

Evaluation of LoRa in a Real-World Smart City: Selected Insights and Findings

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Abstract—We present an evaluation of a LoRa based smart city network in Osnabrück, Germany. The main characteristic of this network is a significant gateway density in the city center. To assess the network coverage, a measurement-based study using sensors mounted on garbage trucks has been conducted. This work presents selected insights and findings emerging from the collected data. We report on inaccuracies of the RSSI reported by the deployed LoRa infrastructure which also affects various other deployments. We discuss the distribution of the SNR and the resulting Spreading Factors. In addition, we relate outdoor measurements to indoor results from different buildings and present a first idea about building attenuation. Finally, we discuss how many gateways are needed to build a LoRa based smart city network with a desired coverage for a typical city environment like Osnabrück.

Index Terms—LoRa, SNR, RSSI, Outdoor, Indoor, Coverage, Gateway density

I. INTRODUCTION

For companies providing basic public services (i.e. electricity, gas, water, ...) a modern and reliable communication network is essential to cope with new digital challenges. These new tasks mainly emerge from the transition of classical utility infrastructure towards various smart grids. The end devices in these networks are sensors (and actuators) to monitor (and interact) with different physical components (i.e. meters, valves, relays). Due to the absence of wired communication paths towards most of these end devices, wireless wide area networks are preferred. In addition, many sensors require to be operated on batteries, motivating the networking concept of low-power wide-area networks (LPWANs).

One common technology for LPWAN is Long Range (LoRa) which operates in Europe at an unlicensed frequency band of 868 MHz. Due to the availability of this unlicensed band and compared to 3GPP technologies like NB-IoT or LTE-M, LoRa can be self-planned and self-operated by utility companies like the “SWO Netz GmbH”.

As a fully owned subsidiary of “Stadtwerke Osnabrück”, the “SWO Netz GmbH” is the network operator for electricity, natural gas, water and wastewater in Osnabrück, Germany. By founding a dedicated division for digitization, the company actively diversifies their portfolio for future tasks in a modern smart city. One key part of this digitization strategy is to operate a local LoRaWAN infrastructure for different real-world smart city use cases.

Among others, the main use cases for this infrastructure are metering, monitoring and smart parking. The metering use case focuses on remote district heating meters. A remote reading of these meters has recently become mandatory for an infrastructure company in Germany [1]. The monitoring use case addresses local transformer stations in the electricity grid as well as pressure control systems in the gas grid. Especially stations that are not already connected with conventional wired technologies (fiber or copper) will use this LoRaWAN infrastructure since adding new wired connections results in huge civil engineering costs. Considering the full roll-out of this monitoring use cases, this affects about 80% of all stations. Smart parking is a use case that “SWO Netz” offers commercially for showing the current utilization of different electric vehicle charging stations.

To provide these services successfully, certain requirements for the LoRaWAN infrastructure exist. One of these requirements is to have detailed knowledge about the scalability and the reception quality of the network. This knowledge leads to a better predictability for the deployment and operation of the described services and provides guidelines for further enhancements of the network.

Therefore, we conducted a measurement campaign similar to our previous work in the city of Bonn [2]. In this work, we present selected insights and findings from this campaign which we believe are in particular useful for other real-world LoRaWAN network operators. Specifically, given a typical urban LoRaWAN network with a high density of Gateways (GWs), we answer the following questions:

- 1) What is the distribution of the signal-to-noise ratio (SNR) and Spreading Factor (SF)?
- 2) What is the average radius of a LoRa cell?
- 3) How many GWs receive a LoRa packet simultaneously?
- 4) If LoRa transceivers are deployed indoor, what is the average additional attenuation due to a building?
- 5) How many GWs are needed to provide a city-wide reception? Are certain GWs more important than others?

We believe that the answers to these questions are in particular useful for planners and operators of LoRaWAN networks. In addition, we provide statistically sound data to enhance mathematical models and simulations of LoRaWAN networks with real-world measurement data.

The rest of this work is structured as follows: Section II provides an overview of related work about large-scale LoRaWAN deployments and previously conducted experimental evaluations. In Section III, we present our methodology and details about the conducted measurement campaign. The aforementioned questions are discussed in Section IV and this work ends with a summary and possible future work items in Section V.

II. RELATED WORK

In this section, we summarize previous work which focused on LoRa in real-world urban scenarios and which includes any kind of experimental verification.

In [2], we studied path loss models and their impact to network planning, e.g., when making predictions about possible new locations. We compared numerous previous studies [3]–[10] and their results to a new measurement campaign similar to the one conducted for this work. We found that simple path loss models (i.e. log-distance) provide good estimations in an urban environment.

In their comprehensive article [11], the authors experimentally verify key performance indicators of LoRa such as transmission distance, end node lifetime and node capacity which are important for network operators.

In [12], the authors focus on two aspects in a city-wide LoRa network: the energy efficiency of the end nodes and the Packet Delivery Ratio (PDR) under different conditions. Experiments have been conducted in a stationary scenario with 10 end nodes. The authors conclude that LoRa is well suited for such environments. Similar results have been described in [13].

The focus in [14] is the influence of environmental factors (temperature, wind, humidity) to the PDR and SNR. The authors show that a relationship between an increasing temperature and a decreasing SNR exists.

III. METHODOLOGY

The goal of this section is to introduce our methodology and the conducted measurement campaign in detail. First, we briefly characterise the environment and the network infrastructure where the measurement took place. Second, we describe the measurement sensors used, including irregularities which we encountered with the Received Signal Strength Indication (RSSI) of the GWs. Third, we provide general facts about the measurement campaign.

A. Environment and Network

The LoRaWAN infrastructure of “SWO Netz” in the area of Osnabrück has 54 active LoRaWAN GWs of the type MTC DTIP-L4E1-266A from the manufacturer Multitech at 32 different locations. More GWs are currently planned and deployed. The GWs at 22 locations, are equipped with two dedicated LoRaWAN modems, each with its own connected antenna and assigned device Extended Unique Identifier (EUI). The antenna configurations and, as a result, the transmission

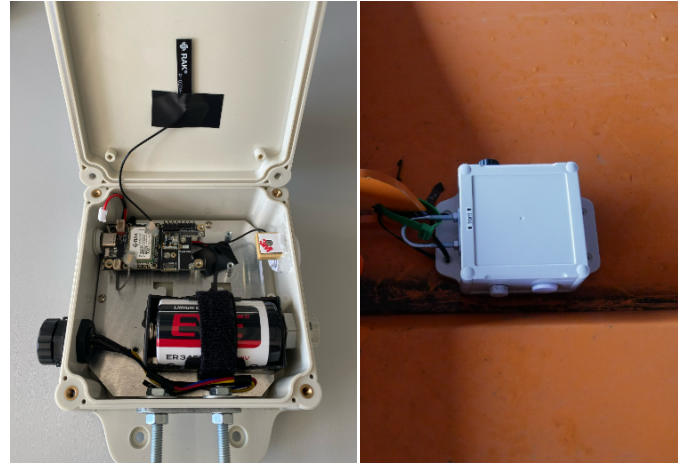


Fig. 1: Developed sensor. Left, the system inside the enclosure. Right, one mounted sensor on one of the garbage trucks.

power settings of the individual LoRaWAN cards differ between the GWs. Configurations in which the antennas are both in the immediate vicinity of the gateway include an antenna with 3 dBi gain and an antenna with 6 dBi gain. This configuration is the result of previously conducted internal studies.

Osnabrück is characterized by a green and hilly, geologically varied landscape, which provides huge challenges for predictability of reception. The conducted measurement is therefore interesting for the “SWO Netz GmbH” to have a clear visualization of the reception in the city center.

B. Measurement Setup

To conduct the measurements, we designed and built a sensor directly targeted for our needs. This GPS/LoRa sensor is an enhancement of the one we used in [2] with the advantage that it is completely built from commercially available components and therefore easily reproducible for other researchers.

We used the WisBlock modular system offered by RAK Wireless. In addition to a comprehensive documentation, the system provides the required flexibility to develop sensors for a variety of use cases. In detail, we selected the RAK4631 Core Module, which is based on an NRF52840 microcontroller and a Semtech SX1262 LoRa transceiver. We also combined it with multiple sensor modules, including an accelerometer, a GNSS chipset, and an environment module to monitor the system health. The LoRa antenna (RAKARB04 PCB Antenna) is placed in the cover of the enclosure to minimize the influence of the surrounding metal and to be flexible with the placement of the sensor. As power supply we used one EVE ER34615 (Lithium-thionyl Chloride) battery that allows for several months of runtime. The WisBlock system’s low power consumption and sleep modes, combined with the use of efficient components, contribute to longer battery life, making it a practical and reliable solution for long-term measurement applications.

Similar to our work in [2], we measured the up-link signal quality from our sensors to the different LoRa GWs. The main advantage is that multiple GWs will receive a single up-link transmission. This multiplies the amount of generated data in our campaign compared to downlink transmissions. In addition, up-link communication from a sensor to a GW is the major use case in the local network.

Overall, we mounted nine sensors on nine different garbage trucks which traveled through the city on different routes. While on these routes, a LoRa packet with the last determined GPS coordinate of the truck was sent to all surrounding GWs. We used a fixed SF of 12 with disabled Adaptive Data Rate (ADR) function. The used bandwidth was fixed to 125 kHz at a coding rate of 4/5. Each GW which received the packet first determined different parameters such as the received SNR and then forwards the packet to our logging database.

To account for GPS inaccuracies, we mapped GPS locations to the nearest street using the Open Source Routing Machine (OSRM) service [15].

1) *SNR Reporting*: A common choice to evaluate the network quality and coverage is the RSSI [2]. However, in this work we use the SNR due to the following observation.

Before we started the measurement campaign, we conducted a laboratory experiment with one of the deployed GWs and one of our sensors to verify the correctness of the RSSI. We used the same measurement method which we already discussed in [2]. A central part of this method is to send out numerous artificially crafted packets. Overall, for one experiment we transmitted 1260 packets each with 10 bytes payload. After a certain amount of transmitted packets, the RSSI begins to fluctuate significantly before it gets stable again. This is shown in Figure 2.

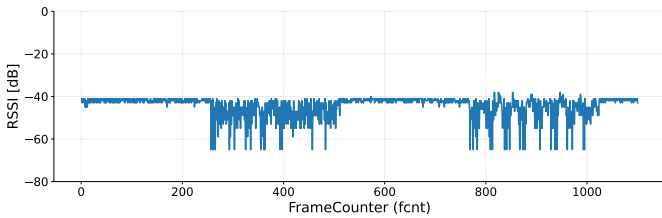


Fig. 2: RSSI reporting issue with common LoRa transceiver. The RSSI fluctuates depending on the frame counter.

We further analyzed these RSSI fluctuations and found the following unexpected correlation. If the frame counter of the transmitted packet is in the range from 256-512 or 768-1024, the reported RSSI varies significantly. If the frame counter is in the range from 0-256 and 512-768 the RSSI is stable. The fluctuating only occurs for a SF of 12, however, using this SF is a central aspect of our measurement campaign to assess the maximum coverage. We were able to reproduce this behavior using combinations of different GWs from different vendors, different sensors and different payload data. We reported this issue to the company Semtech. In addition, other users have confirmed our findings [16]. However, until the moment of writing, no solution has been proposed.

Luckily, we could not observe this issue for the reported SNR. Therefore, we will use the SNR as quality indicator for the signal throughout this work.

C. Campaign facts

In the following, the most important facts of our measurement campaign are described. The campaign lasted for a period of 87 days from December 2022 to March 2023. We limited the evaluation to LoRaWAN GWs and measurement samples that are strictly located in the urban area of Osnabrück in order to have clear boundaries for the analysis and make the results comparable with other cities. Furthermore, samples where the mapping to the nearest street exceeds 20 m were dropped to remove non-reliable measurements. We monitored 46 different GW modems at 28 different GW locations (cf. section III-A). Our sensors have transmitted 55,794 LoRa packets, each with an individual GPS value as payload. Since these packets are received by multiple GW cards, this result in 303,791 measurement samples.

IV. RESULTS

This section provides our selected insights and findings which we derived from the data obtained in the measurement campaign described in Section III.

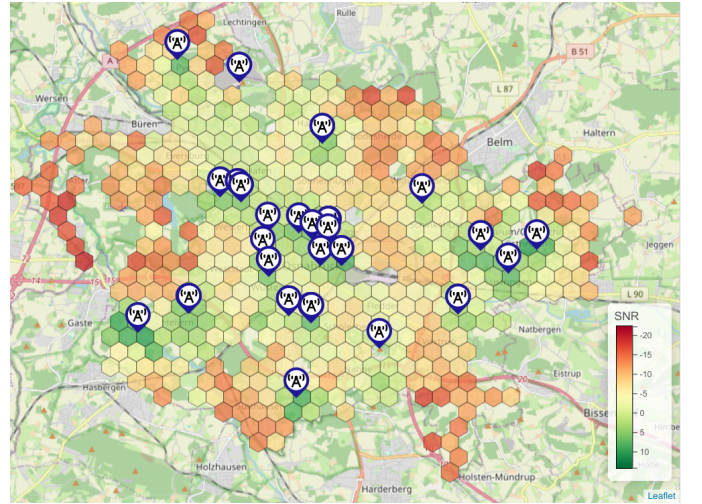


Fig. 3: Map of Osnabrück. SNR measurements are grouped in hexagons. Green color corresponds to good reception, red color corresponds to bad reception.

Figure 3 shows a map of Osnabrück with the resulting SNR as an overlay. In addition, we have marked all GW locations, which we included in our evaluation. For a better visual representation, we grouped multiple measurement points using hexagon shapes. Each hexagon represents the mean of the SNR values located in that shape. Clearly, the reception in the city center is very good. The primary reason is the high density of GWs in that area.

In the remainder of this section, we will address common questions which may occur for a LoRa network operator either during the build-up phase or during the operation of a network.

Question 1. What is the distribution of the SNR and SF?

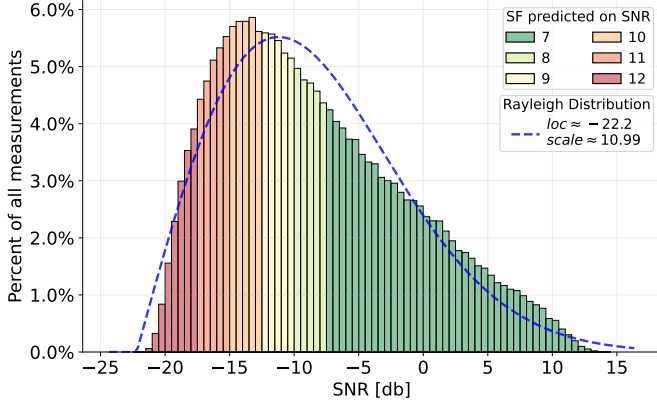


Fig. 4: Distribution of the SNR and the resulting possible SF. In addition, a scaled and shifted Rayleigh distribution.

Figure 4 shows the distribution of the SNR for all measurement samples. This figure confirms the indication already observed in Figure 3: due to the high GW density in the city center, most transmissions have a very good SNR. In addition to the raw data, Figure 4 shows a fitted Rayleigh distribution of the following form:

$$\frac{x+k}{\sigma^2} * e^{-(x+k)^2/2\sigma^2} \quad (1)$$

with $k \approx -22.2$ and $\sigma \approx 10.99$. From an operator perspective, optimizing the average SNR in the network is important, since a better SNR leads to a better possible SF when techniques such as ADR are enabled. In particular, this leads to a better scalability of the network since either more sensors can be deployed or more data can be transmitted before the duty cycle limit is reached. Especially when additional transport security (such as Transport Layer Security (TLS)) on top of LoRaWAN are required, high SFs greatly limit the possible use cases for an operator [17].

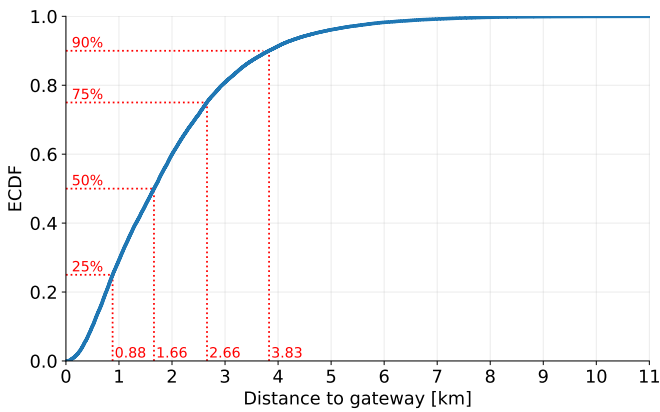


Fig. 5: Empirical distribution function of the distance from the sensor to the receiving GW.

Question 2. What is the average radius of a LoRa cell?

Figure 5 shows the empirical distribution function of the distances from the sensor to the GWs. The average distance is 1.97 km and the median is 1.66 km. In our urban scenario, only a few long range transmissions took place. Only 10% of the transmissions had a distance greater than 3.83 km.

Question 3. How many GWs receive a LoRa packet in parallel?

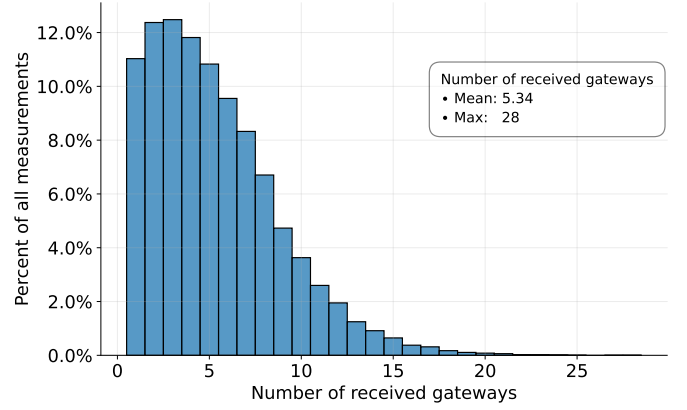


Fig. 6: Reception redundancy quantified by the parallel number of GWs which received a single transmission.

In a LoRaWAN network, a LoRa transmission can be received by multiple GWs. A certain overlap for the individual cells of the different GWs is desired to maximize coverage and increase the probability of a successful reception by at least one GW. We analyzed what we called the redundancy factor based on our measurement data. The results are visualized in Figure 6. On average, every transmission has been received by 5 GWs. Only 11% of transmissions have been received by only one GW.

Question 4. If LoRa transceivers are deployed indoors, what is the average additional attenuation due to a building?

So far, the presented results are based on measurements taken on top of the roof of garbage tracks. From a reception perspective this corresponds to an ideal scenario, as the measurements were taken outdoors at a height of approximately 3.2 m. However, for different real-world use cases, LoRa transceivers are being placed inside a building, sometimes even in the basement. One of these use cases is the monitoring of heat meters. Network operators need to incorporate the additional attenuation of the building during the planing phase of the network. Therefore, in addition to our outdoor measurements, we obtained SNR values from different heat meters already deployed by the “SWO Netz GmbH”. Overall, we collected 92,716 values from 29 heat meters at 10 different indoor locations. We compared these indoor SNR values with outdoor measurements taken in the immediate vicinity of that location from the garbage truck dataset. In more detail, we calculated the differences between

the measured outdoor and indoor SNR values. An example of the SNR values we compared is shown in Figure 7. This figure shows one heat meter, one gateway and the corresponding outdoor measurement locations.

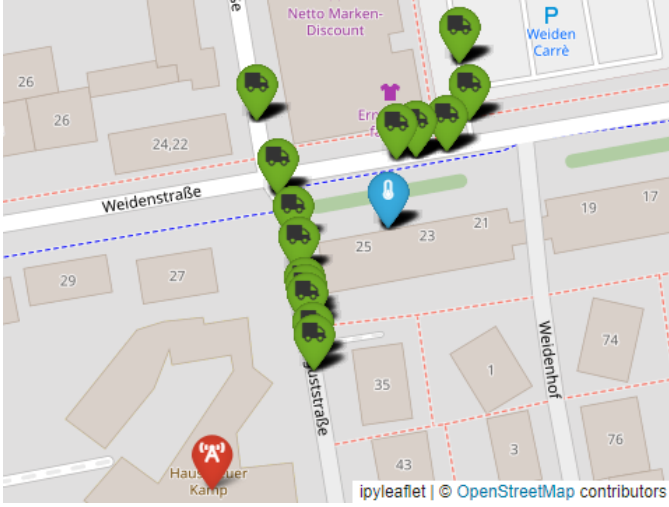


Fig. 7: Specific map section showing one GW (red), one heat meter sensor (blue) and the corresponding outdoor measurement locations (green) used as comparison.

Figure 8 visualizes the results. The difference varies significantly among the different locations which can be attributed to the different kinds of buildings, placements of the heat meters and the materials of these buildings. For example, at location B, a difference of 25 dB exist between the outdoor and indoor data, which shows a significant attenuation of this particular building. At other locations, for example location A, this difference is much less and just between 0 and 5 dB. Also for single locations, a significant spread of the differences was measured. At location F the difference between indoor and outdoor SNR ranges from 2 to 24 dB. And at location I, we observed slightly stronger signals from the inside of the building compared to the nearest measurement points from the outside. In general, the average difference between indoor and outdoor measurements were 8.14 dB with a standard deviation of 6.58 dB. We note that our method is not perfect for providing a clear picture of LoRa building attenuation. The mapping of the nearest measured outdoor location to the building is error-prone (cf. Figure 7). However, our results show that network operators face a challenge when LoRa transceivers are placed indoor and this fact needs to be incorporated during the planning phase of the network.

Question 5. *In a typical urban scenario, how many GWs are needed to provide a city-wide reception? Are certain GWs significantly more important than others?*

In our analyzed scenario, there is a significant GW density in the city center which is great for a certain redundancy factor and for various indoor use cases. However, each GW needs to be purchased, installed, integrated and maintained by a network operator. From an operator perspective it is in

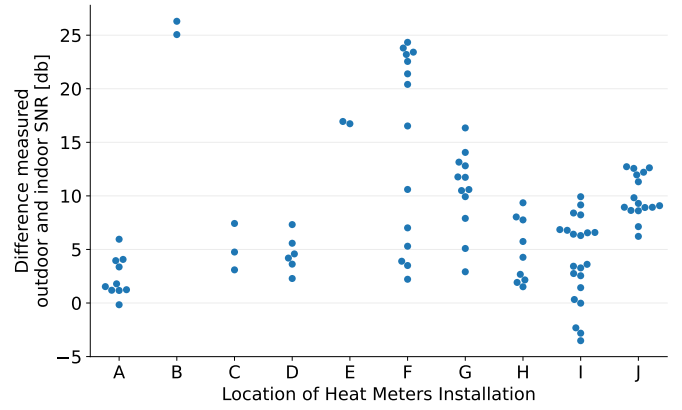


Fig. 8: Difference between indoor and outdoor measurements for selected heat meters and locations.

particular challenging to find good exposed locations for these GWs. Based on the measurement data, our goal is to analyze how many GWs would have been needed to provide a good reception coverage in the city center. The defined baseline is the current scenario with the 46 different LoRaWAN GW modems at the 28 different locations.

To answer these questions, we incrementally remove GWs from our measurement dataset and recalculate the resulting coverage. However, this task is very computationally intensive since for 46 GWs there are 2^{46} combinations of GWs which need to be considered. We have developed the following method to reduce the computational complexity.

We segmented the area of Osnabrück into 50x50 meter tiles and mapped all measurement samples onto this segment grid. This results in 10,344 segments with measurements, which covers more than the cultivated area of Osnabrück (parts of parks and fields are covered as well). A bitmask is assigned to each segment, representing the corresponding GWs by which all measured samples in this segment are reached. As soon as a GW of this bitmask is removed, the corresponding segment is no longer considered covered. To calculate the best case coverage for n GWs to be removed, one GW after the other is removed. The resulting gateway bitmask is combined with the segment masks and the number of lost segments is counted. The calculation can be aborted as soon as the coverage is worse than the optimum determined so far, because the coverage can only get worse by removing further GWs. This means that large parts of the search tree do not need to be considered, which significantly reduces the complexity of the calculation. The analysis of the worst case coverage is performed analogously.

The results are shown in Figure 9. As expected, when GWs are removed from the network, coverage decreases in the city center. However, the amount of the decrease significantly depends on the particular subset of GWs which are removed. For example, if 20 GWs are removed from the network, this removing can either lead to a coverage of 97% or 38%. This illustrates the importance of certain GWs and their locations.

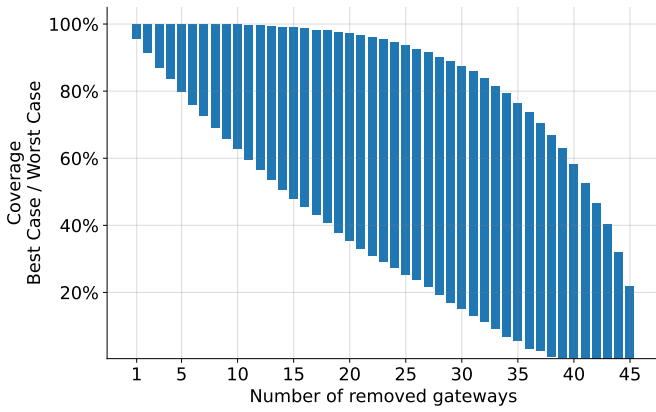


Fig. 9: Number of GWs removed from the network and the effect on the coverage. Depending on the subset of GWs removed, the coverage decreases differently.

Surprisingly, it would be possible to realize 80% of the current outdoor coverage with just 13 (46-33) GWs. However, these 13 locations need to be a perfect subset of all evaluated GWs. It is important to note that this only holds for the outdoor case and would significantly reduce the redundancy factor and therefore also the probability of successfully transmitted packets.

V. SUMMARY AND FUTURE WORK

This work presents selected insights and findings from a measurement study of a typical urban LoRaWAN network evaluating more than 300,000 individual SNR values. We used garbage trucks to collect these values. In addition, we also included SNR values from already deployed indoor heat meters. Based on this dataset, this work answers typical questions for operators of urban LoRa networks.

What is the distribution of the SNR and SF? The analysis of our dataset reveals that the up-link packets have a very good average SNR in our scenario. In addition, we show that the SNR and therefore also the SF can be mathematically modeled using a simple Rayleigh distribution. This knowledge can be incorporated into network planning tools.

What is the average radius of a LoRa cell? Our dataset shows that the average transmission distance is 2 km in a hilly, urban environment. In addition, less than 10% of the transmissions had a distance larger than 4 km. It is important to note, that these are best-case outdoor values since our sensors were mounted on the roofs of trucks.

How many GWs receive a LoRa packet in parallel? Due to the high GW density in the “SWO Netz” network, the average number of GWs receiving a LoRa transmission is more than 5. The effect of this redundancy to a PDR is an interesting future research topic worth to investigate.

If LoRa transceivers are deployed indoors, what is the average additional attenuation due to a building? To provide an initial assessment of building attenuation, we compared our outdoor results with SNR values obtained from 29 different indoor heat meters at 10 different locations. Overall, the average difference between indoor and outdoor measurements

was 8.14 dB with a standard deviation of 6.58 dB. This factor can be incorporated by network operators to better assess the feasibility of different indoor use cases. We acknowledge that a better measurement method is needed to provide a more precise quantification of this value. In particular, we are planning to perform measurements with a variable GW position in direct proximity to different buildings to quantify the attenuation of individual walls.

In a typical urban scenario, how many GWs are needed to provide a city wide reception? Are certain GWs significantly more important than others?

Our analysis reveals that it would be possible to realize 80% of the current outdoor coverage with just 13 GWs cards instead of 46. In addition, we clearly show that certain GWs are more important than others.

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