LoRaWAN Network Planning in Smart Environments: Towards Reliability, Scalability, and Cost Reduction

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I. INTRODUCTION AND PROBLEM DESCRIPTION

Recent Internet of Things (IoT) development is driven by new technologies, extended requirements for data monitoring, and new possibilities for simple, and affordable network access and sensors. Extended possibilities to monitor and process data are crucial to provide these novel services since data monitoring changed fundamentally in recent years. With the adaption of faster networks, in particular the rollout of 5G, it is possible to monitor and process a large quantity of data, even in mobile environments. However, there are still areas without coverage, bad accessibility, or no access to wired energy. For these areas, so called Low Power Wide Area Networks (LPWANs) with LoRaWAN as one of their most prominent representative has been proven as useful. The small power requirements that can be served by tiny batteries for years, and the transmission possibilities across large distances are ideal for scenarios like environmental monitoring or in the smart city context. However, LoRaWANs are still in the development phase and complete, geographically large rollouts are rare.

Nevertheless, because of the simple and free to use principle, LoRaWAN is one interesting technology to solidify IoT networks as part of our everyday life. This is one reason why LoRaWAN already made 36 % of the total LPWAN technology market in 2021 [1]. Since this market is growing with 32.7 % per year [1], mechanisms to guarantee reliability are required and scalability potential is highly interesting. But the cost component for further expansion and network operation must be taken into consideration to not lose one unique selling point of LoRaWAN: cheap and simple access.

However, the fast and steady growth of LoRaWAN provides several challenges. While small network instances work reliable, do not require all available frequency resources, and can transmit data with little loss in a cheap way, larger networks are limited by the currently used random channel access approach. Furthermore, current literature mainly tackles coverage and gateway reduction in their studies [2], [3] without taking the transmission quality investigation into consideration. This is changed recently by a local search [4] and a graph-based approach [5]. On the other hand, the way sensors transmit data in LoRaWAN can be managed by intelligent channel access approaches like Slotted ALOHA [6], [7], Listen before Talk [8] or Scheduled MAC [9]. Furthermore, colliding packets can be recovered based on collision location [10] or message decoding [11].

The goal in this work is to present a guidance for LoRaWAN planning to improve overall reliability for message transmissions and scalability. At the end, the cost component is discussed. Therefore, a five step approach is presented that helps to plan a LoRaWAN deployment step by step: Based on the device locations, an initial gateway placement is suggested followed by in-depth frequency and channel access planning. After an initial planning phase, updates for channel access and the initial gateway planning is suggested that should also be done periodically during network operation. Since current gateway placement approaches are only studied with random channel access, there is a lot of potential in the cell planning phase. Furthermore, the performance of different channel access approaches is highly related on network load, and thus cell size and sensor density. Last, the influence of different cell planning ideas on expected costs are discussed.

II. LORAWAN TRANSMISSION QUALITY

In this section, the general LoRaWAN background is provided with focus on important parameters and channel access management.

A. LoRaWAN Background

The transmission quality in LoRaWAN is mainly influenced by two factors. Device coverage and collision probability in the network. Since device coverage can be optimized through intelligent gateway placement, the focus is on collision probability reduction to improve reliability. The collision probability is influenced by the way available channel resources are used, the number of devices using the network, the individual transmission behavior by means of transmission rate and message size, and the used channel access strategy. Since the number of sensors and the transmission rate is dependent on the application and deployed vertical, it can not be influenced directly by the network operator. Thus, the focus is on channel access management and transmission duration control. Please note that additional decoding, message recovery, or error detection is also available. However, since this is only possible after an unintended collision occurred, it is not studied here.

B. Channel Access Management

Channel access management can reduce collision potential in LoRaWAN based on three different techniques: intelligent channel access using time division multiple access (TDMA), cell size adjustment using space division multiple access (SDMA), and the usage of different frequency channels for the messages using frequency division multiple access (FDMA). Furthermore, the quasi orthogonality of different spreading factors can theoretically also increase the number of messages transmittable in parallel [12]. However, since this effect is influenced by among others, spreading factor difference, additional interference, and antenna transmission strength, it is not considered in this work.

TDMA Approaches: With no collision avoidance strategy and a theoretical maximal throughput of 18.4 % [13], the overall transmission quality with regard to data loss is not optimal with the currently used random channel access approach. One alternative is slotted ALOHA which improves the overall collision probability and can theoretically double the maximal throughput [13] at the cost of decreased energy efficiency under certain load conditions [14]. However, since the transmission duration variance for different LoRa messages is large, dependent on the used spreading factor and the payload length that must be transmitted, the practical improvement is smaller. In particular if the variation in transmission duration of all messages is large, slotted ALOHA is no improvement compared to the currently used pure ALOHA [9]. Another option is listen before talk that performs in the worst case, if no sensor can hear any other one, similar to pure ALOHA. However, it can lead to a complete collision avoidance in the best case [9]. Thus, if devices support listen before talk, it is a good option to improve LoRaWAN performance with little overhead. However, many cheap sensors can not listen to the channel or have no possibility to receive data and prevent the network from using listen before talk. In addition, channel sensing increases the energy consumption and in return decreases the expected lifetime of the battery [14]. Last, a completely scheduled MAC approach can avoid collisions entirely [9]. Furthermore, it is very robust against cross-traffic and can thus, coexist in networks in which not all transmissions are controllable or synchronizable. The large drawback is the synchronization overhead to keep all messages in their respective slots. This increases energy consumption, the overall number of messages in the network, and requires sensors without large clock drift.

SDMA Approaches: In addition to a TDMA concept, where different channel access mechanisms are used, SDMA can be realized in LoRaWAN through intelligent gateway placement and thus, cell planing. First and foremost, the most important constraint is coverage that must be guaranteed to provide network access to all devices. Furthermore, decreasing cell sizes can reduce the number of sensors transmitting to a single gateway and thus, the overall message load. However, the second improvement when cell sizes are decreased is the reduction of the mean used spreading factor that has the largest improvement potential with regard to collision probability [5]. Therefore, the goal is to minimize the spreading factor without the requirement of too many redundant gateways. Furthermore, dependent on the geographic location in the network, sensor density is different and thus, cell size can be selected based on network load. In addition, the cell size can be further adjusted by transmission strength adjustments at sensor side. Note that a minimization of the number of gateways and the used spreading factors are opposing objectives and an optimal network setup hence presents a trade-off between both values.

FDMA Approaches: Additionally, FDMA can increase the overall throughput by using different frequency channels for different tasks or applications. Furthermore, it is possible to just randomly distribute messages across all available channels. Thus, the theoretical message throughput can be increased with the number of channels. However, our pre-studies show that reserving channels for dedicated management or synchronization tasks is not advisable since message load for these tasks is low compared to goodput traffic. For that reason, we assume that each sensor can always randomly choose one of the available frequency channels. Thus, we do not go into detail regarding FDMA in this work.

Sensor Adjustments: Last, when all network planning related improvements are applied, additional performance adjustment at the sensor side is possible. Next to intelligent transmission time planning, message overhead can be decreased by avoiding unnecessarily large coding rates, headers, or retransmissions. Furthermore, if possible, message aggregation by saving multiple measurement results directly at the device and transmitting data only if a specific number of data points is available. However, this is a trade-off between storage space at the sensor, additional energy consumption for data write and read operations to the device memory [10], and transmission delay if data is backed up at the device for a specific duration.

III. FIVE PHASE APPROACH TOWARDS BETTER LORAWAN NETWORK PLANNING

LoRaWAN application areas are extremely heterogeneous leading to different sensor transmission behavior. Hence, this must be taken into consideration during channel planning. For that reason, we suggest the following five phase planning approach for more reliable and scalable LoRaWAN deployments. The phases are defined as follows: setup phase (1), placement phase (2), channel access planning phase (3), adjustment phase (4) and an optional replacement phase (5). An overview of all phases is given in Figure 1.

Setup Phase 1: During the setup phase, all devices are discovered and potential gateway locations are examined. Furthermore, to understand the expected network load for the final network deployment, sensor transmission behavior or the target application of sensors - if available - is requested. In addition, further important metrics that can influence network planning are gathered. This includes, among others, message importance, sensor transmission strength adaptability, sensor mobility information, device battery capabilities, or sensor quality that triggers potential clock drifts.

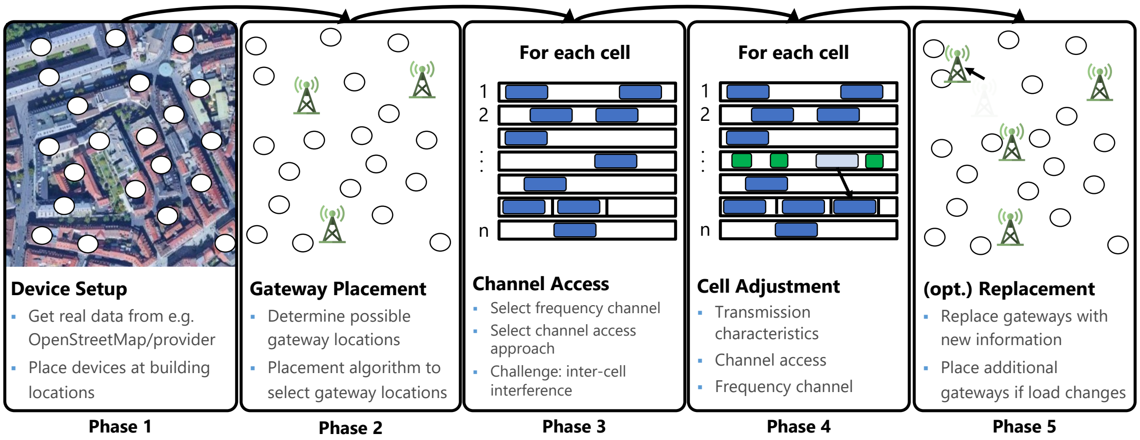

Figure 1: Overview of network planning process process

Placement Phase 2: The gateway placement is then based on geographical sensor distribution. While the general coverage constraint must be satisfied, additional network constraints with regard to collision acceptance level and possible gateway locations are taken into consideration as already introduced in previous works [4], [5]. Furthermore, room for scalability can be left if current networks are small and a large immediate deployment is too costly. However, literature shows that a good initial planning is preferred compared to frequent redesign and subsequent gateway placement [4]. After the initial placement phase is done, the result must be evaluated carefully by means of the target metrics like collision probability. For example [15] presents a general tool for that purpose.

Channel Access Planning Phase 3: After gateway placement is finished, an in-depth frequency and channel access planning is required for each cell. There, the usage behavior of each sensor must be requested or monitored, appropriate access approaches must be selected, and by means of in- and inter-cell interference, expected collision probability must be calculated. The best channel access is determined according to the following principle. The base approach is random access. It is the most cost-effective way to transmit data when network load is small. If sensors are able to sense the channel and the device battery allows it, listen before talk is preferred [9]. If devices show similar transmission characteristics by means of spreading factor and payload, which lead to a similar time on air, slotted ALOHA is suggested [7]. However, it only works if clock drifts are small and devices can be synchronized. The same holds true for scheduled MAC. It is the most complex approach and can avoid collisions completely without cross-traffic or reduce it drastically with little cross-traffic [9]. But not all devices support the approach. In addition, our pre-studies show that reserving dedicated channels for management traffic can reduce or avoid collisions for that specific traffic type. The drawback is an overall reduced throughput and higher collision probability for the remaining traffic. Thus, channel reservation for specific traffic is an option if zero collisions must be guaranteed for specific tasks.

Adjustment Phase 4: Next, if the initial planning phase is finished, first complete network simulations or measurements can be conducted. In this phase, the results are evaluated carefully to improve channel access, evaluate the potential of sensors by means of possible synchronizations, real communication behavior, and time drifts. This is used to adjust frequency and channel access approach selection for all devices. Furthermore, this phase can also run constantly to react to changing circumstances like new devices, transmission behavior, or unexpected situations. The goal here is to reduce the overall load per cell without the requirement of redundant gateways leading to over-provisioning and cost overhead.

Optional Re-placement Phase 5: Last, gateways can be relocated based on initial simulation results or measurements. This happens in the planning phase and is usually too costly after the network has been deployed. In addition, subsequent placement of gateways is possible in this phase if network load increases to react to an increasing provisioning demand and efficient scalability. Options how to place additional gateways is proposed in [4], [5]. However, it is important to design the network in the planning phase with some scalability potential without the need of further gateways. In general, efficient and scalable planning shows better results as frequent network extension with more gateways [4].

IV. DISCUSSION

In LoRaWAN, a trade-off between increasing reliability by means of a reduced collision probability, good scalability in the planning phase by robust future-proof gateway placement, and a gateway reduction to reduce cost is crucial. However, from an energy consumption point of view, and thus battery requirement perspective, all additional transmissions that lead to collisions, data loss, or increasing management overhead increase cost. Thus, a robust initial planning covering the complete network with a maximal spreading factor of 8 or 9, as proposed in [5] can occasionally compensate the additional cost to place gateways. In addition, a robust initial deployment requires less need for frequent extension which in return generates significant additional cost. Furthermore, the influence of mobile sensors need to be taken into consideration in future studies.

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