Studying Slot Assignment for Multi-Gateway Time Scheduled Channel Access in LoRaWAN

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***Abstract*—LoRaWAN stands out as one of the fastest growing Internet of Things access networks, thanks to its extensive coverage and operation within the license-free ISM band. This feature enables individuals to easily establish wireless access for their devices. However, a notable drawback of LoRaWAN is its unregulated channel access, which can lead collisions and data loss. While scheduled MAC approaches theoretically offer a solution to such collisions and aim to enhance the reliability of LoRaWAN, their real-world applicability, particularly in scenarios involving multiple gateways, remains unexplored. Consequently, we have devised a slot assignment strategy tailored for LoRaWANs with multiple gateways and demonstrate its effectiveness in large deployments across various cities worldwide. The chromatic number as a graph metric of the communication network can predict its suitability for supporting scheduled MAC operation. Additionally, we have developed a methodology to optimize gateway placement based on slot assignment, thereby reducing the number of gateways needed for a given network.**

***Index Terms*—LoRaWAN, IoT, channel access, scheduled MAC**

I. Introduction

In the transformative landscape towards increasing automation, the Internet of Things (IoT) is the main driver. It impacts everybody in the daily life with simple application areas for environmental monitoring, but also more sophisticated solutions in the Smart City or Industry 4.0 context. However, this progress presents notable challenges, particularly in managing the growing number of end devices. Therefore, mobile networks are constantly improved and research already discusses the sixth generation (6G) mobile network standard. While 6G promises improved service quality for end users, Key Value Indicators (KVIs) also include energy efficiency and sustainability [1]. As certain application areas do not demand high bandwidth or low latency, the Low Power Wide Area Network (LPWAN) market is growing rapidly as complementary technology to 6G, offering long-range communication with low power demand. This market, currently valued at $ 5 billion, is projected to grow annually by 50 % until 2032, with LoRaWAN as one of the most prominent representatives [2].

From an end user's perspective, LoRaWAN has many benefits. End devices are relatively cheap and network access is rather simple. Major companies like Amazon, with their Sidewalk access, contribute to extensive coverage for a significant portion of the US population [3]. From the perspective of a provider, the large transmission distance using LoRa requires only a small number of gateways to cover large geographical areas. However, optimizing LoRa message transmission in a LoRaWAN, minimizing costs, and maximizing reliability by reducing collision probability remain critical challenges. While existing literature has explored efficient gateway placement [4], several studies focus on random channel access, leading to message collisions and occasional data loss. In addition, the applicability of a time scheduled channel access for a single gateway LoRaWAN has already been examined, eliminating collisions completely [5]. But the applicability to real networks with several gateways is still not clear.

Therefore, we develop a novel methodology for slot assignment in a multi gateway scheduled MAC LoRaWAN and assess the effectiveness of a time scheduled channel access approach in a comprehensive network deployment encompassing multiple gateways across a large geographical area. To achieve this, we examine the impact of various factors such as different spreading factors used for synchronization and data transmission, maximum sensor clock drifts, traffic load, and the expected number of sensors within such a network. We analyze the practicality of a scheduled MAC, as proposed in the literature [5], in real-world scenarios featuring multiple gateways, while also identifying limitations and challenges.

This work offers a threefold contribution. Firstly, we devise a slot assignment methodology applicable to single and multi-gateway LoRaWANs employing scheduled MAC. Through a large-scale simulation study utilizing real-world networks and varying load scenarios, we evaluate the viability of our slot assignment approach. Secondly, we describe the slot assignment as a graph coloring problem and explore the potential utility of the chromatic number to achieve decisions regarding a network's ability to support channel access using a scheduled MAC strategy. Lastly, we introduce a methodology to optimize gateway placement procedures based on the chromatic number, aiming to minimize the required number of gateways.

To this end, we identify and answer the following three research questions (RQs) in this work.

- **RQ1:** Can graph coloring theoretically be used to assign slots for a multi gateway network using scheduled MAC in a LoRaWAN?
- **RQ2:** Can we identify whether scheduled MAC can be used on a specific, existing or envisioned network?
- **RQ3:** Can we optimize gateway placements in a LoRaWAN through comprehensive slot assignment?

In the remainder, background and related work is discussed in Sec. II followed by our methodology in Sec. III. The evaluation is presented in Sec. IV and Sec. V concludes.

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II. Background and Related Work

This section provides fundamental background and related literature to understand this work.

A. General LoRaWAN Background

LoRa is the proprietary LPWAN modulation technique used by LoRaWAN [6]. In Europe, LoRa operates primarily in the unlicensed ISM band between $863.0\,\mathrm{MHz}$ and $870.0\,\mathrm{MHz}$ [6]. LoRa offers a transmission range between $2\,\mathrm{km}$ and $15\,\mathrm{km}$ and allows battery life times of up to 10 years [6]. Due to an operation in the ISM band, LoRa end devices and gateways are limited to a maximum duty cycle of $0.1\,\%$, $1\,\%$, or $10\,\%$, depending on the used channel [7]. LoRaWAN is organized as a star of stars topology with a centralized network server managing multiple gateways to which end devices can connect. Different spreading factors (SF) allow for a trade-off between the transmission distance and the transmission time [8].

B. LoRaWAN Channel Access

LoRaWAN uses a variation of ALOHA without synchronization for channel access [9]. End devices can transmit whenever they have data available which can lead to many message collisions. Consequently, only a maximum channel capacity of $18.6\,\%$ can be utilized [10], but achieving only $8\,\%$ utilization in half duplex LoRaWAN [11]. Alternative channel access approaches have been proposed by related work, including Slotted ALOHA, Listen before Talk, and Scheduled MAC. Scheduled MAC, as content for this work, has recently been investigated in different works [5], [12]. The channel is divided into time slots and only allows end devices to transmit during a predefined slot. This channel access planning procedure can theoretically eliminate collisions completely. However, a thorough slot length planning is required in a real network [5]. The contributing factors to the length of these slots is shown in Figure 1. The actual data transmission time on air (ToA) from the end device to the gateway is shown in orange. A guard time, shown in gray, is required due to the inability to perfectly synchronize the end devices as a result of time drift. LoRaWAN end devices commonly drift in the range of $2\,\mathrm{ppm}$ to $100\,\mathrm{ppm}$ [5]. As this guard time is used up with advancing time, a synchronization packet is sent to the end device once a maximum time drift is reached. The precise slot length can be calculated based on related work [5]. With the determined slot length, a time slot assignment to end devices is required. In a single cell network, any unique mapping between end devices and time slots is a valid assignment. With multiple gateways, slot assignment is more complex. Assigning a single time slot to multiple end devices is possible, if these end device can not interfere with each other, increasing the number of supported end devices in the network.

C. Related Work

To investigate channel access for LoRaWAN, a simulation of the collision probability based on interference measurements is done in [13]. A similar simulation is used to analyze redundant message transmissions in [14]. Multi gateway networks are analyzed in [15]. The authors analyze a real network in the city of Shanghai, identifying gateway placement as a key contributing factor to the overall network quality. Algorithmic gateway placement is accomplished using clustering in [16]. Approaches specifically tailored to LoRaWAN are presented in [17], using Voronoi cells, and in [8] using graph centrality metrics. The approach in [8] can also be pre-clustered to support larger instances [4]. These works also analyze the impact of the gateway placement on the collision probability. Collision probability reduction using slotted ALOHA channel access is pursued in [11]. Additionally, the authors provide an overview for the clock drift and details on synchronizing end devices. A similar analysis is performed in [18], using a custom simulation. Both approaches show improved performance against ALOHA, if the slots are sufficiently sized. Listen before talk is mathematically defined and evaluated in [19]. The authors show a clear improvement for the collision probability, without causing a large delay increase. One implementation for scheduled MAC is developed in [12] and subsequently implemented in [20]. The authors use on demand first come first serve to assign the slots, instead of a centralized approach. The slot assignment is distributed using bloom filters. To completely eliminate collisions, the authors of [5] develop a collision free scheduled MAC and mathematically define the ideal slot length, resynchronization timeout, and the capacity. In contrast, this work is focused on an optimization for scheduled MAC in LoRaWAN with multiple gateways using graph coloring.

III. Methodology

We present a slot assignment approach for a multi gateway scheduled MAC for LoRaWAN. Therefore, we differentiate the slot assignment approach for a network with a single gateway from a multi gateway network first and the assignment approach for multiple gateways afterwards.

A. Slot Assignment for Scheduled MAC

The slot assignment for a deployment with a single gatway is significantly easier than with multiple gateways. Thus, both problems defined and compared in the following.

a) Single Gateway Networks: Networks with a single gateway are shaped in a star topology, with a gateway in the center and multiple end devices connecting to the gateway. Simultaneous transmissions from more than one end device cause interference at the gateway, resulting in a collision and the potential loss of data. Note, we assume that all colliding message get lost in this work to analyze the worst case. For other approaches we refer to literature [14], [21]. Thus, a slot assignment must ensure that message transmission from two or more end devices at the same time is not possible in the network. To accomplish this task, the channel is split into time slots of a fixed length, calculated according to Section II-B c). Each end device is allowed to transmit in a different time slot. As a result, any injective function, mapping from end devices to time slots leads to a valid slot assignment. The simplest

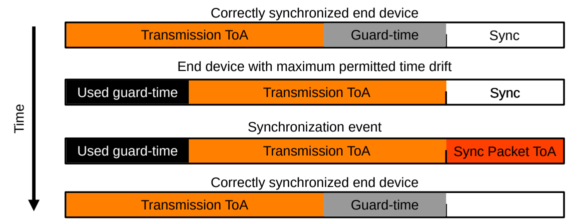

Fig. 1: Slot length contributing factors.

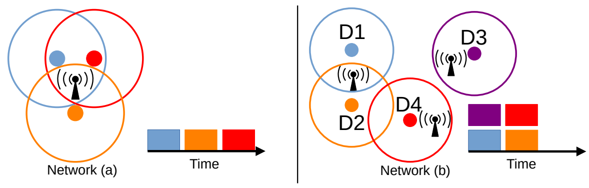

Fig. 2: Overlapping collision zones in single and multi gateway networks with possible slot assignment.

approach for this is assigning each end device and time slot a unique ID. Then, each end device ID is matched to the corresponding slot ID and only transmits in this specific slot.

b) Multi Gateway Networks: A network with multiple gateways could also use this strategy to assign time slots to end devices. However, not all simultaneous transmissions automatically result in a collision because of the existence of multiple cells and end devices transmitting to different gateways. The authors of [17] define the idea of a collision zone, where a circular region around LoRa devices with the radius of their transmission distance is assumed. Any other LoRa device in this collision zone is capable of receiving the transmission from this end device. If two end devices are close enough to share an overlapping collision zone, LoRa end devices or gateways in this overlap can receive transmissions from either end device. If a gateway is located in the overlapping collision zone, the end devices responsible for the overlap can interfere with each other. If a multi gateway network is large enough, not all gateways can receive the transmissions of all end devices. End devices with either no overlapping collision zone, or when the gateway is located outside the overlapping collision zones, can not interfere and can reuse the same slot. This difference is illustrated in Figure 2. The colored dots represent one end device each, with the circles of the same color representing the coverage area of the particular end device. Other end devices or gateways located in this area can potentially interfere with the device. Network (a) has only a single gateway located visibly in the overlapping collision zones of all end devices. In network (b), only end devices D1 and D2 share an overlapping collision zone with a gateway inside the overlapping portion of the zones. Thus, these two devices must use separate slots. End device D3 can use the same slot as either of the other devices, as it does not share an overlapping collision zone. End device D4 can also reuse the same slot as D2, as both gateways inside the collision zones of these end devices are not located in their overlapping collision zone. While an injective function is still a valid solution for a multi gateway network, slots can be assigned to multiple end devices, which do not share an overlapping collision zone, or the gateway is not located in the overlapping zone. This increases the number of supported end devices or shortens the time until the slot pattern repeats.

c) Graph based Slot Assignment: To assign slots in networks with multiple gateways we first define a graph based on the network topology, representing the relationship between the collision zones. This graph is hereafter referred to as the interference graph $G = (V, E)$. The individual end devices represent the vertices V. An edge E connects two vertices, if both of the following conditions are true. (1) The corresponding end devices have an overlapping collision zone. (2) A gateway used by at least one of the end devices is located in the overlapping collision zone. Thus, if an edge $e_{i,j}$ connects two vertices i and j, the corresponding end devices can not share the same slot. Afterwards, this graph is colored. Graph coloring for a graph $G = (V, E)$ with vertices V and edges E is defined in [22] as an assignment of an integer $c(v) \in 1, 2, \ldots, k$ to each vertex v, where

$$c(v) \neq c(u) \forall v, u \in E \wedge k \text{ is minimal.}$$

In this context, k is referred to as the chromatic number of the graph G. However, the graph coloring problem is NP-complete [22]. To ensure scalability for large networks, this work uses an approximation developed in [23] to create the collision zones and color the interference graph in polynomial time. To determine, whether a desired transmission periodicity can be met, e.g., every end device wants to transmit once per hour, $\frac{p}{s} \leq k$ must be fulfilled. The period p must be large enough to allow for at least k slots of length s. The slots must be long enough to cover the transmission, a guard time to avoid transmissions in the wrong slot because of the devices time drifts, and synchronization messages, as explained in Sec. II. Consequently, we can answer our first research question RQ1 as follows: *As nodes connected with an edge can not share the same color, the function $c(X)$ is a valid solution for the slot assignment problem. The chromatic number k directly corresponds to the number of required slots before the pattern can be repeated. This provides an exact boundary on the number of required slots and the slot assignment itself.*

B. Simulation Overview

To evaluate the graph coloring based slot assignment, we investigate LoRaWANs with end device locations as close as possible to reality, using a custom simulation approach. First, similarly to the literature [4], we assume to have sensors on building locations in real cities to achieve realistic locations. These datasets are obtained through the centroids of building locations from OpenStreetMap similarly to [17] and we apply a state-of-the-art gateway placement approach from the literature [8] to place gateways ensuring coverage and small collision probability. Afterwards, to assess the performance of a LoRaWAN, a four step simulation for scheduled MAC is developed considering information, like gateway reachability, collision zones, and SF assignment:

Step 1: Read Data and Device Setup First, the fundamental parameters for all end devices are configured. End devices are assumed to transmit to their closest gateway. Then, the spreading factor is set based on the distances between end devices and gateways using distance per spreading factor limits from the literature [8]. The time slots are set by the proposed graph coloring approach. End devices receive random realistic clock drifts ranging between 2 ppm and 100 ppm [5].

Step 2: Generating Message Transmissions Each end device then receives a random payload between 1 B and 51 B for each transmission, representing the minimum and maximum supported payload, which is compatible with all spreading factors. A random payload is chosen, as the payload depends on the specific use case and is not always consistent. Each end device initiates one downlink transmission per simulation cycle and the transmission start is calculated by multiplying the slot length with the assigned slot number. We assume one transmission per device per hour. However, the approach also works with different transmission rates. The simulation does not model the method to distribute the slot timings to end devices. Therefore, we refer to the literature [20].

Step 3: Packet Processing To process the synchronization, each transmission is checked for interference, i.e., overlapping transmissions, chronologically. If overlapping transmissions are found and the corresponding end devices share an edge in the interference graph, a collision occurs. If no collision is detected and the message exceeds its slot after a time drift, a synchronization message with a length of 6 B is sent from the gateway to the end device as an uplink, similarly to the synchronization in the literature [5]. After correct reception of this message, the end device is re-synchronized back to a total time drift of 0 ms. To validate the simulation, achieve a valid simulation duration, and identify whether each device can be synchronized without exceeding the duty cycle limit of the gateway, a test scenario is devised using the suggested slot length and time drifts available in the literature [5]. This allows 430 end devices transmitting once per hour, placed around a single gateway with all spreading factors present in the network. We simulate until each device is synchronized at least once to accurately achieve the expected duty cycle. This results in a simulation time of 553 h, which is extended to 560 h to account for a margin of error. During this test, no message collisions are detected, validating that the slot length and time drift limits identified in the literature [5] also apply to this simulation. Finally, to achieve statistically significant results, we repeat each 560 h simulation 30 times.

Step 4: Calculating Metrics and Export After all messages are transmitted and sequentially processed, we can calculate the gateway duty cycle based on the ToA of all synchronization messages generated by a single gateway. As we assume message transmission per sensor once an hour, the duty cycle of the sensor is never exceeded. Furthermore, we can count the number of overlapping transmissions per sensor, which results in the number of collisions. To verify the simulation adheres to the model from literature [5], two pre-studies are conducted on a network consisting of a single gateway and 430 end devices randomly placed in a circle around the gateway. The maximum radius is 1960 m, representing 90 % of the maximum achievable transmission range using SF12 with the Hata model used in the literature [5]. For the first test, the slot length is varied between 200 ms, representing the smallest possible slot length for SF7, and 8372 ms, representing the maximum possible slot length with 430 end devices and one hour repetition period. The maximum time drift is set to 3980 ms, matching [5]. The simulation achieves a collision free network using a random time drift between 2 ppm and 100 ppm with slot lengths longer than 7800 ms, compared to 7980 ms, as determined by the literature [5]. For the second pre-study, the maximum time drift is varied between 380 ms at the lower end, representing a ten fold reduction from the value obtained in literature and five times increase in time drift for the upper bound. The slot length is set to 7980 ms. In the simulation, collisions do not occur up to 4100 ms maximum time drift, which is close to 3980 ms, the maximum value identified in [5]. This leads to the conclusion, that this simulation exhibits the same behavior, as the model from the literature and their findings also apply to this simulation.

TABLE I: Scenario Overview.

Scenario	Dataset	Maximum gateway distance	Research goal
S1	Würzburg	300 m - 2600 m stepsize 50 m	Study applicability of slot assignment approach
S2	Würzburg	according to occupied slots	Study maximum load in network
S3	Various	300 m - 2600 m stepsize 50 m	Study slot assignment for other cities

C. Scenario Overview

To study scheduled MAC and the proposed slot assignment, the scenarios in Table I are defined. All scenarios use constant settings for key LoRaWAN parameters defined in [24]. The preamble is set to eight symbols, the coding rate is four, header and CRC are enabled, while data rate optimization is disabled. Each scenario is described in the following briefly.

a) S1: Slot Assignment Analysis: This scenario studies the applicability of our slot assignment approach for a real world network. To compare our results and validate our approach with scenario S1 from state-of-the-art literature [8], we use the same dataset from the city of Würzburg, Germany. The maximum distance from the gateway is likewise varied between 300 m and 2600 m with a maximum of 1000 end devices per gateway. This provides a known reference and also allows for the evaluation of every spreading factor. To determine, if these placements can theoretically be used with scheduled MAC, the interference graphs for these networks are

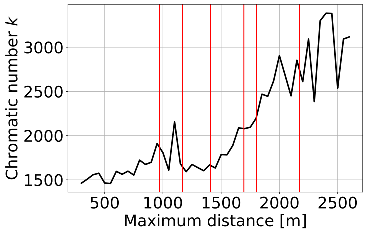

Fig. 3: Chromatic number for different max. gateway distance.

constructed and the chromatic number is shown in Figure 3. The x-axis presents the maximum distance from the gateway, while the chromatic number in the network is shown on the y-axis. The red vertical lines show the maximum distance for each spreading factor according to the Hata model, with SF7 corresponding to the leftmost line, and SF12 to the rightmost line. The chromatic number increases with the maximum distance. However, outliers are observed for specific distances, corresponding to a different spreading factor distribution. This shows the dependency of the chromatic number on the network topology. Thus, these results are only valid for this specific network and do not represent a general relationship.

Analyzing the chromatic number shows, that more than 1500 slots are always required in Figure 3. Using the model from literature [5], only 548 distinct slots are available in a single channel if all end devices use SF7. The authors always use SF12 for synchronization, referred to as S1.1 during evaluation, limiting the number of slots. Note, we investigate the usage of a single channel only. For real deployments, slot assignment can be performed per channel to increase the number of possible end devices in the network. To investigate the scalability of the scheduled MAC approach, we study two additional variations of this scenario. First, using the same SF, as the transmission yields up to 2238 slots for SF7, referred to as S1.2 during evaluation. Second, synchronizing with one SF larger than the transmission, referred to as S1.3. In this case, if we transmit messages with SF7, we use SF8 for synchronization. With this configuration, 1821 slots are possible in the network. If SF12 is present in the network, all configurations are limited to 430 slots. Using S1.2 and S1.3 enables this network to support scheduled MAC for SF7. For S1.2, the number of slots for SF8 shrinks to 1757, exceeding the chromatic number. S1.3 exceeds the chromatic number with a maximum distance of $900\,\mathrm{m}$. However, analyzing larger spreading factors than SF7 is required for a comprehensive analysis. Only using SF7 especially eliminates potential interactions between different spreading factors and long ToAs.

Accordingly, the chromatic number must be reduced. This can be achieved by reducing the number of end devices, decreasing the transmission rate or adding channels. As we focus on a single channel, and the transmission rate is often fixed by the requirements of an application, we reduce the number of end devices by removing a random subset proportional to the difference between the number of available slots and the chromatic number. This is not always expected to result in a valid selection, as not all end devices have the same influence on the chromatic number. This is most clearly observed with completely disconnected nodes, whose removal does not alter k. The selection approach is repeated until one network per SF does not exceed the number of available slots.

TABLE II: Evaluated cities.

City	**District**	**Country**	**Number of end devices**	**End devices per km^2**
Würzburg	entire city	Germany	10,000	114
Bangkok	entire city	Thailand	14,443	4.7
London	City of London	UK	1,959	412
Munich	Schwabing-West	Germany	3,094	489
Shanghai	Pudong	China	17,210	5.8
Sydney	City of Sydney	Australia	1,058	193.1
New York City	Manhattan	USA	11,592	46.2
San Francisco	entire city	USA	20,048	19.2

b) S2: Maximum Load Analysis: For a correctly operating scheduled MAC in LoRaWAN, it is required that no collisions occur, even if all potential slots in the network are filled to their theoretical limit. Unfilled slots leave multiple possibilities for the slot assignment algorithm, potentially sidestepping an issue with the fundamental approach. Thus, analyzing a network with all slots filled ensures that the slot assignment produces a valid result and the chromatic number is a sharp boundary for the number of required slots. To construct a maximum load scenario, all end devices must use SF7 to ensure a consistent ToA. The spreading factor used for synchronization is not relevant for this evaluation, as any failed synchronization results in a collision. Due to the small number of slots and long synchronization messages, synchronization with SF12 is chosen. For the Würzburg dataset used in S2, a maximum gateway distance of $650\,\mathrm{m}$ results in $99.27\,\%$ of slots being occupied. This network is chosen for evaluation, with all end devices transmitting a consistent payload of $51\,\mathrm{B}$.

c) S3: Slot Assignment for Different Cities: The previous scenarios only cover a single network. To evaluate the possibility of using scheduled MAC in other environments with different properties, this scenario analyzes other cities from around the world. To compare to the literature and analyze the feasibility of the proposed approach, we analyze the same cities as [8]. The chosen cites cover a wide range of different end device densities and total number of end devices summarized in Table II. For a broader study, $50\,\%$ of end devices are selected for Manhattan and Bangkok, and $30\,\%$ for San Francisco. The goal of this scenario is to determine, whether these networks support scheduled MAC and to determine the maximum distance between sensors and gateways, where scheduled MAC results in no collisions. The maximum gateway distance is therefore varied between $300\,\mathrm{m}$ and $2600\,\mathrm{m}$ with $50\,\mathrm{m}$ increments. The number of available slots is computed similarly to S2.

IV. Evaluation

The following section presents the results for the evaluation conducted on the scenarios defined above.

A. S1: Slot Assignment Analysis

This scenario aims to determine, if the slot assignment with graph coloring achieves a valid result for a multi gateway network, where the chromatic number does not exceed the number of slots available. The result for the end device selection is shown in Figure 4. The x-axis shows the maximum distance from the gateway configured in the placement and the y-axes show the percentage of occupied slots. The orange lines delimit SFs, similar to Figure 3. The following paragraph refers to synchronizing with SF12 as S1.1, synchronization with the same SF as the transmission is S1.2, and synchronization with the next higher SF is S1.3. Exceeding $100\,\%$ results in a network with more end devices than available slots, resulting in systematic collisions. The results for the simulations are shown in Figure 5. The x-axis shows the maximum range between sensors and gateways, while the y-axes show the collision probability. The median collision probability is represented in black and the shaded areas show the $99\,\%$ quantiles, which are barely visible as only little variance in the results is achieved. The red lines delimit SFs, similar to Figure 3. Analyzing the collision probability shows a clear relationship. Networks, where not all slots are occupied in Figure 4, always result in a collision probability of $0\,\%$, while networks with a chromatic number larger than the number of available slots, exhibit systematic collisions. This behavior is consistent, regardless of the sub-scenario and proof our approach again.

These results are only valid, if the gateway duty cycle does not exceed regulatory limits. As the duty cycle is measured per device, only the gateway with the largest duty cycle is important [7]. The results for all networks, which exhibit a $0\,\%$ collision probability are shown in Figure 6 with the maximum range for the gateway placement on the x-axis. The y-axes are split between the duty cycle in black and the number of gateways in orange. For all networks which exhibit a $0\,\%$ collision probability, the gateway duty cycle always remains below $1\,\%$. All sub-scenarios show an increasing gateway duty cycle between $300\,\mathrm{m}$ and $970\,\mathrm{m}$ as the number of gateways drops, causing individual gateways to serve more end devices. S1.1 stabilizes for longer distances, as the synchronization ToA is fixed. For S1.2 and S1.3, the synchronization ToA depends on the SF distribution, reducing the required ToA for end devices close to the gateway, reducing the duty cycle.

These results confirm the proposed methodology for slot assignment and we can answer our second research question RQ2: *All networks with a chromatic number k below the number of available slots are able to operate without collisions, regardless of the maximum distance from the gateway and the gateway duty cycle is inline with the regulation. The exponential drop in the number of required gateways leads to a trade-off between the number of gateways and the number of supported end devices. Contrary to pure ALOHA, single end devices with a larger SF can not be supported, reducing the flexibility of scheduled MAC. Thus, the ideal configuration depends on the application and end device requirements. The maximum gateway distance should be maximized, while synchronization with the SF of the transmission should be used, if supported by the end devices.*

TABLE III: S3 Results.

City	Max. gateway distance	Avg. gateway duty cycle
Bangkok	$1650\,\mathrm{m}$	$0.1125\,\%$
London	$1350\,\mathrm{m}$	$0.1644\,\%$
Munich	$1350\,\mathrm{m}$	$0.0971\,\%$
New York City	$1200\,\mathrm{m}$	$0.0882\,\%$
San Francisco	$1350\,\mathrm{m}$	$0.1217\,\%$
Shanghai	$1000\,\mathrm{m}$	$0.2041\,\%$
Sydney	$1650\,\mathrm{m}$	$0.0567\,\%$
Würzburg	$1150\,\mathrm{m}$	$0.2410\,\%$

B. S2: Maximum Load Analysis

This scenario expands on S2 to analyze if the slot assignment approach achieves valid results, if all slots are filled, and if all devices can transmit the maximum possible payload. The simulation results show no collisions in this network. A mean duty cycle of $0.343\,\%$ with a $99\,\%$ confidence interval length close to zero is achieved. Consequently, the slot assignment remains valid even under maximum load conditions.

C. S3: Slot Assignment for other Cities

Finally, the applicability of our slot assignment for other cities, defined in Table II, is investigated. The maximum distance between sensors and gateways is determined, where the chromatic number remains below the number of available slots. These results can be used to maximize the distance from the gateway, reducing the number of required gateways. The results are shown in Table III with the cities in the first column and the maximum possible distance, where the chromatic number remains below the number of slots in the second column. The number of slots is calculated using the same spreading factor for the transmission and the synchronization. All evaluated cities are capable of supporting scheduled MAC with a maximum supported spreading factor between SF8 and SF10. Comparing the achieved maximum distance to the end device density in the network reveals no correlation, with a Spearman correlation coefficient of 0.11 and a p-value of 0.795. For all cities, we achieve no collisions. The average required gateway duty cycle is shown in the last column of Table III. Since the maximum length of the $99\,\%$ confidence intervals is again close to zero, we see a small variance in the results and the duty cycle never exceeds $1\,\%$. Thus, we can answer our final research question RQ3 as follows: *We can optimize the gateway placement for a LoRaWAN using our comprehensive slot assignment strategy. The largest maximum distance, where the chromatic number remains below the number of available slots then represents the ideal configuration.*

Analyzing the behavior of the gateway duty cycle further shows an inverse relationship between the maximum distance

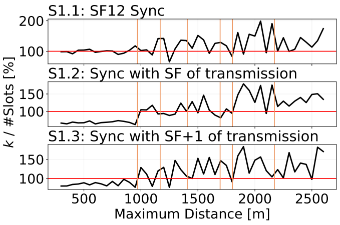

Fig. 4: Chromatic number to available slots for diff. max. gateway distance.

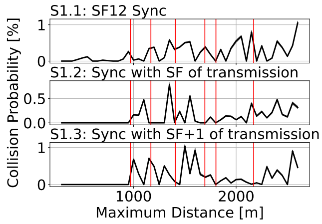

Fig. 5: Collision probability for different maximum gateway distance.

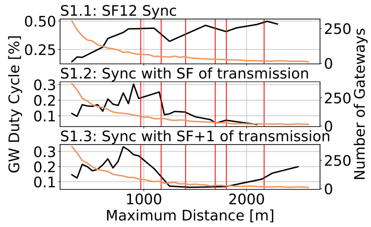

Fig. 6: Gateway duty cycle and num. gateways for diff. max. GW distance.

between end devices and gateways, and the gateway duty cycle. This is expected, as a shorter distance requires additional gateways to cover a city, reducing the load on individual gateways. The Spearman correlation for this relationship is 0.626, with a p-value of 0.097. However, the gateway duty cycle is also dependent on the actual geographic spread of end devices, as the results for London and Munich show significant differences in the gateway duty cycle with the same maximum distance from the gateway configured.

V. Conclusion

To enhance the transmission reliability in LoRaWAN, literature suggests scheduled MAC for channel access. While theoretical solutions have been proposed [5], the task of assigning time slots can be challenging, especially in large networks with multiple gateways. Consequently, we propose a novel solution to the multi-gateway slot assignment problem using scheduled MAC for LoRaWAN. We leverage the potential interference among end devices to construct a graph representation of interfering devices and use graph coloring. This yields two outcomes: the assigned colors to the end devices and the chromatic number, representing the total number of colors used. Our findings indicate that the assigned colors effectively serve as slot assignments for scheduled MAC in multi-gateway networks. We validate the applicability across various example deployments in different cities worldwide. Additionally, we establish that the chromatic number derived from graph coloring corresponds to the required number of slots. By considering the network layout and gateway placement, we can determine if a network can support scheduled MAC. Moreover, by optimizing the maximum distance between sensors and gateways, we can minimize the necessary number of gateways to cover the network. In summary, our slot assignment approach ensures valid and collision-free networks, with all gateways adhering to duty cycle restrictions.

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