IoT Cloud RAN Testbed for Indoor Localization based on LPWANs

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***Abstract*—Indoor localization is a highly researched topic as applications such as asset tracking can provide an enormous benefit for users. As GPS is typically not available indoors, smart phones employ WiFi fingerprinting to locate themselves inside buildings. Such localization is also highly interesting in context of Internet of Things (IoT). Low Power Wide Area Networks (LPWAN) offer cost-effective and long-range connectivity for IoT. Employing this approach, LPWAN sensor nodes can be localized using the received signal level at multiple LPWAN receivers. For testing the performance of LPWAN fingerprinting and the development of new algorithms we developed and installed a network consisting of 21 LPWAN receiver stations on the area of the NuernbergMesse, i.e. the international fair of Nuremberg, Germany. The infrastructure is realized as Cloud RAN (Radio Access Network). This means that the receivers only digitize the channel and the actual decoding of the signals is realized in the Cloud. As a result, the infrastructure is able to support the localization of many state-of-the-art LPWAN system. Initial measurements show the high performance and flexibility of the system. This paper gives an overview of the developed network components and shows the initial measurement results.**

***Index Terms*—IoT, Indoor Localization, LPWAN, Cloud RAN, Software Defined Radio**

I. Introduction

Low Power Wide Area Networks (LPWAN) enable cost-effective and long-range connectivity for the Internet of Things (IoT). This technical goal is achieved by very low payload bit-rates that are used by these systems [1]. Transmitter with only $10\,\mathrm{mW}$ can transmit over distances of several kilometers. Typical examples for LPWAN systems are LoRa[1], mioty[2], or sigfox[3]. However, many IoT use-cases do not only require data connectivity, but also localization. The use of satellite based localization systems may require too much energy for tiny LPWAN sensor nodes. Additionally, it may not even be possible in case of indoor localization. An interesting alternative approach – which is extensively used with WiFi – is the use of localization algorithms based on fingerprinting [2]. In the context of a LPWAN multiple base-stations receive the data of a specific sensor node. Based on the Received Signal Strength Indicator (RSSI) in addition to a fingerprinting database the position of the sensor node can then be estimated. The localization precision then depends on a variety of parameters, e.g. the number of base-stations that receive the signal, or the accuracy of the database. Work on the localization of LoRa and sigfox already exists [3]. However, in order to enable precise comparisons between different LPWAN systems we developed a Cloud RAN (Radio Access Network). This extends our system presented in [4] and offers the possibility to test the different LPWAN systems with respect to localization based on fingerprinting in a realistic application scenario.

The remainder of this document is structured as follows: Section II presents our Cloud RAN concept and its main components. Then section III shows the LPWAN testbed located at the NuernbergMesse. Finally, section IV shows initial measurement results and section V concludes the document.

II. Components of the Cloud RAN

The main advantage of the Cloud RAN is its flexibility. The network only digitizes the communications channel with sufficient bandwidth. The data are then transfered to the “Cloud” via broadband access and decoded there [5]. Hence, multiple LPWAN systems can be supported, and also multiple decoders for the same LPWAN system can be operated simultaneously to compare their performance. In contrast to many other communication systems, LPWAN are very suitable to Cloud RAN as the required signal bandwidth, and hence, also the resulting data rate for the transmission of the digitized data is limited.

Figure 1 gives an overview of our developed Cloud RAN. Multiple receiver stations at different locations digitize the transmission channel between $868\,\mathrm{MHz}$ and $868.3\,\mathrm{MHz}$, and transfer the data via the open Internet to a gateway that collects the data of the different receivers. Multiple LPWAN decoders access this data and then publish the decoded data as well as additional meta information on a MQTT broker and store it in a database. This information is then accessible to the localization algorithms. The complete Cloud RAN chain is realized using Software Defined Radio (SDR) based on a

[1]https://www.semtech.com/lora (accessed June 2021)
[2]https://mioty-alliance.com (accessed June 2021)
[3]https://www.sigfox.com (accessed June 2021)

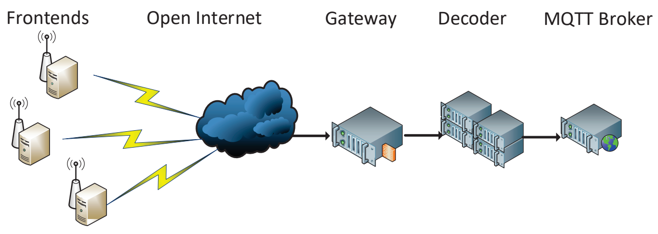

Fig. 1. Overview of the developed Cloud RAN system.

DFC++, a SDR framework implemented in the programming language C++ [6]. The next sub-sections will give additional insight to the different blocks of the reception and decoding chain.

A. Receiver Stations

The precise localization based on fingerprinting algorithms requires a high density of receiver stations. Consequently, low costs are essential for these stations. On the other hand sufficient processing power offers more flexibility. Hence, the receiver stations base on the Raspberry Pi 4b[4]. This platform is cheap, has high processing power, and offers excellent software support due to a big community. Furthermore, the SDR frontend bases on the low-cost Realtek RTL 2832u chipset[5]. Figure 2 shows the block diagram of the receiver station.

The RTL receiver chip was originally developed for the reception of digital television, but also supports the sampling of the channel up to a bandwidth of approx. $2\,\mathrm{MHz}$ utilizing an eight bit A/D converter. Due to its low-cost design, the frontend has a high noise figure (approx. $8\,\mathrm{dB}$) and linearity issues, especially caused by nearby cellular phones. In order to improve the overall performance of the frontend we added an additional SAW (surface acoustic wave) filter. The filter has a very narrow passband of $868\,\mathrm{MHz}$ to $868.3\,\mathrm{MHz}$ and offers a stopband attenuation of up to $40\,\mathrm{dB}$, which makes the system very robust against interference, e.g. from nearby cellular phones. A drawback of SAW filter is its high attenuation in the passband, which is approx. $3\,\mathrm{dB}$ for the used filter type. Therefore, we added an additional low-noise amplifier to reduce the effect of the high noise figure of the frontend. This finally results in an overall measured noise figure of approx. $5\,\mathrm{dB}$ of the complete receiver. Thus, the system is able to receive mioty LPWAN packets down to a level of $-135\,\mathrm{dBm}$, whereas first clipping of the device starts at above $-70\,\mathrm{dBm}$. Consequently, the eight bit device offers a significant dynamic range for measurements. The receivers are calibrated with an accuracy of better than $1\,\mathrm{dB}$. For this purpose, the system also compensates the frequency response of the SAW filter in the passband.

[4]https://www.raspberrypi.org/products/raspberry-pi-4-model-b (accessed June 2021)

[5]https://www.realtek.com/en/products/communications-network-ics/item/rtl2832u (accessed June 2021)

Fig. 3. Picture of the frontend.

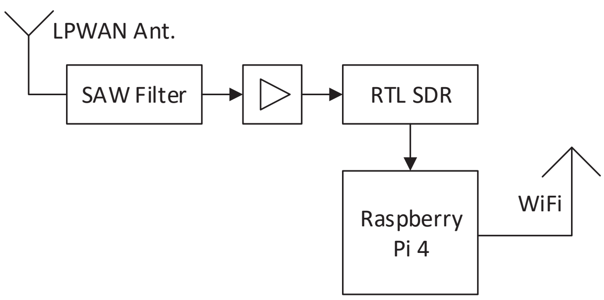

Fig. 2. Block diagram of the low-cost receiver stations.

Figure 3 shows a picture of the complete receiver station, which has a size of $160 \times 100\,\mathrm{mm}$ and consumes an electrical power of approx. $5\,\mathrm{W}$. All stations are equipped with a simple $\lambda/2$ omni-directional rod antenna. The receiver station furthermore pre-processes the data and sends it to the gateway via the open Internet using WiFi or Ethernet.

B. Data Communication

The receivers digitize the channel with a bandwidth of $300\,\mathrm{kHz}$. If transmitted uncompressed, this would result in a data rate of $4.8\,\mathrm{Mbps}$. This rate can be theoretically transmitted via the open Internet, but is sums up if many receiver stations are used. Consequently, the receiver stations compress the sampled data to reduce the required bit-rates. This goal is achieved by algorithms already known from audio compression standards. First, the sampled frequency range is segmented into different frequency bands [7]. Then, the bit-resolution of each frequency bands is reduced to sufficiently represent the received data. Finally, the entropy coding based

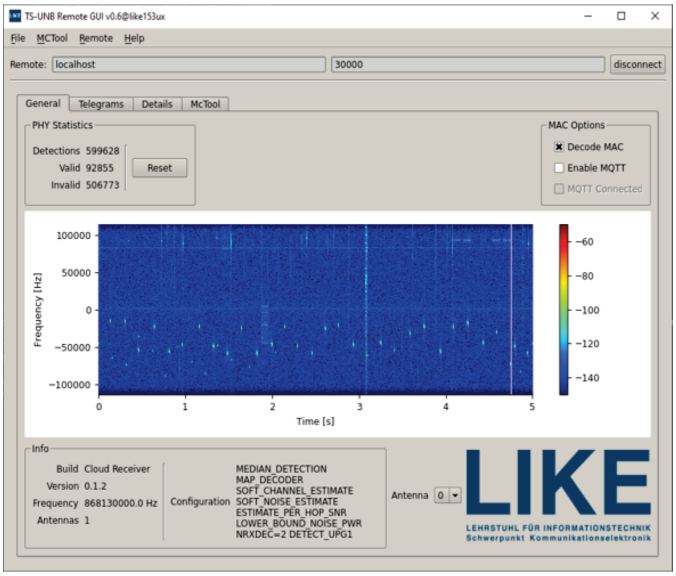

Fig. 4. Mioty (ETSI TS 103 357) decoder.

on Huffman [8] coding is used to further reduce the required bit-rate. This finally results in a required bit-rate of approx. 300 kbps to sufficiently represent the sampled channel.

C. Decoder

The actual decoding of the data packets to obtain the payload data is the task of the decoder. This gives maximum flexibility, as the decoder is fully implemented in software. Furthermore, the decoders are located in the premises of the LIKE, giving maximum flexibility for future extensions, as multiple decoders may access the same data stream. Currently, the decoders are only able to decode data according to ETSI TS 103 357 [9, Sec. 6] alias mioty. For this purpose SDR receivers of the Fraunhofer Institute for Integrated Circuits IIS[6] as well as our own SDR mioty decoder are used. Figure 4 shows a screenshot of our decoder that is fully implemented in the programming language C++ using the DFC++ SDR framework [6]. Furthermore, the graphical user interface bases on the programming language Python. Our decoder is optimized for the precise estimation of all transmission parameters using iterative decoding schemes. The decoder then passes the payload data as well as the corresponding meta data to the MQTT broker for further processing.

As aforementioned, the system currently only supports mioty. However, extension to cover also other systems are planned. Due to the flexible Cloud RAN approach only the decoder has to be created, while extensions to the other parts of the reception chain are not required.

D. MQTT Broker

As aforementioned the system consists of multiple decoders. These are essential as precise fingerprinting localization requires the RSSI values of multiple decoders. Additionally, multiple programs using different localization algorithms may have to process the very same data. An efficient way to handle this multiple source and multiple client problem is the use of the Message Queuing Telemetry Transport (MQTT) protocol [10]. MQTT is a well known protocol in the area of IoT. As it is optimized for short messages it exactly fits the needs of LPWAN systems. Additionally, powerful open source implementations (e.g. Mosquitto[7]) are available. Furthermore, the Fraunhofer IIS decoder as well as our decoder support MQTT, and other communication systems can be added easily. The MQTT messages use the JavaScript Object Notation (JSON) Data Interchange Format [11] as shown in Figure 5. Hence, additional meta-information – such as the RSSI level – can be easily added to the payload data.


```
{
  "bsEui": 70B3D56770FF00FF,
  "data": [8, 6, 16...
  "rssi": -127.12289810180664,
  "snr": 4.014908075332642,
  "time": 1626705776736984004,
  ...
}
```


Fig. 5. Format of the MQTT messages: The data and the additional meta-information use the JSON format. Besides the payload data in the "data" field the JSON data also contains the identifier of the receiver ("bsEui"), the RSSI, the SNR, or the receiving time.

III. NuernbergMesse Test Network

The actual Cloud RAN test network has been installed within the buildings of the NuernbergMesse. This is the international fair of Nuremberg, Germany, which covers an area of approx. $1\,\mathrm{km}^2$. Figure 7 shows the locations of the receiver stations. There are in total 21 receiver stations distributed across the site. Stations 1 to 20 are low-cost receivers as described in section II-A. In contrast, station 21 bases on a high-end frontend, as it is intended to cover the complete south of Nuremberg with LPWAN connectivity. It uses an Ettus URSP B210[8] frontend. Using additional filters and amplifiers it reaches a noise figure of about 2 dB with high robustness against nearby cellular base-stations.

Figure 6 shows the antenna installation of station 21, which uses two antennas (marked N for north and S for south) and is located on top of the tallest fair building. It is able to receive LPWAN nodes – typically transmitting with 10 mW – within a radius of up to 15 km.

The locations of the low-cost receiver stations were optimized to enable localization based on fingerprinting algorithms across the whole site. The antennas 1-10, 12, 14, 15, 17-19 are placed in the ground floor. The antennas 11, 13, 16, and 20 are located in higher floors (11-third; 13-second;

[6]https://www.iis.fraunhofer.de/en/ff/lv/net/telemetrie.html (accessed June 2021)

[7]https://mosquitto.org (accessed June 2021)

[8]https://www.ettus.com/all-products/ub210-kit (accessed July 2021)

Fig. 6. Receiver 21 on the rooftop of the tallest fair building. The Cloud RAN antennas are the two antennas in the center of the picture. The spacing between the antennas is exactly four wavelength, i.e. $1.38\,\mathrm{m}$ with N/S.

16-fourth; 20-fifth). This shall also offer localization on the different floor levels. The proper functioning of the network was validated with measurements across the different halls in NuernbergMesse. Some initial measurement results for the the measurement point M_1 (located in NCC (Nuernberg Congress Center) East) will be presented in section IV.

The localization algorithms can then obtain the required data from the MQTT broker as described in section II-D. Furthermore, all data is stored in a database for later processing.

IV. Initial Measurement Results

In order to test the function of the complete network, initial measurements were performed to analyze the performance as well as the stability of the overall installation. In each of the halls (numbered from 1 to 12) and the larger buildings transmission characteristics were recorded. Within this paper we will only present the measurement results taken in building NCC East, marked by M_1 in Figure 7.

A. Asset Tracking Sensor Nodes

For the test network we developed special sensor nodes for asset tracking applications. Figure 8 shows the node that has a size of $60 \times 30 \times 15\,\mathrm{mm}$. The sensor node is equipped with a variety of different sensors (light, temperature, acceleration). The used coin type battery CR 2032 is able to power the device for more than one year. Furthermore, the node uses mioty [9, Sec. 6] and the effectively radiated power is in the order of $1\,\mathrm{mW}$. Due to its small size the sensor can be attached to different items in order to track them. The sensor then transmits data in regular intervals or if specific sensor conditions (e.g. free-fall detection) are fulfilled.

Fig. 8. Image of the sensor node used in the measurements. The size of the complete sensor node is approx. $60 \times 30 \times 15\,\mathrm{mm}$.

For calibration purposes we used another sensor node shown in Figure 9. This node has been also developed by us and offers the possibility to connect an external antenna, which leads to better calibration results. We used this node equipped with an omni-directional rod antenna and a transmit power of $10\,\mathrm{mW}$ during the initial measurements.

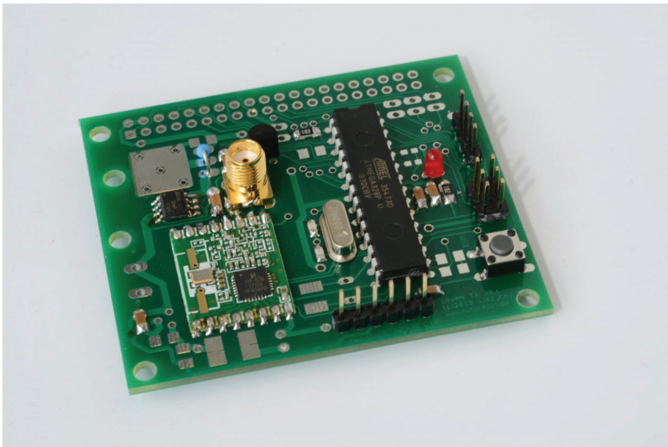

Fig. 9. LPWAN sensor node for calibration purposes.

B. Network Coverage and Stability

As aforementioned, measurements were performed at different locations. The main target was the estimation of the network coverage as well as the stability of the network. For this purpose, approx. 30 positions were characterized across the fair area. At each position data were collected over a time-span of 5 minutes with a packet rate of 5 packets per minute, which leads to about 25 measurements for each location.

Generally, the sensor nodes were always received by multiple receivers, which is an important requirement for precise fingerprinting localization. Furthermore, the measurement results indicate that the received RSSI also remains stable if the transmitting sensor node is not moved.

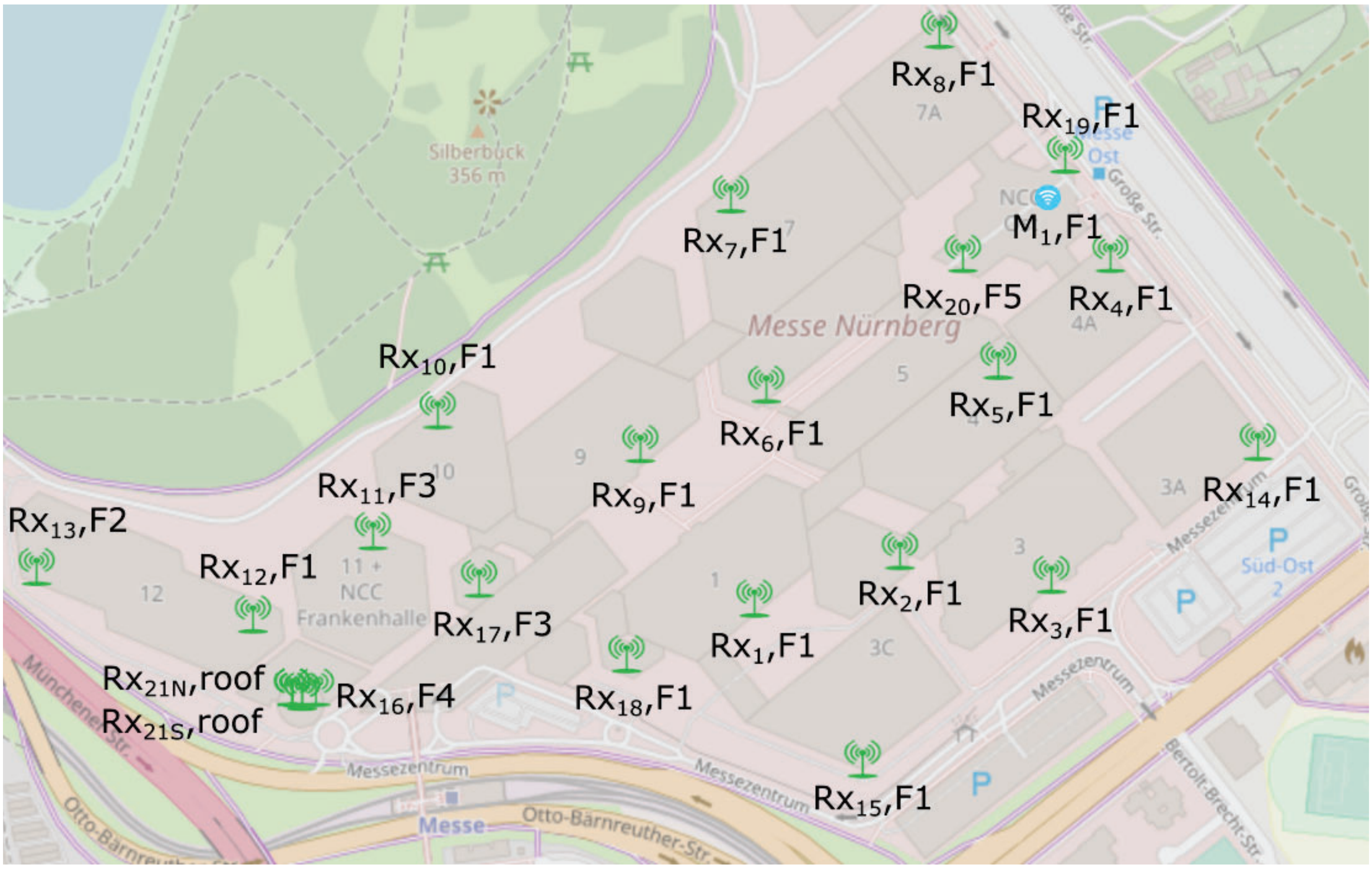

Fig. 7. Distributed LPWAN receivers forming the IoT infrastructure at the NuernbergMesse. The “F” indicates the floor level of the receiver. The width of the map corresponds to approx. $1\,\mathrm{km}$. © OpenStreetMap-Contributers.

Figure 10 shows the received RSSI of a node placed at location M_1 (cf. Figure 7) over 5 minutes. This exact location is the ground floor in the entry hall of the building NCC East. Receiver 19 shows the highest RSSI levels. The level of $-63\,\mathrm{dB}$ indicates that the receiver is already clipping and the actual RSSI may be even higher. Though, this is no real surprise as there is a line of sight connection and the distance is in the order of $30\,\mathrm{m}$. Also receiver 20 shows a high reception level. This receiver is located in the same building on the fifth floor without line of sight. However, the big atrium of the entry hall offers excellent propagation conditions to the higher floors. The other receiver stations are located in other buildings, leading to significantly higher propagation losses.

TABLE I
MEAN AND STANDARD DEVIATION OF THE RSSI FOR DIFFERENT RECEIVERS.

Receiver ID	4	8	19	20	21N	21S
μ [dBm]	-129.7	-117.3	-62.8	-83.7	-125.4	-128.2
σ^2 [dB]	0.5	0.6	0.3	0.2	0.8	1.3
Distance [m]	70	100	30	50	700	700
Floor	1	1	1	4	Roof	Roof

Table I shows the mean reception levels μ as well as the dB standard deviation σ^2. Generally, the mean reception level μ depends on the distance and the number of walls between the transmitter and the corresponding receiver station. However, the dB standard deviation between the different measurements is very small. This indicates that the receivers are able to precisely estimate the RSSI, even in case of lower reception levels and higher distances. Also the use of different channels within the supported frequency band between 863 and $863.3\,\mathrm{MHz}$ has no noticeable effect. However, due to Covid-19 the fair was closed to the public. Consequently, there were almost no people on the fair area during the measurements. Hence, a significantly higher variance can be expected during a fair. This will most likely especially hold for the RSSI values in other buildings. Keyholes for the propagation – e.g. open doors between the halls – will show significantly changing propagation conditions with people walking around.

V. Summary and Conclusions

This article presented a Low Power Wide Area Network (LPWAN) testbed for the deployment of Internet of Things (IoT) and indoor localization using fingerprinting algorithms. The network uses a Cloud RAN (Radio Access Network) approach that offers the flexible support of different LP-WAN systems. Furthermore, this paper presented the different building blocks of the developed Cloud RAN. The system

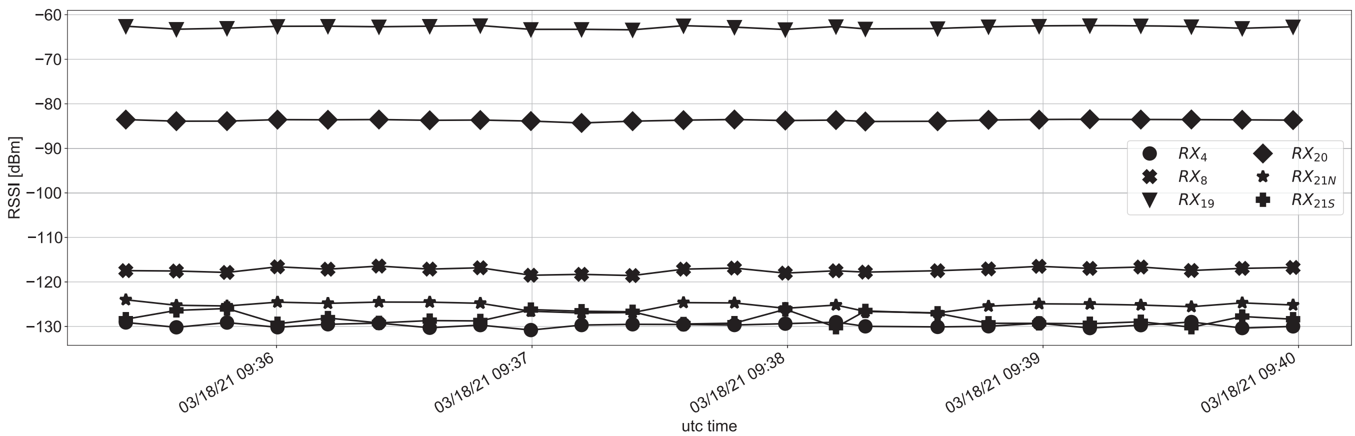

Fig. 10. RSSI of different receiver stations for a transmitter placed at position M_1 (entrance hall of NCC East).

consisting of 20 low-cost and one high performance receivers was installed on the area of NuernbergMesse, the international fair of Nuremberg, Germany. First measurements prove the robustness of the installed system. Especially the Received Signal Strength Indicator (RSSI) shows a very precise estimation, even at very low reception levels.

The future work will mainly focus on the detailed analysis of different IoT systems based on LPWANs and fingerprinting algorithms for indoor localization. The goal is to provide higher location accuracy within the buildings. Therefore, also other algorithms – e.g. in the area of machine learning – are considered and will be analyzed using the presented testbed. Of special interest is also the performance in case of highly changing environments, e.g. during fairs.

Acknowledgment

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