chosen: enabled header, enabled low data rate optimization for SF 11 and SF 12 and disabled low data rate optimization for smaller SFs, a coding rate of 4/5, and 16 B payload. This is used to obtain reproducible results and to isolate the impact of placement decisions on the observed collision probabilities. With the simulation approach presented in [4], each sensor creates one packet randomly per hour for a duration of 100 h for each scenario run. This setting allows to minimize the influence of randomly created packets on the collision probability. The very lightweight simulation approach is written in Python. It generates much less overhead in contrast to more general LoRa simulators like FLoRa [32] or different ns-3 [33], [34], or SimPy [35] based simulators. The used simulation approach is based on the following three steps:

Step 1: First, each sensor receives a SF it transmits all messages with. Therefore, the distance between the sensor and the closest gateway is determined. Based on this distance the used SF is achieved with the Hata model according to Table I.

Step 2: Next, a potential collision list is created for each sensor. Therefore, all other sensors in its potential collision radius are added with the respective SF. The collision radius for a sensor k is calculated according to [4] and it includes (1) all sensors where k is in their direct transmission radius with their specific SFs according to Table I, (2) all sensors transmitting to the same gateway as k, and (3) all sensors where the transmission radius is intersected by the direct line of sight transmission from k to the closest gateway from k.

Step 3: Last, the actual collision simulation is performed individually for each sensor. In this step, a random transmission start timestamp between 0 s and 3,600 s is calculated for the sensor itself and all other sensors in its collision radius. This is valid for a sufficiently large number of sensors according to [36]. With the payload of 16 B and each individual SF, all time on airs for all sensors in range can be calculated and thus, the end time of each transmission. If one transmission overlaps in time with the transmission of this specific sensor, a collision occurs. This simulation is repeated 100 times for each sensor which is equal to 100 h of simulation. This collision probability calculation is in accordance with [4] to also compare the general placement approaches. Please note that overlapping transmission intervals always lead to collisions, independent on the used SF. We did not include potential quasi-orthogonality of SFs. Thus, this study can be

Table III: Scenario overview

Scenario	Gateway range	Number sensors	Research goal
S 1	300 m - 2,600 m stepsize 50 m	1,000	Achieve optimal sensor to gateway distance limit
S 2	2,177.15 m	300 - 3,000 stepsize 50	Achieve optimal sensor per gateway limit
S 3	according to best performance	750	Study approach for different locations and compare to related work
S 4	different settings	1,000	Study different transmission patterns for load increase
S 5	2,177.15 m	1,000	Placement for large deployments

seen as worst case investigation.

Pre-Study - Centrality Metrics: To identify the usability of the betweenness centrality and the degree centrality as reasonable metrics for gateway placement, we define a test scenario with the subset of 10,000 sensors in Würzburg, Germany. The constraints for a valid placement are the coverage of all sensors, the maximal transmission distance achieved with the Hata model and SF 12 for the sensors, and a limit of 1,000 sensors per gateway. Results using betweenness centrality and degree centrality to select gateways are compared.

The placement approach places 15 gateways for the degree centrality approach and 16 gateways for the betweenness centrality approach. The degree centrality approach results in a mean collision probability of 3.67 % for 100 simulation repetitions with values ranging from 2.93 % to 4.36 %. The betweenness centrality approach shows a mean collision probability of 3.99 % with a minimum of 3.33 % and a maximum of 4.62 %. Furthermore, the complexity to calculate betweenness centrality is $O(n^3)$ for dense networks [37] with n as the number of nodes in the network, compared to $O(n^2)$ for the degree centrality. For that reason, the degree centrality is chosen as graph metric for further evaluation.

Scenario Overview: The five scenarios defined in this work are summarized in Table III. Each scenario is designed to answer one question, listed in the following.

Scenario S 1: What is the optimal sensor to gateway distance limit used as a constraint in a LoRaWAN gateway placement?

Scenario S 2: What is the optimal number of maximum sensors covered per gateway during graph creation and does this limitation influence the collision probability?

Scenario S 3: How does the presented approach perform in different environments and in comparison to related work?

Scenario S 4: How much is the performance influenced by different network load, in particular by changing payloads and transmission rates?

Scenario S 5: Is it possible to overcome computational limits by splitting the network into multiple smaller networks and perform a gateway placement without much overhead?

V. EVALUATION

This section summarizes the results conducted during the scenario studies defined above. Each scenario is tackled in detail in the following, starting with scenario S 1.

A. Scenario S 1: Distance between Sensor and Gateway

The first scenario S 1 studies the optimal distance between sensors and gateways since larger sensor to gateway distances require larger SFs. This leads to a higher collision probability because of a larger time on air for each message.

Spreading Factor: The first investigation is the SF usage based on the set distance limit to the next gateway. Figure 3 shows the result as the percentage of sensors using a specific SF on the y-axis based on the distance limit between sensor and gateway on the x-axis. The colors indicate the different SFs. The vertical dashed white lines show the distance limits for the usage of different SFs with SF 7 on the lower end and up to 973.63 m, and SF 12 to the right with up to 2,177.15 m. Table I shows the exact values for all SFs. Please note that the study is conducted up to 2,600 m, which is outside the reach of a sensor transmitting with SF 12. This setting is chosen to study larger maximal distances in graph creation and can influence the graph centrality metrics and thus the final placement of gateways. However, the final gateway placement guarantees a maximal distance from every sensor to the next gateway of 2,177.15 m, so that it can transmit data with SF 12. For that reason, the coverage constraint is still fulfilled.

The figure shows more larger SFs shortly before each dashed line and more smaller SFs again afterwards. This is especially visible before the third and the last dashed line. Since the goal is to minimize the usage of larger SFs, it is thus not advisable to perform a gateway planning with the exact distance limits of a single SF. This is especially visible for SF 12 and the last dashed line. There, a distance limitation of 2,200 m performs much better than 2,150 m, although the distance limit to transmit data with SF 12 is 2,177.15 m. In this case, the *coverage*-constraint in combination with a distance limitation of 2,200 m gives the placement more flexibility than the hard distance constraint alone.

Collision Probability: Similar results are achieved when the average collision probability in Figure 4 is studied. The brown line shows the collision probability on the left y-axis, based on the maximal allowed distance between sensor and gateway on the x-axis. The shaded area around the line indicates the minimal and maximal collision probability observed for all 100 runs. This visualization is chosen since even the 99 % confidence interval is very narrow and hence not visible. However, this lead us to the conclusion that visible collision probability differences presented by the brown line are statistically significant with a 99 % confidence. The yellow line presents the number of required gateways on the right y-axis for different distances shown on the x-axis. The dashed black lines again indicate the SF-distance limits.

The brown line shows an average collision probability of less than 5 % when the distance is below 1,150 m. This is equal to a maximal SF of 7 or 8. An increase in collision probability is visible for larger distances, and in particular larger required SFs. However, shortly before the maximal distance is equal to the next SF-distance limit, an increase in collision probability is visible and shortly after it, a decrease is detected. This is explained by the SF distribution already discussed in Figure 3. Furthermore, we see a drop in collision probability for distances larger than 2,500 m. However, distance limits larger than 2,100 m are not advisable because of a large increase in collision probability. The best results are detected with maximal distances smaller than 1,150 m, which is equal to a usage of SF 7 or SF 8 as maximum.

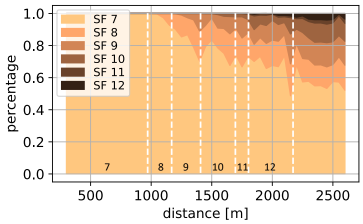

Figure 3: SF distribution for different distance to gateway settings

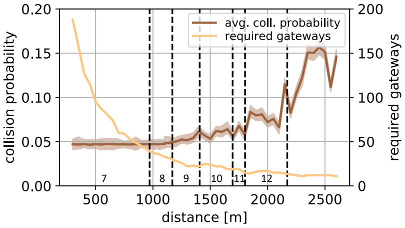

Figure 4: Collision probability and required number gateways for different possible distances

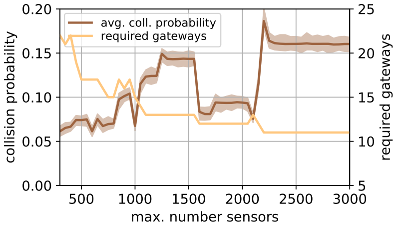

Figure 5: Collision probability and required number gateways for different possible distances

Number of Gateways: Furthermore, the number of required gateways for different distances is shown by the yellow line and the right y-axis of Figure 4. As expected, the number of gateways is decreasing with increasing distance between sensor and gateway. However, it is visible that the gradient of the yellow line is decreasing with larger distances. Especially, only a small gradient is visible for more than 1,300 m. Between 1,400 m and 1,500 m, it is even increasing again. Thus, we see a good trade-off between the number of gateways and collision probability between 1,000 m and 1,400 m, and thus when SF 8 or SF 9 is used as maximal SF.

Additional Performance Metrics: In addition, other performance metrics can be evaluated with respect to placement quality. To avoid covering very dense areas with only a single gateway and therefore increase the collision probability, we set the number of sensors per gateway in the graph creation phase to 1,000. Pre-studies show that this is a good reference value and saves much performance, however other values or unlimited number of sensors work accordingly. For that reason, each node in the graph can have a maximum of 1,000 edges to other nodes. However, because of different network densities, this does not necessarily mean that a maximum of 1,000 sensors connect to single gateways. If more than 1,000 nodes are in a dense area of the network and the middle node becomes the new gateway, the most far nodes of that dense network area have no edge to the gateway in the graph. However, since sensors always connect to the closest gateway, more than 1,000 sensors can connect to single gateways if no other gateway is closer. Thus, another performance metric is the load distribution and thus, the number of sensors single gateways must cover.

For scenario S 1 and 300 m or 350 m distance between sensor and gateway, the results show that no gateway covers more than 4.3 % of all available sensors. Up to 750 m, the limit is 12.3 % or 1,226 sensors in total. The average number of sensors per gateway is for 850 m to 1,250 m distance easy to handle with 200 to 400 sensors. For larger distances of 1,800 m or more, the variance in number of sensors per gateway is increasing. Some gateways need to cover many sensors in dense areas while some gateway need to cover only a few sensors. Thus, also from this perspective, it is not advisable to increase the sensor to gateway distance too much.

Another performance metric is the number of redundant gateways that cover single sensors. Although double coverage makes a network more robust against gateway failure, the drawback of redundant coverage is additional interference. For small distances below 400 m, each sensor is covered on average by more than four gateways. This number decreases, like expected, with larger distances. Up to 900 m, the average sensor is covered by more than three gateways while for the remaining distances, the average sensor is covered by two or three gateways. Furthermore, this number is not decreasing anymore for distances larger than 1,100 m (2.89 gateways on average). For comparison only, 2,200 m shows 2.85 gateways on average and 2,500 m shows 2.86 gateways on average. Furthermore, we see that dense areas are covered by more gateways while less dense areas are often only covered by a single gateway, like intended in a good placement.

B. Scenario S 2: Number of Sensors per Gateway

The goal of scenario S 2 is to identify the influence of sensor limits per gateway. Therefore, Figure 5 shows the average collision probability on the left y-axis for different maximal sensor numbers between 300 and 3,000 on the x-axis. The shaded area shows minimal and maximal values again. We see an increase in collision probability starting from 750 sensors up to 1,250. However, between 1,600 and 2,100 sensors per gateway a smaller collision probability is detected again. For more sensors, it is increasing again. Thus, no clear statement about a good sensor number per gateway with focus on collision probability is possible.

Furthermore, the yellow line in the figure shows the required gateways on the right y-axis. There, the behavior is different. The required number of gateways is decreasing. For 300 sensors per gateway we require 22 gateways and for 1,100 sensors only 13 gateways. Finally, the number of required gateways decreases to 11 gateways for 2,250 sensors per gateway and more.

Thus, in general, the maximal number of sensors per gateway has an influence on the overall collision probability. However, the distance between sensors and their gateway dominates the sensor limit. This is also visible when studying the SF distribution for scenario S 2. Even for a sensor limit of 500, several sensors need to transmit with SF 12 because of the large distance to the next gateway. This increases the average time on air and the collision probability. This increase is visible in Figure 5 where the average collision probability is never below 5 %. In contrast, it is below 5 % for all maximal sensor to gateway distances below 1,150 m in Figure 4.

Additional Performance Metrics: If the sensor number per gateway is large, redundant coverage of sensors is lower, similar to S 1. But although the sensor limit is a constraint for gateway placement, it is none for sensor to gateway connection. It is possible that sensors are assigned to a gateway in the graph creation phase but end up closer to other gateways and thus, transmit data to others, like already seen in S 1. Although opposing a limit of 500 sensors per gateway during graph creation, we observed up to 2,194 sensors connecting to the most frequently used gateway and 1,362 to the second frequently used one. Thus, we conclude that the sensor limit is a good constraint to limit the overall sensors per gateway at some specific point, but does not work without additional constraints like the distance between sensors and gateways.

With these results, we can answer the first research question with

yes, a graph based approach shows satisfactory results, in particular with the degree centrality as graph metric. Furthermore, the most important constraint influencing the placement and the collision probability is the gateway range.

C. *Scenario S 3: Comparison to Related Work*

The only approach studying the collision probability based on different gateway placements in LoRaWAN in literature is, to the best of our knowledge, the Voronoi-Cover approach [4]. For that reason, we compare our results with the Voronoi approach for different cities by means of collision probability and number of required gateways.

Collision Probability: Therefore, Figure 6 shows the average collision probability as a barplot on the y-axis and the different cities pair-wise for our Graph (G) approach and the Voronoi (V) approach on the x-axis. The error bars indicate 95 % confidence intervals.

Our approach achieves in the worst case a similar collision probability than the Voronoi approach. For the small networks, London (LDN), Munich (M), and Sydney (SYD), we see no statistically significant difference in the mean collision probability with the 95 % confidence interval. However, the graph based approach performs better in all other deployments. For San Francisco (SF), much better results are achieved with a collision probability reduction of about 70 %. There, the graph-based approach shows a mean collision probability of 2.16 % and the Voronoi approach has 6.83 %. Thus, we conclude that the graph-based approach performs in the worst case similar to state-of-the-art from literature and can reduce the mean collision probability by up to 70 % in the best case, especially in large network deployments with many sensors or in placements in a large geographic area.

Number of Gateways: Another placement quality indicator is the number of placed gateways. It is summarized in Table IV for the different cities of Figure 6 for the Graph (G) approach and the Voronoi-Cover (V). The Graph approach requires fewer gateways in all cities except Munich. In particular, a large difference in required gateways is visible for Bangkok, San Francisco, Würzburg, and Shanghai. The largest improvement is visible in large deployments, especially if the number of sensors per km^2 is small. However, also for small deployments with fewer sensors, like for the city of London, significant improvements with only about 2/3 of the required gateways compared to related work is possible.

Thus, we can answer our second research question as follows.

The presented graph-based gateway placement approach works independent on geographic network size, number of sensors, and for different cities. Furthermore, it performs similar in the worst case and better compared to state-of-the-art literature for all scenarios by means of required gateways and collision probability in the resulting network.

Table IV: Required gateways

City	**Graph**	**Voronoi**	**City**	**Graph**	**Voronoi**
Bangkok	287	329	**London**	4	6
Manhattan	41	52	**Munich**	7	7
San Fransisco	71	93	**Shanghai**	242	355
Sydney	4	5	**Würzburg**	30	50

Table V: Sub-scenarios for scenario S 4

Abbr.	**Payload**	**Gateway range**	**Number sensors**	**Explanation**
R	1 B - 51 B	1,150 m	10,000	random payload
B$_1$	16 B	1,150 m	10,000	baseline SF 8
B$_2$	16 B	1,150 m	20,000	baseline SF 8 double load
D$_1$	16 B	2,000 m	10,000	increased gateway range
D$_2$	16 B	2,000 m	20,000	increased gateway range double load
E$_1$	16 B	950 m	10,000	extended placement SF 7
E$_2$	16 B	950 m	20,000	extended placement SF 7 double load

D. *Scenario S 4: Different Transmission Patterns*

To study the performance of the placement for different transmission patterns, a random message payload is assigned and studied first. Afterwards, the total number of sensors in the networks is increased to emulate an increase in transmission load. An overview of all studied sub-scenarios is given in Table V. The collision probability results are summarized in Figure 7 with the 95 % confidence interval. Details for all sub-scenarios of scenario S 4 are given in the following. For all scenarios, the test dataset from Würzburg, Germany is used.

Random Payload Assignment: A random payload scenario R is created to study a variable message payload between 1 B and 51 B for each transmission. This is the maximum possible payload with SF 11 and SF 12 in LoRa. In contrast, scenario B$_1$ is configured with a fixed payload of 16 B and serves as baseline from the previous results. The gateway range is set to 1,150 m, so that each sensor transmits with SF 7 or SF 8. The average payload is increased from 16 B in scenario B$_1$ to 26 B in scenario R. The remaining placement, simulation, and gateway placement is kept the same. The goal is to study the collision probability only.

The results show a mean collision probability of 5.79 % for scenario R compared to 3.70 % in the baseline scenario B$_1$ with 16 B payload. Thus, the increase in collision probability is with 56.49 % a little smaller than the proportional increase in payload (62.5 %) because of header and preamble overhead of LoRa messages. However, we see in the results that the approach is not limited to a single payload but also usable for random payload assignments.

Increasing Transmission Rate: Another parameter is the network load achieved by increasing the number of sensors or messages in the network. Since we do not model individual sensor behavior, increasing the message rate of single sensors has the same influence as increasing the number of sensors. To study this, the number of sensors of the baseline B$_1$

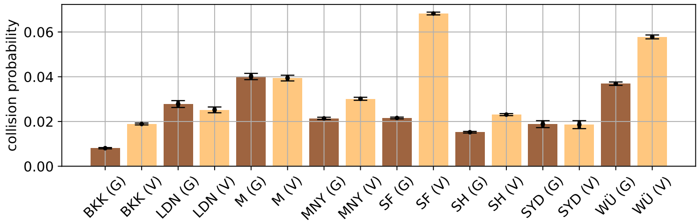

Figure 6: Comparison Graph (G) to Voronoi (V) for different cities; Bangkok (BKK), London (LDN), Manhattan, New York (MNY), Munich (M), San Francisco (SF), Shanghai (SH), Sydney (SYD), Würzburg (WÜ)

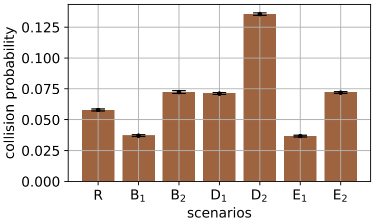

Figure 7: Scenario S 4, transmission pattern sub-scenarios according to Table V

is doubled in sub-scenario B_2. Compared to the collision probability of 3.70 % from the baseline B_1, the collision probability increases to 7.11 %, as shown in Figure 7. Furthermore, additional studies have shown that linearly increasing the number of sensors nearly linearly increases the collision probability.

One possibility to deal with increasing traffic is the placement of additional gateways in an already deployed LoRaWAN instance. Therefore, we create a distance scenario D_1 where we set the gateway range to 2,000 m with 10,000 sensors. If our graph based approach is used for an initial placement, the complete network is covered by 17 gateways. A mean collision probability of 7.3 % is achieved shown by sub-scenario D_1 in Figure 7. However, deployments are expected to grow in size and number of sensors. If the number of sensors is doubled, the mean collision probability is increasing to 13.7 % shown by sub-scenario D_2 where 20,000 sensors are in the network, but the same number of gateways is used compared to D_1.

To tackle this issue, the gateway range can be reduced, thereby reducing the number of sensors covered by each gateway. Sensors that are no longer covered by one of the existing gateways, will need to be processed during iterative placement. Due to the graph-based nature of our approach, this iterative placement is achievable, by simply constructing the graph on now uncovered sensors. This is done in scenario E_1 that iterates the placement used in D_1 with 10,000 sensors and with in scenario E_2 that adjusts the initial placement of D_2 with 20,000 sensors. For both scenarios, the initial gateway range was 2,000 m, and is adjusted to 950 m. Both adjustments can reduce the collision probability by roughly 50%. However, the extended placement requires 46 gateways for E_1 and E_2. To achieve a similar collision probability for 20,000 sensors, 16 additional gateways are required after re-placement. For that reason, a good initial placement is preferred to constant re-placement on demand.

E. Scenario S 5: Placement for Large Deployments

Gateway placement for LoRaWAN in large networks is still challenging [4] or not possible with approaches from literature [25]. However, this is in particular important for growing networks in the future.

Since our approach places gateways at dense network parts, we can apply clustering to split large problems into several sub-problems. We attempt this for the data from Würzburg by applying k-means clustering before computing placements on the resulting clusters of devices. As a baseline, we use a gateway range of 2,177.15 m, for which we need 15 gateways to cover all sensors. Afterwards, we divide the network into two, four, five, ten, 15, and 20 clusters and perform individual placement on each cluster. We require 16, 16, 17, 16, 17, and 20 gateways, while the maximal segmentation using 20 clusters only requires one gateway per cluster.

Thus, we achieve good results with only few additional gateways. With this approach, it is possible to place gateways in arbitrarily large networks. Furthermore, the average collision probability for splitting the network in clusters and calculating the placement for each cluster individually is in the worst case the same compared to performing the placement approach at the complete network. Since either the same or more gateways are placed, the average distance between sensor and gateway is similar or less. Thus, the collision probability is in the best case even better, at the cost of few additional gateways.

With these results, we can answer the third research question as follows.

Larger deployments show computational limits, in particular for the graph creation and gateway selection process. However, a pre-clustering can handle arbitrarily large network instances with only minimal overhead. Furthermore, the limits from LoRaWAN perspective are reached when all sensors use SF 7. Then, additional collision avoidance mechanisms like intelligent channel and frequency planning or message decoding are required.

F. Further Scenarios and Edge Weights

While the general graph for gateway placement is unweighted, additional edge weights can be added. This improves the importance of specific nodes or influences the node centrality, and thus the general gateway placement. In the course of this work, we tested an additional weight for the distance between nodes, the SF, the payload the sensor wants to transmit, and the time on air to transmit a message. However, no influence on the collision probability and the number of required gateways is detected for all additional weights except the time on air. For the time on air, no statistically significant influence is detected and is thus not further studied. However, our results show that in future approaches, additional weights based on the time on air show most potential.

VI. CONCLUSION

The trend towards the deployment of massive swarms of IoT sensors is no longer avoidable. However, not every connected sensor requires low delays and large bandwidths. Especially low energy consumption and long battery life times combined with transmissions across large geographic distances are two unique features of LPWANs with LoRaWAN as one of their most prominent representatives. For a comprehensive deployment, the general performance in the network must be known as well as optimized. Thus, the currently often unplanned gateway deployment combined with a random channel access leaves much room for improvement.

For that reason, we provide a novel gateway placement approach for LoRaWAN by transforming the network into a graph. Through different graph creation constraints, we can adjust the placement and thus, the overall collision probability. Our results show a general trade-off between the number of required gateways and average collision probability in the network. However, we see the best results when the gateway range is limited in a way, that each sensor can use SF 7 or SF 8. Furthermore, our placement requires in the worst case the same number of gateways and achieves similar collision probability in the network as related work but can reduce the number of gateways by 40 % in combination with a reduction in collision probability by up to 70 %.

Finally, our approach is independent of the underlying network, number of sensors, or network size. Increasingly large deployments can be split into several problem instances, solved individually, and combined afterwards with a minimal reduction in placement quality.

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