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LoRaMeter: Signal Mapping in LoRa Networks

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***Abstract*—Knowledge of signal properties of IoT radio technologies like LoRa is usually scarce, although necessary for optimizing such networks or modeling expressive simulation models. This work introduces a small signal-tracking device for LoRa networks, the LoRaMeter, which allows for collecting and determining signal characteristics of received LoRa transmissions within an available LoRa network. LoRaMeter is simple and easy to use, allowing its application as a simple throw-box for static measurement or as a mobile signal-tracking device. The gathered data is automatically uploaded to a backend server to construct a map view of the tracked LoRa signal properties.**

***Index Terms*—LoRa, IoT, LPWAN, Prototyping**

I. Introduction

Resulting from the rise of the Internet of Things (IoT), extensive networks of small battery-powered sensors and actuators are deployed in various applications like Smart Cities or environmental monitoring. Emerging wireless communication technologies specifically designed for IoT applications, such as NB-IoT, SigFox, or LoRa, allow the long-term construction of *Low-Power Wide Area Networks* (LPWANs) with long communication ranges and low power consumption in exchange for low data rates. Especially LoRa networks are getting increasingly common due to relatively cheap and accessible hardware, and the ease of deploying own gateways. This also allows using LoRa communication in locations where no cellular infrastructure for using of NB-IoT or no proprietary SigFox gateways are available.

Another advantage of LoRa is its adaptability to various environments and use cases by adjusting its transmission power and the LoRa parameters of Spreading Factor, Bandwidth, and Coding Rate. Each parameter has a direct impact on the possible transmission range and throughput. Although both can be theoretically calculated based on parameter settings, the actual transmission range depends significantly on environmental factors such as the terrain topology, weather, or obstructing objects like buildings or trees [1]. In addition, national or international regulations may impose a duty cycle or transmission power limitation depending on the used frequency band.

Specific knowledge of possible transmission ranges and expected signal strength is highly valuable and mandatory for deploying and improving LoRa networks. This knowledge dictates the placement of gateways that need to be reachable by all IoT sensors, but also the placement of new sensors that need to reach available gateways, respectively. Thus, there is a need to optimize the placement of sensors and gateways, which

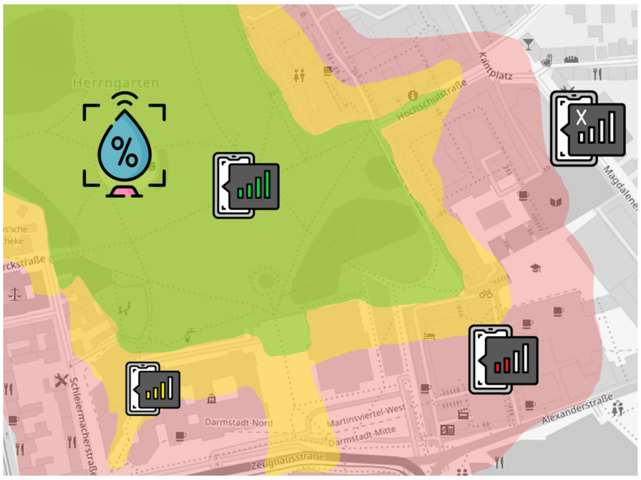


Fig. 1. Exemplary signal strength map of an IoT humidity sensor. (Map and Data © www.osm.org/copyright)

has been actively researched over the last few years. However, this requires a significant effort as LoRa transmissions easily cover several kilometers, and signal propagation is subject to change due to weather and seasons [2], [3]. Furthermore, the self-evaluation of existing networks is only possible if the IoT sensors are programmed for signal measurements in the first place.

To address these issues, this paper makes the following contributions:

- We present the design of the *LoRaMeter*, a handheld LoRa-based metering and tracking device for the non-intrusive evaluation of LoRa networks. *LoRaMeter* does not require interaction and can either be carried around for mobile signal-tracking or used as a simple throw-box for long-time measurement at a specific location.
- We provide a prototypical implementation of the *LoRaMeter* based on an ESP32 microcontroller in combination with a Raspberry Pi-based backend for the evaluation of measurements.
- We applied the prototype in a forest and a city environment to assess the signal propagation with a LoRa sender, respectively, and discuss the results in this context.

The remainder of this paper is structured as follows. Section II discusses related work. Section III describes the design considerations for LoRa signal assessment, followed by the presentation of the *LoRaMeter* prototype and its backend system in Section IV, respectively. Section V provides insights into initial measurements with the *LoRaMeter* prototype in two different environments. Section VI concludes the paper and gives an outlook on future work.

II. Related Work

The assessment of applicability — focusing mainly on connectivity and throughput — is one of the major challenges to face before any deployment of a wireless communication network. Especially for Wireless Sensor Networks (WSNs) and Low-Power Wide Area Networks (LPWANs) in the context of the IoT with hundreds and more devices, evaluation and simulation models are required to determine a suitable deployment before its implementation [4].

However, wireless communication is highly susceptible to obstruction, reflection, or interference [5] on the one hand, but also to external influences like weather and seasons [2], [3] on the other. Assuming a fixed communication range in the network is, therefore, not suitable for most real-world implementations [6], [7]. The typical approach is the use of channel models, which allow the estimation of communication properties [8]. However, they are highly dependent on the right choice of parameters and are, therefore, usually specifically designed for certain scenarios like indoor [9], [10], outdoor [11], [12], or underwater [13] applications, as well as fostered to specific environments [1], [14]–[16]. Furthermore, communication properties also depend on the used technology, that is, for example, WiFi for WSNs and LoRa for LPWANs [3], [5], [11], [17].

With the rise of LoRa as a widespread LPWAN solution, appropriate channel models are required, e.g., for urban IoT networks [14], [15] or within smart buildings [10], [18]. Similar approaches were adopted for large-scale and long-term wildlife monitoring [12]. Determining channel models and communication properties is tedious and expensive because it requires empirical data from within the corresponding environment for a specific model, as it was performed for European, Chinese, or tropical forests [1]–[3], [16]. Furthermore, a realistic assessment for a long-term deployment also requires a model that includes changing influences of weather and seasons, like rain or foliage [2], [3], which also requires a long-term empirical study under realistic conditions.

Overall, assessing LoRa communication properties is challenging. Especially with the large set of possible communication parameters and long communication ranges [19], only a small subset of the available parameter space is typically addressed. Approaches to measure communication properties in already installed large-scale networks under realistic conditions are nonexistent. Typical measurement setups are placed at fixed locations and tailored to specific needs. Therefore, the goal of the LoRa Meter is to provide a small, lightweight, and mobile tool that is inexpensive and applicable for most LoRa applications covering a wide parameter set.

III. Design Considerations

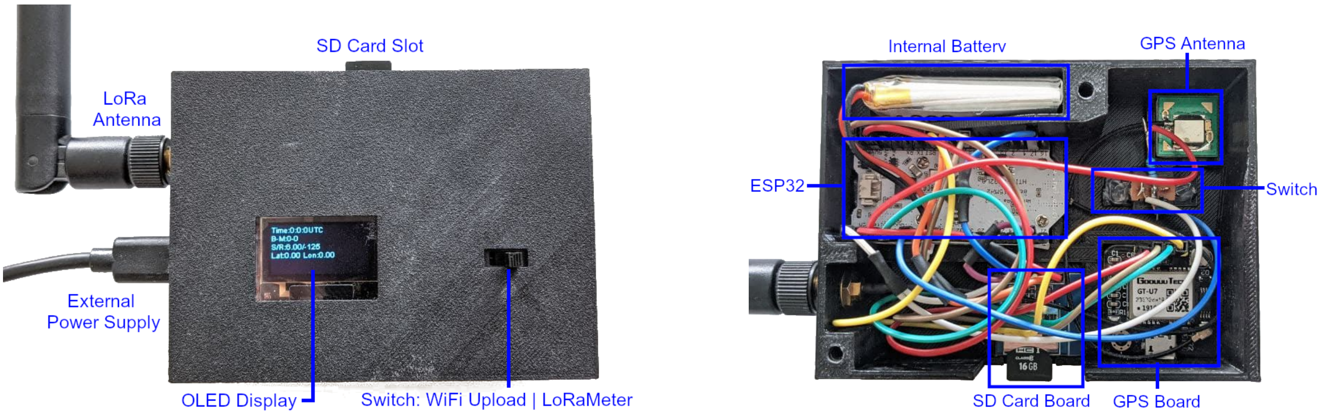
LoRa (short for Long Range) is a low-power, long-range communication technology on the physical layer, which uses a spread-spectrum modulation to allow for robust communication with the tradeoff of low throughput. Its main application lies, therefore, within LPWANs and IoT applications, where sensors only transmit small datasets occasionally, and sensor longevity is most important. The network typically resembles a star topology; thus, multiple sensors send data to a LoRa gateway in a single hop, although it is possible to have multiple gateways serving the same sensors for increased delivery robustness. Prevalent community-driven or commercial gateway providers typically use the LoRaWAN networking protocol. However, LoRa allows setting up own networks and gateways easily without using LoRaWAN. One of the main advantages of the LoRa technology is its adaptability to various environments and scenarios based on the parameters *Transmission Power* (TP), *Spreading Factor* (SF), *Bandwidth* (BW), and *Coding Rate* (CR). A large number of parameter combinations are theoretically possible, influencing signal robustness and, thus, transmission range, throughput, and power consumption, respectively. The interested reader is referred to the work of Bor and Roedig [20] regarding the influence of LoRa parameters. Table I provides a condensed overview of the most common LoRa parameters for usage in EU countries based on regulations given by the *European Telecommunications Standards Institute* (ETSI) [21]. Furthermore, using different *Sync Words* distinguishes several LoRa networks communicating on the same frequency and parameter set.

From a practical standpoint, it is often infeasible to simply change LoRa settings in an existing network, for example, to adapt to external influences or increase coverage to allow the integration of more sensor nodes. Especially low-cost sensor nodes use static settings and cannot be adapted over the air. Manual adaption, on the other hand, requires significant effort especially for large number of sensors. Thus, instead of adapting the network, an additional gateway is placed, or the existing gateway is enhanced with multi-channel capability to allow network extension. Nevertheless, this still requires determining if existing nodes can reach the new gateway on the one hand and where new nodes can be placed on the other.

Therefore, we must first measure the signal properties be-

TABLE I
Overview of commonly used LoRa parameters. Specifications for transmission power and duty cycle are required for usage within the European Union under ETSI regulations [21].

Parameter	Settings
Frequency Band	868 Mhz (SRD), 433 MHz (ISM)
Transmission Power	Up to 14 dBm, channel-specific
Duty Cycle	0.1% or 1%, channel-specific
Bandwidth (BW)	62.5 kHz, 125 kHz, 250 kHz, 500 kHz
Spreading Factor (SF)	7, 8, 9, 10, 11, 12
Coding Rate (CR)	4/5, 4/6, 4/7, 4/8



(a) Outside view of the *LoRaMeter* prototype.

(b) Hardware inside the prototype.

Fig. 2. *LoRaMeter* prototype using an ESP32 with built-in OLED display.

tween the communicating devices. But since LoRa can provide communication over several kilometers, the corresponding areas are vast. Thus, measurements should be conducted automatically, allowing simple throw-boxes to measure specific locations over time or carrying measurement devices around to gather data on an area. As sketched out in Figure 1, the results are used to construct a map view of the signal propagation. In the example of a sending IoT sensor, this allows assessing where gateway placement is possible. If gateways are sending, on the other hand, this similarly allows assessing the gateways' communication distance and, thus, possible sensor placement. In our specific case, we want to collect extensive data on a planned LoRa network in the Marburg Open Forest, an approximately $4\,km^2$ forest of the University of Marburg, Germany. To allow the collection of an extensive dataset in this large area, devices are intended to be given to groups of pupils or students visiting the university forest within the collaborative project *Nature 4.0*[1]. Thus, measurements should not only be conducted automatically without any interaction required, but the device itself should be easy-to-use, small, and lightweight. In the following, we present a prototypical implementation for a metering device as well as preliminary test results for the Marburg forest and an urban environment, respectively.

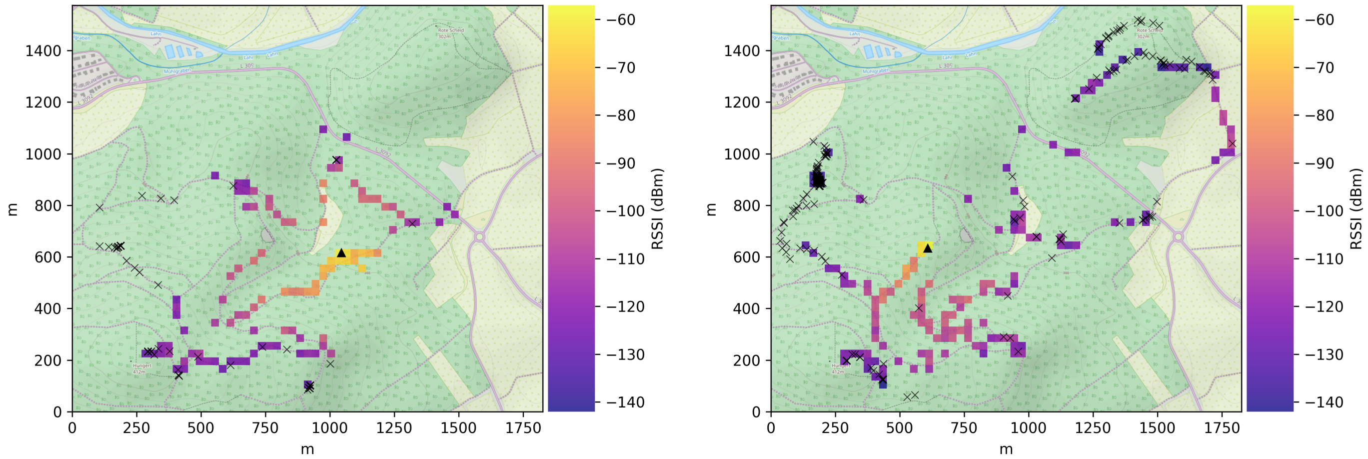
IV. *LoRaMeter* Prototype

Based on these requirements, we designed the *LoRaMeter*, a small metering and tracking device for LoRa signals. Our prototype is realized on the *Heltec ESP32 LoRa WiFi v2*[2] board, providing a 32-bit dual-core 240 MHz LX6 microcontroller and 529 kB internal SRAM with a weight of only 20 g. Bluetooth LE, 2.4 GHz dual-mode WiFi, and one SX1276 LoRa transceiver are available for communication. A 0.96 inch OLED display with 128x64 pixels allows showing important information. The available SPI interface is used to connect a GPS device[3] as well as a standard SD card breakout board. The main program is written in C++ for Arduino and uses the standard library of the Heltec ESP32[4] for LoRa communication and the display, respectively. The entire hardware is located within a 3D-printed casing; front and inside views of the prototype are shown in Figure 2. The prototype can be powered from an external power supply like a standard power bank over a micro-USB port or directly via an internal battery[5] over the ESP's 1.25 mm JST LiPo battery interface. An outside SMA port allows switching antennas for LoRa communication if required. Furthermore, the OLED display, the SD card, and a two-way switch are accessible from the outside. The entire hardware for one *LoRaMeter* costs less than 50 EUR/USD, which is significantly cheaper than comparable off-the-shelf hardware or customary solutions, e.g., based on Raspberry Pi and a LoRa-capable hat.

The *LoRaMeter* backend, where data is collected from different devices and evaluated, is realized on a Raspberry Pi 4 running on Pi OS Lite. The RPi4 serves as a WiFi access point using the RaspAP software and provides an SQL database using MariaDB. Furthermore, a background network service is running, which allows uploading data into the database.

The parameters Frequency, Spreading Factor, Bandwidth, Coding Rate, and Sync Word are specified on each *LoRaMeter* via a config file. Since the ESP32 provides only a single LoRa transceiver, only a single LoRa channel — defined by the combination of parameter settings — can be measured at a time. Furthermore, the SX1276 chip requires a stable and reliable reference frequency to provide robust communication with high spreading factors or low bandwidths[6]. The integrated XO of this ESP device, however, seems to lack the necessary tolerances since communication becomes unreliable for such settings [12]. Therefore, our prototype reliably supports only

[1] Project website: https://www.uni-marburg.de/en/fb19/natur40
[2] https://heltec.org/project/wifi-lora-32/
[3] https://github.com/adafruit/Adafruit_GPS
[4] https://github.com/HelTecAutomation/Heltec_ESP32
[5] The currently installed 1000 mAh battery allows running the prototype for approximately 10 hours.
[6] The current datasheet for LoRa transceivers is provided by Semtech Corporation, www.semtech.com



(a) Beacon 1 located in a lower part of the forest.

(b) Beacon 2 located at an elevated position.

Fig. 3. Preliminary tests performed in a part of the Marburg Open Forest (SF 10, BW 250 kHz, CR 4/5) for two different beacon locations (▲). Maps show RSSI values aggregated within 30x30 m^2 cells. The largest distance between *LoRaMeter* and beacon with a successful reception was approximately 1280 m. The hilly terrain provided an additional challenge to communication with several missed signals (×).
(Maps © www.thunderforest.com, Data © www.osm.org/copyright)

spreading factors 7 to 10 and a bandwidth of 125 kHz or higher.

On startup — i.e., when a power source is connected to the device — parameters in the config file are used to set up the transceiver. A new file is created for the data logging on the SD card with the respective parameter set and the device ID. Afterward, the functionality of the *LoRaMeter* is adjusted with a two-way switch on the front side. On the right-hand position, it continuously listens for LoRa transmissions, collecting information for each received message:

- LoRa signal: Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR)
- LoRa message: Header and Payload size
- Optional items like sender ID, if given in the message
- GPS data: Time, Position (Lat/Lon), HDOP

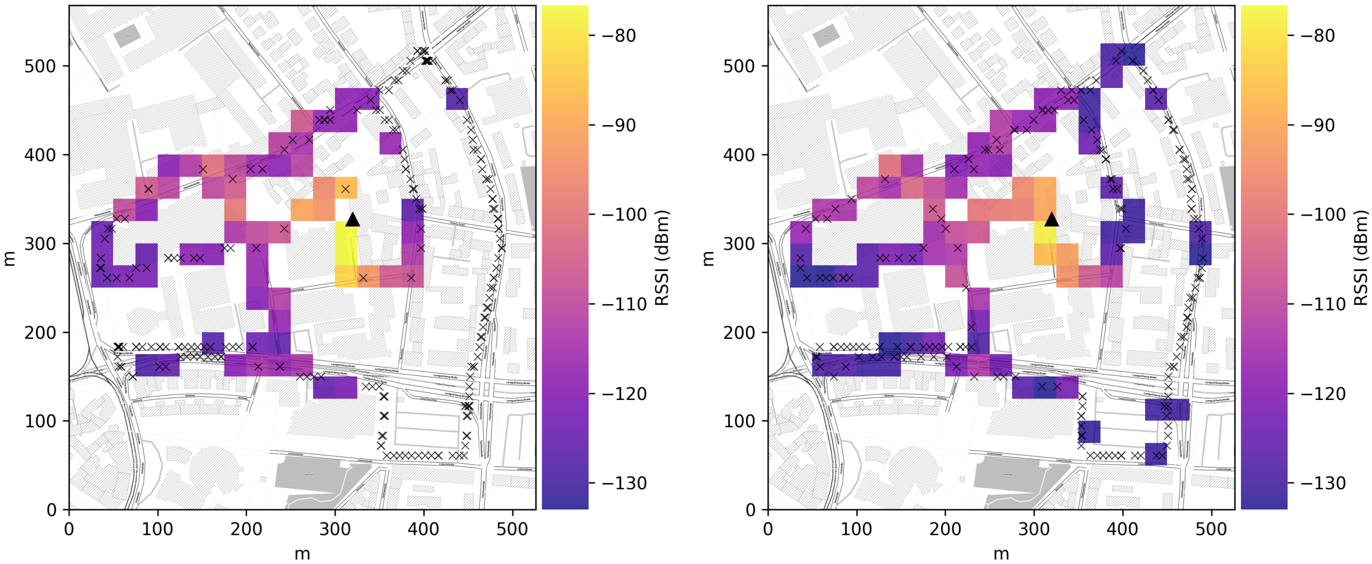
On the left-hand position of the switch, the device actively searches for a connection to the pre-defined WiFi network of the backend server. After the connection is established, all gathered data is automatically uploaded and subsequently inserted into the database via the background service. Information is saved per device; thus, multiple *LoRaMeters* can be used simultaneously for measurement and later be differentiated in the database.

V. Test Results

We conducted a preliminary test in a part of the Marburg Open Forest during the autumn season to assess the applicability of the *LoRaMeter* prototype and the general communication properties in the forest. A LoRa sender similar to our prototype was configured to transmit small beacon messages. The parameter set SF 10, BW 250 kHz, CR 4/5 was chosen to achieve a robust signal while maintaining a relatively small transmit interval of 10 seconds within legal regulations. The beacon was placed on trees approximately 5 meters above ground in two different locations, indicated by a black triangle in Figure 3a and 3b, respectively. The first location was within a lower part of the forest, while the second location was more elevated For both locations, the *LoRaMeter* listened to the beacons of the sender and tracked its GPS location while being carried around. In total, more than 2000 beacon messages were tracked over approximately 8 hours. Missed beacon messages are estimated based on the meter's GPS data and the fixed transmission interval, visualized with a black X mark.

LoRa communication generally performed well despite foliage and the densely forested environment (cf. Figure 3). As expected, the received signal strength is very high within the first 100 meters around the sender. Despite the natural, gradual decrease of the signal with increasing distance, several hundred meters in range were reached without any problems. However, the hilly environment of the forest provides a more significant challenge to LoRa communication than foliage or trees. Even slight elevations in the terrain are able to block signals completely — as, for example, best seen in the eastern part of the forest where a hill slope blocked communication entirely. The largest distance measured for a successful reception was around 1280 m between beacon and *LoRaMeter*, to the North-East part seen in Figure 3b. Nevertheless, the terrain did not allow any further increase, but we expect larger distances to be possible with no terrain in-between. Furthermore, a few beacons were also missed at locations where other beacons were received, which could be addressed to an unfavorable antenna orientation due to the movement of the *LoRaMeter* that prevented a reception.

An additional problem we encountered during these tests was the GPS satellite signal quality in the forest. The *horizontal dilution of precision* (HDOP) was, on average, around



(a) Spreading Factor 8.

(b) Spreading Factor 10.

Fig. 4. Experimental results for SF 8 and 10 (BW 250 kHz, CR 4/5) in a city environment. For both tests, the sender is placed at the same location (▲). RSSI measurements are aggregated within 25x25 m^2 cells. The westward area is shadowed by dense rows of buildings, indicated by missed signals (×). The eastward area with more open space provides longer communication distances in general.
(Maps © maps.stamen.com, Data © www.osm.org/copyright)

15 meters. Thus, we use tiles of 30x30 m^2 to aggregate the measured RSSI values in the map view. Furthermore, the *LoRaMeter* occasionally lost its GPS signal and required several minutes to find enough satellites again for localization. Presumably, this can be accounted to influences of the terrain and foliage, as the signal was lost regularly on the path north of beacon 2 (approx. 600/800 in Figure 3) and in a narrow trench leading to the road in the east (approx. 1000/1000). There, we can neither attribute received beacons to a specific location nor estimate missed beacon messages within our prototypical implementation. However, interpolating between known GPS locations could be used to estimate missing measurement points, but his is out of the scope of this work.

To assess the impact of different LoRa parameters with the LoRaMeter, we ran additional experiments with varying parameter sets on a smaller scale around the university city district in Darmstadt, Germany. A beacon was placed on a west-facing balcony in front of a building at approximately 10 m height. Experiments were conducted with a bandwidth of 125 kHz and 250 kHz, as well as a spreading factor of 8 and 10, respectively. The coding rate was set to CR 4/5, and beacons were sent at the maximum possible rate in adherence to the duty cycle restrictions. Figure 4 visualizes the results for the experiments of BW 250 kHz using SF 8 and SF 10, respectively. As the GPS HDOP was between 10 to 15 meters, we chose to aggregate measurements in 25x25 m^2 cells. Clearly, the densely built-up area poses a more significant challenge to LoRa communication than the forest, which was to be expected as a result of the more severe signal attenuation from buildings. In contrast to the forest, more beacons are missed despite a reception of other beacons in the same area. Furthermore, only a few transmissions were received behind the buildings in the west, with SF 10 only performing slightly better than SF 8, i.e., at streets or pedestrian passages with fewer blockages. Larger distances were covered eastwards, as this area was more open in the facing direction of the beacon antenna, although only attributing to around 300 meters.

Comparing the results for the different parameter settings in each experiment run, we see that the city layout is the most prominent influence factor on signal propagation. Although the anticipated benefit of using a higher spreading factor or a lower bandwidth to increase RSSI and SNR is recognizable from the experimental data, its influence on the overall communication properties is rather small. That is, signals can be better at a specific location for a more robust parameter setting, but moving just a few meters in the shadowing area of a building can block signals for both, regardless. The perceived packet loss — which is roughly 51% for the experiments with SF 10 and increases to more than 60% for SF 8 experiments — also highlights the problematic propagation of LoRa communication in tightly built-up environments. Nevertheless, using the *LoRaMeter* revealed that the beacon placement was unsuitable for providing LoRa coverage to the west of it due to blocking buildings.

The direct comparison of experiments for the forested and the city environment underline that, on the one hand, LoRa is well suited for long-range communication but, on the other hand, highly susceptible to environmental influences that restrict its application. Clearly, longer transmission ranges were reached in the forest environment with the most restrictive feature being the terrain, while trees and foliage are only a lesser influence factor. In the direct surrounding of the sender, very low RSSI values around –60 dBm were measured, increasing up to –142 dBm for the largest distance at 1280 m.

Contrastingly, the lowest RSSI in the city environment was around –75 dBm even in the direct vicinity of the beacon, while the highest RSSI was –133 dBm before no communication was possible at all. We used the *LoRaMeter* in both environments to determine the signal and communication characteristics from a specific sender we placed for the respective experiments. However, it could be similarly applied to track signals of multiple senders of an existing LoRa network to determine a suitable placement for a receiving gateway. On the other hand, a gateway could be configured to send beacons, such as performed in the experiments, which allows using the *LoRaMeter* to determine its reach and suitable locations for sensors. In addition, whenever the sender uses a fixed interval the knowledge of the *LoRaMeter*'s GPS location allows determining packet loss and, thus, identifies hard-to-reach or unreachable areas.

VI. Conclusion

Assessing radio propagation characteristics is crucial for deploying and optimizing LPWAN networks but is also highly specific to the scenario, environment, and used communication technology. This work presents the *LoRaMeter*, a small measurement device that automatically tracks LoRa signals. It can be used as a throw-box to make static measurements or carried around for mobile measurements without any interaction necessary. *LoRaMeter* is easily configurable to a wide variety of LoRa parameter combinations, like spreading factor and bandwidth, and is intended as a generally utilizable LoRa measurement tool for researchers. A prototypical implementation with an internal battery allows measurements of up to 10 hours while tracking incoming signals. Initial experiments in a forest and a city environment highlighted its applicability as a measuring tool and its capability to assess signal propagation under realistic conditions. Thus, *LoRaMeter* provides the basis for extensive measurements to help evaluate and model LoRa channel characteristics in detail.

In the future, we will address some issues that emerged during the experiments with the *LoRaMeter* prototype. For example, the GPS module suffers from temporary signal losses and a long recovery time, probably due to the integrated GPS antenna. Attempts to use a larger external GPS antenna solved these issues and showed a significantly quicker initial detection of satellites. Nevertheless, the applicability of incorporating a significantly larger antenna in the device design still needs to be clarified as it opposes the third issue, that is, the yet relatively large extent of the prototype device. A size reduction could further increase its acceptance by students, pupils, or researchers alike to carry the *LoRaMeter* around for extensive measurements.

Overall, improving the *LoRaMeter* and the showcased map visualizations are essential factors to advance the practical evaluation of LoRa communication properties using various parameter sets and within a plethora of environments.

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