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Urban Channel Models for Smart City IoT-Networks Based on Empirical Measurements of LoRa-links at 433 and 868 MHz

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***Abstract*—The vision of Smart City is to enable new use cases being overall connected. Considering a large number of Internet of Things sensors and challenging channel characteristics, new technologies evolve facing these new challenges. A promising solution to meet such requirements are Low Power Wide Area Networks. In this paper, a LoRa availability analysis is carried out to analyze performance of a Low Power Wide Area Networks representative in the 433 MHz and 868 MHz ISM bands considering a Smart City Internet of Things scenario, resulting in signal ranges up to 5.8 km. Additional reliability measurements show that indoor and outdoor LoRa nodes are able to achieve a Packet Delivery Rate of over 99% within a range of 4.8 km, depending on their installation side. The results of these measurements are compared with established empirical channel models. Due to the insufficient prediction accuracy of the established models in the examined Smart City area of Dortmund, Germany, two new path loss models for urban areas are presented for both the 868 MHz and 433 MHz frequency bands.**

***Index Terms*—Smart City, LoRa, Range analysis, Path loss models**

I. Introduction

With the sustained fast digitalization of everyday life, existing communication technologies are faced with new challenges. Upcoming scenarios like Smart Waste Management where all garbage cans in the city inform the waste collection services if they need to be emptied, promise a better planning of services, making the city smarter. To meet resulting challenges of high scalability as well as low energy consumption and high communication range for easy and low-cost deployment, new technologies have emerged, facing the rising Internet of Things (IoT) with billions of devices being developed digitally. In doing so, the establishment of suitable communication networks should be handled quickly, simply and affordable.

To examine and evaluate the requirements deploying an urbanized Smart City communication network, the TU Dortmund university has set up a Low Power Wide Area Network (LPWAN) in the city of Dortmund, Germany, using LoRa as a network technology. LoRa modulation promises long lifetime of battery powered end devices, low cost installation and high ranges with data rates between 0.3 kbit/s and 11 kbit/s [1]. Though the actual range depends on the data rate and frequency used as well as on the propagation conditions found on the installation site. This paper focuses on the range and performance evaluation considering a real world availability and reliability analysis in the urban area of Dortmund, comparing the results with established empirical path loss models. Most LoRa installations are using the 868 MHz band in Europe, which has significantly better propagation characteristics compared to the 2.4 GHz ISM band. Additionally, LoRa systems are also available for the 433 MHz ISM band, which further reduces path loss, but comes with a reduced maximal equivalent isotropically radiated power (EIRP) of 10 dBm in contrast to 14 dBm using 868 MHz. This paper examines both 433 MHz and 868 MHz systems, analyzing which system performs better.

For designing a Smart City communication system the knowledge of propagation characteristics is fundamental. Reducing the costs of a Smart City rollout, the number of LPWAN gateways should be as low as possible. For this purpose empirical path loss models can be used to estimate the necessary amount of gateways. Reflecting the measurement samples of the availability analysis, the suitability of established empirical path loss models such as Okumura Hata, ITU Advanced, Winner+ and 3GPP Spatial Channel Model for narrow band LoRa signals will be examined.

Therefore, this paper is organized as follows: Section II briefly outlines previous studies of LoRa range and performance analysis, while Section III introduces LoRa as an emerging LPWAN technology for the IoT. In Section IV the Smart City scenario of Dortmund as well as the measurement setup is introduced, followed by presenting the results of the availability and reliability analysis in Section V. Finally a suitability analysis of path loss models is

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examined in section VI, whose results are concluded in Section VII.

II. Related Work

In order to analyze the coverage of LoRa, the authors in [2] provide real world measurements in the mostly rural area of Oulu, Finland, using commercially available equipment. The measurements were executed for scenarios when a node is located on land (attached on the roof rack of a car) or on water (attached to the radio mast of a boat), reporting their data to a base station.

In [3] the authors present a preliminary set of measurements evaluating the performance of LoRa in a high density urban area (Melbourne's Central Business District). The results show that loss free communication is assured only within a radius of approximately 200 meters from the base station and total loss of transmission occurs at around 600 meters, showing the high challenges of gateway installations in high density urban areas. This paper also uses a high building for the gateway installation, but in a medium density urban area, resulting in better propagation results up to 5.8 km.

The authors in [4] simulatively compare the coverage and capacity of SigFox, LoRa, GPRS and NB-IoT, using a real site deployment covering $8000\,\mathrm{km}^2$ in Northern Denmark using the positions of the Telenor cellular site grid hardware. The simulation based analysis shows that all four technologies were able to reach 99 percent outdoor coverage. Taking these results into account, it is shown that cellular installation points are suitable for LoRa gateways, too, approving the installation site introduced in this paper, as it is a cellular installation point as well.

III. LoRa: A long range IoT network solution

With the increasing interest in IoT various technologies are being developed to address the requirements for the integration of intelligent devices, purposing low power consumption and wide area signal coverage. This paper focuses on the requirements of high coverage with respect to an easy and low cost installation and operation.

As some of the LPWAN technologies are still under development, technologies like LoRa and SigFox are already widely available on the market. Regarding to low cost operation, LoRa based networks should be chosen over SigFox based networks, considering the need of a SigFox subscription for each device, resulting in running expenses for each connected device [5]. Being able to set up a proprietary network, this paper focuses on the evaluation of a LoRa based Smart City network.

When using LoRa, a distinction must be made between LoRa and LoRaWAN. While LoRaWAN describes a full communication protocol mapping to the second and third layer of the OSI model, LoRa is the physical modulation used to transmit data for high ranges [1]. LoRa modulates the signal using a proprietary spread spectrum technique, which spreads a narrow band input signal over a wider channel bandwidth. The spreading of the spectrum is achieved by generating a chirp signal, that continuously varies in frequency, allowing distant receivers decoding a severely attenuated signal several dBs below the noise floor.

The achievable data rate using LoRa modulation is based on the following factors:

1) Spreading factor: To ensure an adaption of data rate and signal range, various spreading factors (SF) between 7 and 12 are available, affecting the gradient of frequency variation and thus the energy per symbol. The higher the energy per chirp symbol, the higher the achieved signal range will be. Though a higher spreading factor leads to a longer symbol transmit time, decreasing the overall data rate.[6]

2) Bandwidth: LoRa based devices support bandwidths (BW) from 125 kHz up to 500 kHz [7].

3) Coding Rate: To further improve the robustness of the LoRa communication link, the devices implement cyclic error coding performing forward error correction. Such error coding incurs an additional transmit overhead, which depends on the chosen coding rate (CR) [7].

IV. Field Test Environment: Smart City Dortmund

The real world range analysis is performed in the urban area of Dortmund, Germany. Dortmund is inhabited by 600,000 people on an area of $280\,\mathrm{km}^2$, which leads to an average inhabitants density of 2143 people per km^2 [8]. Due to the definition of different area types [9] the real world range analysis presented in this paper is based on a well urbanized area and thus a high attenuation is expected.

For the measurement of LoRa in the 868 MHz ISM band Pycom LoPy modules are used as LoRa nodes and gateway to determine the performance of the LoRa technology. For the analysis of LoRa's 433 MHz characteristics the gateway uses a Dragino LoRa 433 MHz/GPS Hat mounted on a Raspberry Pi. Although the regulations allow the transmission in the 433 MHz ISM band with up to 10 dBm, the gateway transmits with 3 dBm due to hardware restrictions. The 433 MHz node uses an Adafruit Feather 32u4 RFM96 433 MHz LoRa radio. Tables I and II list the used parameters for the real world range and performance analysis. Note that for the real world measurement parameters are set to the most robust

Fig. 1: Installation site of Smart City LoRa Gateway antennas in 30 m height and fixed LoRa nodes A to F (left) as well as Pycom LoRa measurement node (middle) mounted on car (right).

communication link for the complete measurement, determining the maximum range of the installed LoRa based network.

TABLE I: LoRa 868 MHz parameters.

Characteristics	Gateway	Node
Module	Pycom LoPy	Pycom LoPy
LoRa Chip	Semtech SX1272	SX1272
Antenna gain	4.15 dBi	2.2 dBi
Ping interval	15 sec	
Frequency	869.5 MHz	869.5 MHz
Bandwidth	125 kHz	125 kHz
Transmit Power	14 dBm	
Modulation	LoRa	LoRa
Spreading Factor	12	12
Coding Rate	4/8	4/8

TABLE II: LoRa 433 MHz parameters.

Characteristics	Gateway	Node
Module	Dragino LoRa 433 MHz/GPS	Adafruit Feather 32u4
LoRa Chip	Semtech SX1276	SX1276
Antenna gain	0 dBi	3 dBi
Ping interval	6 sec	
Frequency	433.3 MHz	433.3 MHz
Bandwidth	125 kHz	125 kHz
Transmit Power	3 dBm	
Modulation	LoRa	LoRa
Spreading Factor	12	12
Coding Rate	4/8	4/8

The LoRa gateways are placed on the roof of a building in 30 m height on the campus of TU Dortmund university (Fig. 1). For an extensive range analysis the LoRa nodes are installed on the roof of a car in 1.7 m height, driving through Dortmund (Fig. 1).

In order to analyze the reliability of LoRa communication links several 868 MHz LoRa nodes were placed in the area of Dortmund for several days, receiving a ping signal from the gateway.

V. 433 MHz and 868 MHz Range Evaluation

The range analysis includes two parts. Firstly an availability analysis is performed, using moving 433 MHz and 868 MHz nodes to detect the LoRa signal strength within Dortmund. Afterwards a second analysis is undertaken to determine the reliability of LoRa packet transmissions to various fixed locations.

A. *Availability analysis*

The first part consists of multiple measurement runs using a car as a node moving through the network which results in an availability map of the LoRa network consisting of 546 measurement points for 868 MHz LoRa and 775 measurement points for 433 MHz LoRa. The results are presented in Fig. 2 and Fig. 3. The measured RSSI is cumulated in four segments:

1) RSSI greater than -100 dBm which gives a strong signal with a high anticipated reliability towards fading and interference effects.
2) RSSI between -100 dBm and -116 dBm. According to [10] the additional building penetration loss for basement installed antennas such as smart meters increases the expected path loss by 24 dB. In respect of the additional 24 dB attenuation this segment provides a sufficient signal strength to reach LoRa transceivers installed indoors and even installed in basements.
3) All measurement positions with a Receive Signal Strength Indicator (RSSI) of less than −116 dBm down to -140 dBm (the lowest measured RSSI for successful packet reception).
4) Sections in which no LoRa ping was available (blind spots).

The results of the 868 MHz LoRa measurement show that signal strength and availability of the network highly depends on the actual position. Within a radius of 1.4 km signal strength and availability are sufficient for reaching LoRa nodes in buildings and even in basements. Though from ranges of more than 2 km first blind spots can be found, caused by elevations and shadowing by obstacles. Despite the blind spots the gateway ping can be received in ranges up to 5.8 km, depending on the elevation profile.

Measurement of 433 MHz LoRa results in similar ranges, yet with a slightly lower RSSI compared to the 868 MHz measurements. Due to the lower transmit power the building penetration is more limited. Increasing the transmit power to its maximum of 10 dBm will lead to a higher range and better indoor penetration.

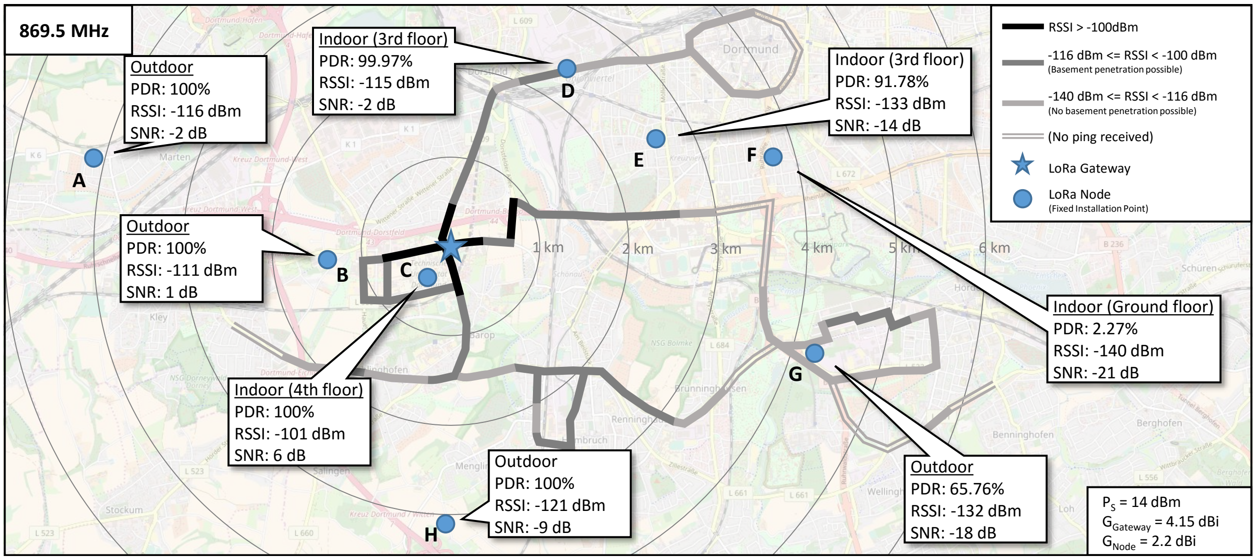

Fig. 2: Range and reliability analysis of 868 MHz LoRa-Network for Smart City Scenario in Dortmund, Germany (Map: OpenStreetMap contributors, CC BY-SA).

B. Reliability analysis

The second part consists of nine typical IoT device installation points. These positions were used for long term reliability measurements consisting of an average of 4300 measurement pings per location. Fig. 2 illustrates the results of the KPI's Packet Delivery Rate (PDR), average RSSI and average Signal to Noise Ratio (SNR) of this long-term measurement.

Measurement installation points A, B, C, D and H result in a PDR of over 99% with good SNR for both 433 MHz and 868 MHz links. Despite of a distance up to 4.2 km, most of the pings were successfully received. With regard to the elevation profiles shown in Fig. 4 it has to be noted that all measurement points A, B, C, D and H have good propagation conditions. However, measurement point F is positioned on the ground floor in the central district of Dortmund. This leads to a high signal attenuation, which results in a packet delivery rate of only 2% and a deficient SNR of -20 dB at 868 MHz. An adequate communication is not possible, while no 433 MHz LoRa ping is received due to insufficient signal strength. The reliability analysis of point G resulted in a slightly better RSSI than with E, only 2 of 3 packets could be received for the 868 MHz link. Taking the SNR into account, the average SNR is 4 dB lower in position G with only 2 dB left to the minimum required SNR of -20 dB for LoRa signal decoding [7], which results in the unsatisfactory PDR of 66% in F and thus an adequate communication is not possible. Using 433 MHz for the communication link leads to an insufficient average SNR of -20 dB and thus only 1 of 4 packets could be received. Taking the elevation profiles in Fig. 5 into account, the propagation to point F and G consists of less clearance, when buildings with typical heights of 8 to 10 m are considered, resulting in additional path loss. The reliability analysis shows, that all indoor and outdoor installation points within a radius of 3 km have a sufficient PDR of more than 90%, which is a good result considering the urban environment. The analysis for installation points of ranges greater than 3 km depict that reliability highly depends on the elevation profile as shown in Fig. 4 and Fig. 5. Comparing the 433 MHz and the 868 MHz communication links with the used hardware constellation the latter performs better at the edge of the coverage area while 433 MHz leads to a more reliable communication link when used closer to the gateway. Finally, the reliability measurements show that, despite the sufficient signal strength, a full packet delivery reliability can not be guaranteed, but packet losses can occur due to interference.

VI. Suitability analysis of path loss models for 433 MHz and 868 MHz

After examining the availability of LoRa based signals, empirical path loss models for urban areas will be analyzed on their suitability for LoRa based networks in urban areas. The output of the previously presented availability analysis consists of 1321 measurement samples, including the signal strength of the received ping (RSSI) and the position of each sample. Considering the free space path loss model, the Okumura Hata Model [11], the ITU-Advanced Channel Model for Urban Macro NLOS Areas [11], the Winner+ Channel Models for Urban

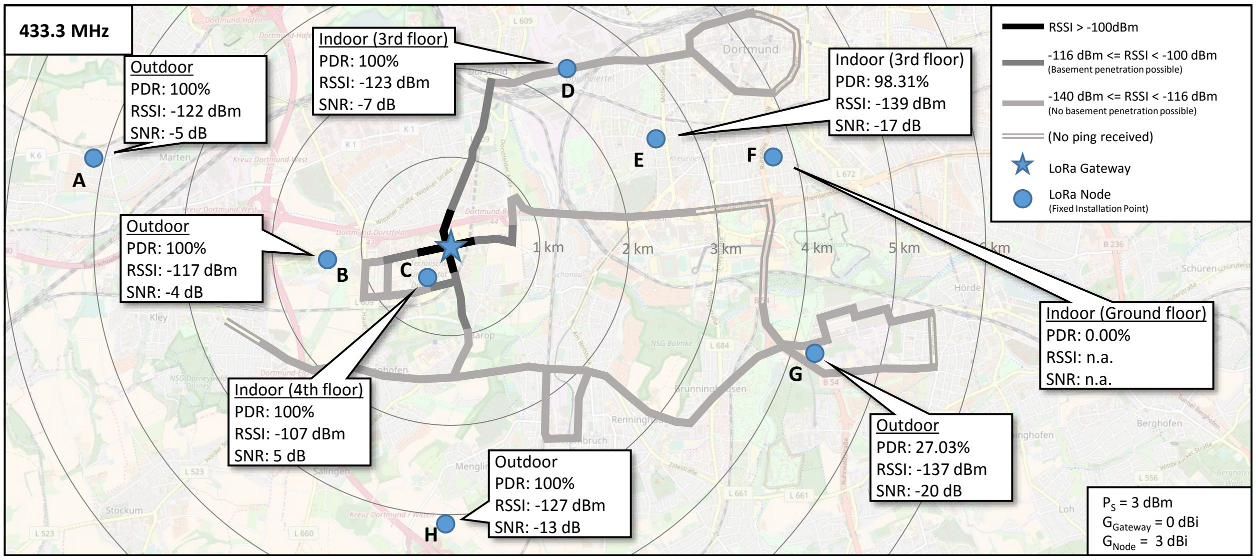

Fig. 3: Range and reliability analysis of 433 MHz LoRa-Network for Smart City Scenario in Dortmund, Germany (Map: OpenStreetMap contributors, CC BY-SA).

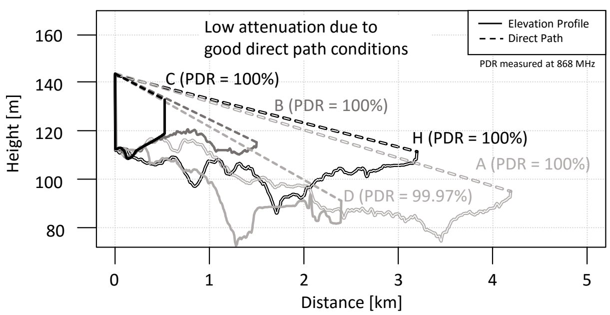

Fig. 4: Elevation profiles for antenna installation positions with feasible communication link (A-D, H).

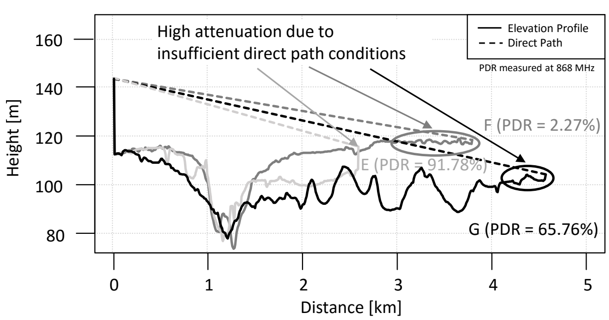

Fig. 5: Elevation profiles for antenna installation positions with critical communication link (E-G).

Macro NLOS Areas [12], the 3GPP Spatial Channel Model for Urban Macro Areas and the Oulu channel model proposed in [2], the path loss (PL) of the measurement samples is determined as

$$PL = P_{TX} - RSSI + G_{TX} + G_{RX} \tag{1}$$

with the transmit power of the gateways P_{TX}, the gain of the gateway antennas G_{TX} and the gain of the node antennas G_{RX}.

The path loss and the distance between gateway and node is used to determine a regression curve for the mean path loss:

$$PL_{mean} = B + 10n \log 10(d) \tag{2}$$

with the distance d in km, the path loss intercept B and the path loss exponent n.

Taking the empirical path loss models into account, it has to be noted, that variation in frequency results in a constant offset of the path loss [11]. In order to increase the statistical relevance of the measurement a mean path loss exponent is computed with respect of the path loss exponents of the 868 MHz and 433 MHz measurements. To adapt the path loss intercepts to the mean path loss exponent, the minimum mean error is computed, resulting in the parameters shown in Table III.

TABLE III: Path loss parameters for Smart City scenario Dortmund [2].

Metric	Oulu 868 MHz	Dortmund 868 MHz	Dortmund 433 MHz
PL exponent	2.32	2.65	2.65
PL intercept	128.95	132.25	126.50

The resulting path loss models for the Smart City scenario of Dortmund are finally shown in Fig. 6 and Fig. 7 and can be used for Smart City Scenarios similar to Dortmund. Due to the higher building density compared to Oulu, the path loss in Dortmund is steeper with increasing distance, though using the lower frequency band of 433 MHz, the path loss is reduced by 5.75 dB, which comes close to the expected 6 dB frequency gain of the free space path loss model.

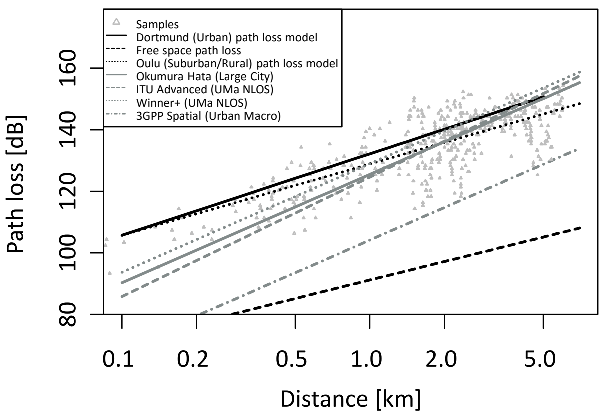

Fig. 6: Comparison of path loss models with measurement regression curve for 868 MHz LoRa.

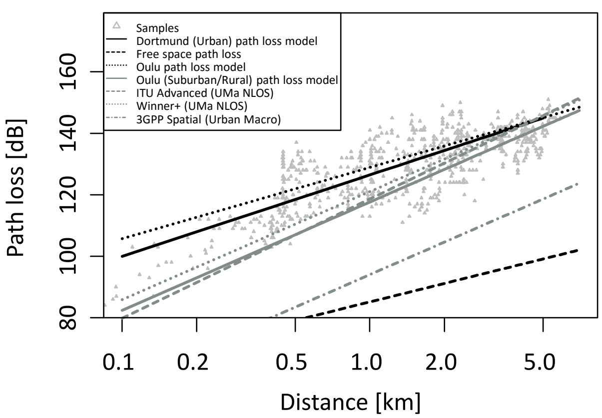

Fig. 7: Comparison of path loss models with measurement regression curve for 433 MHz LoRa.

VII. Conclusion

In this paper the authors present a range and performance evaluation of a LoRa based Smart City IoT network in the city of Dortmund, Germany. First, results of real world measurements with a LoRa gateway installed in 30 m height above ground are presented and discussed. An availability analysis shows that signal reception is possible in coverage areas up to 5.8 km range, considering blind spots with no reception starting from ranges of 2 km, caused by elevations and shadowing by obstacles. Determining the reliability of the LoRa network, 10 LoRa nodes were placed in Dortmund for a long term measurement, resulting in 100% packet reception up to 4 km range and over 99% in over 4.8 km range, depending on propagation path conditions. In the second part of this paper the measurement results are used to examine the suitability of given empirical path loss models for urban environments. It is determined, that the considered channel models are insufficiently predicting the expected path loss. Therefore new path loss models for 868 MHz and 433 MHz LoRa Smart City scenarios are proposed based on the extensive LoRa availability measurement. In future work further LPWAN technologies like Tiny Mesh and Weightless P as well as NB-IoT and eMTC will be analyzed on their performance in Smart City scenarios like Dortmund. In this process the proposed channel model will be verified for these technologies.

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