Preprint, In: 6th International Conference on Building Energy and Environment
Eindhoven University of Technology, The Netherlands
6 - 10 July 2025

LPWAN based IoT Architecture for Distributed Energy Monitoring in Deep Indoor Environments

Christof Röhrig[1] and Benz Cramer[1]

[1] *Dortmund University of Applied Sciences and Arts, Institute for the Digital Transformation of Application and Living Domains (IDiAL), Otto-Hahn-Str. 23, 44227 Dortmund, Germany*
christof.roehrig@fh-dortmund.de, 0000-0002-3286-3703

SUMMERY

Continuous energy monitoring is essential for identifying potential savings and predicting the energy requirements of buildings. Energy meters are often located in underground spaces that are difficult to reach with wireless technology. This paper presents an experimental study comparing different Low Power Wide Area Networks (LPWAN) technologies in terms of building penetration and radio coverage. The technologies Low Power Long Range Wide Area Networks (LoRaWAN®), Narrow Band Internet of Things (NB-IoT), Sigfox 0G and Wireless Smart Ubiquitous Networks (Wi-SUN®) are evaluated experimentally.

It also proposes a distributed hybrid IoT architecture that combines multiple LPWAN technologies using an abstraction layer to optimize cost and coverage. Communication is message-based using the publish-subscribe messaging pattern. It is implemented using the MQTT protocol. The abstraction layer decodes the proprietary binary data and converts it to a normalized JSON format.

Keywords: energy monitoring, smart buildings, smart metering, LPWAN

1. INTRODUCTION

The Dortmund University of Applied Sciences and Arts operates more than a dozen university buildings spread across the city of Dortmund. These buildings are heated and air conditioned using various forms of energy: District heating and cooling networks, gas and electricity. The energy meters are located in underground rooms and energy supply tunnels that are difficult to reach with wireless technology. Continuous energy monitoring is essential for identifying potential savings and for adaptive model predictive heating control of buildings (Wan et al., 2023). The paper presents an experimental study that compares different LPWAN (Low Power Wide Area Networks) technologies in terms of building penetration and radio coverage. These LPWAN technologies differ in terms of topology (star, mesh), power consumption, link budget, radio coverage and radio range. The experiments will be carried out in various university buildings and in a district heating and cooling tunnel linking several buildings on the campus (see Fig 1 (a)).

Furthermore, the paper proposes a distributed hybrid IoT architecture that combines different LPWAN technologies to optimize cost and coverage. The architecture connects existing energy meters and sub-meters with different interfaces (M-Bus, Pulse, SML) via multiple LPWAN radio technologies to the IoT middleware.

2. PROBLEM DEFINITION AND METHODICAL APPROACH

This research compares four LPWAN radio technologies for smart metering applications in deep indoor and underground environments. The aim of the research is to investigate the building penetration loss (BPL) of different radio technologies in real-life scenarios. An empirical evaluation is chosen using a pre-installed radio infrastructure. The measurements are performed with inexpensive off-the-shelf equipment. We focus on measuring the BPL without considering the power consumption of the equipment.

We consider two scenarios: In the first scenario, the radio infrastructure, such as gateways (GWs) and base stations (BSs), is installed inside the building. Radio waves propagate through walls and ceilings. It is assumed that the energy meters are located in the basement of the buildings. In the second scenario, the wireless infrastructure is installed outdoors. The radio waves propagate through the windows or the exterior wall into the building (Outdoor to Indoor, O2I). Theoretical path loss models for indoor environments and O2I penetration can be found in (ITU-R, 2015) and (3GPP, 2024) respectively. It is very difficult to calculate the BPL based only on theoretical models because radio waves propagate in different ways in the building due to reflections and diffraction. Especially in deep indoor and underground scenarios such as basements and tunnels, the real signal path and thus the entire link budget is too complex to be accurately represented by a linear model (Malarski et al., 2019).

Therefore, we chose an empirical experimental evaluation where the received signal strength indicator (RSSI) is measured at outdoor measurement points (MPs) at ground level and then compared with the RSSI measured at indoor MPs on the first floor and underground MPs in basements and a tunnel (see Fig. 1 (a)). The BPL is calculated from these measurements and compared between the different radio technologies.

3. RELATED WORK

LPWAN technologies have received increased attention in recent years. They are characterized by their long range and low power consumption. LPWAN technologies known for their good building penetration include LoRaWAN®, NB-IoT, Sigfox 0G and Wi-SUN®. Kadusic et al. (2022) provides an overview of LoRaWAN®, NB-IoT and Sigfox and the characteristics of these radio technologies. Hoo et al. (2023) compares Wi-SUN® with LoRaWAN® and NB-IoT. The main application is a building management system. Naumann and Oelers (2021) compares the energy consumption and the link budget of NB-IoT, LoRaWAN® and Sigfox based on theoretical models.

Roosipuu et al. (2023) investigates the use of NB-IoT for monitoring and control of smart urban drainage systems. Different depths of devices in manholes are investigated. Persia et al. (2017) presents a connectivity analysis of NB-IoT and LoRaWAN® for smart grid applications in outdoor, indoor and deep indoor environments. Tangsunantham and Pirak (2022) presents an experimental evaluation of Wi-SUN® for advanced metering in smart grids. Thrane et al. (2020) presents an experimental evaluation of an NB-IoT propagation model for deep indoor scenarios. The measurement campaign was conducted in a system of long underground tunnels.

4. TECHNOLOGY OVERVIEW

LPWAN technologies known for good building penetration operate in the sub-GHz spectrum and include LoRaWAN®, NB-IoT, Sigfox 0G and Wi-SUN®. LoRaWAN®, Sigfox 0G and Wi-SUN®operate in the unlicensed spectrum of 868 MHz in Europe, while NB-IoT operates in the licensed spectrum of 800 MHz (band 20) or 900 MHz (band 8) in Europe. To ensure fair use of the unlicensed spectrum, each device is limited in transmit power and duty cycle (DC). In the 868 MHz band, the transmit power is normally limited to 14 dBm (25 mW) and a DC of 0.1%, except in the G1 band (868.0 - 868.6 MHz) where a DC of 1% is allowed and the G3 band (869.4 - 869.65 MHz) where a transmit power of 27 dBm (500 mW) and a DC of 10% is allowed. The G3 band is typically used for downlink (DL) messages where a BS is connected to many devices and transmits at high power. In contrast, quality of service can be guaranteed in the licensed spectrum, where the mobile network operator (MNO) controls the use of the spectrum an the DC is not limited.

The proprietary Sigfox 0G radio technology was developed by the French company Sigfox S.A. (now owned by UnaBiz). It uses Ultra Narrow-band (UNB), achieves long range and requires low power. The Sigfox 0G network is based on a star topology and requires a local 0G network operator to carry the traffic generated. In Europe, Sigfox 0G is using the G1 band for the UL and the G3 band for the DL. Sigfox supports up to 140 uplink (UL, from device to BS) and 4 DL messages per day, each carrying a payload of 12 bytes and 8 bytes respectively, at a data rate of 0.1 kbit/s. Sigfox 0G subscription cost is 10 € per year for one device and 140 UL, 4 DL messages per day (Heliot Europe).

LoRaWAN® is based on the proprietary LoRa radio technology developed by Scemtech. LoRaWAN® defines the communication protocol and system architecture and is managed by the open LoRa Alliance. It can achieve data rates between 0.25 kbit/s and 11 kbit/s in Europe. The payload of the messages can be from 51 to 222 bytes in Europe depending on the data rate. The number of messages is limited by the DC regulations in Europe and may be even lower due to restrictions by the LoRaWAN® network operator. The Things Network's (TTN) fair use policy limits a device's airtime to 30 s per day. LoRaWAN® networks can be operated by a network operator, a community such as TTN, or self-deployed. LoRaWAN® thus offers a high degree of flexibility for the end user.

Wi-SUN® is based on the open IEEE 802.15.4g/e standards. Unlike other LPWAN technologies, it offers mesh and multi-hop features for enhanced reliability and range. In addition to low power consumption and long range, it offers lower latency and higher data rate up to 300 kbit/s compared to the other LPWAN technologies. The downside of Wi-SUN® is the lower link budget and therefore lower range and building penetration, and the lack of off-the-shelf devices for the end user. The target applications of Wi-SUN® are in the field of building automation (Hoo et al., 2023).

NB-IoT operates in licensed spectrum and is standardized by the 3rd Generation Partnership Project (3GPP) as LTE Cat-NB1 and -NB2. It is only available through MNOs. Implementing NB-IoT is cost effective as it is based on existing cellular infrastructure. Compared to other LPWAN technologies that operate in unlicensed spectrum, the transmit power and DC are not limited by regulation. Therefore, the link budget is higher, resulting in better building penetration. The downside is higher power consumption. NB-IoT offers data rates of up to 62 kbit/s in Cat NB1 and up to 159 kbit/s in Cat NB2 in the UL and up to 26 kbit/s and 127 kbit/s respectively in the DL. Applications are typically low throughput, delay tolerant and low mobility. Examples are smart meters and remote sensors. The cost of the subscription is 11 € for a SIM card, 500 MByte for 10 years (1NCE).

Table 1 compares the key parameters of the technologies. The link budget is the maximum possible path loss from transmitter to receiver. A high value is important for penetrating underground environments. The values are taken from (Naumann and Oelers, 2021) and the data sheets of the experimental equipment in Table 2.

Table 1. Comparison of different LPWAN technologies (Europe)

Technology	LoRaWAN®	Sigfox	NB-IoT	Wi-SUN®
Topology	star	star	star	mesh
Band in MHz	868	868	800 / 900	868
Tx power GW in dBm	14 / 27*	27	23	14
Tx power device in dBm	14	14	23	14
Rx sensitivity GW in dBm	-140	-144	-131	-120
Rx sensitivity device in dBm	-136	-132	-131	-120
link budget+ UL in dB	154	158	154	134
link budget+ DL in dB	150 / 163*	159	154	134
price of module	9€	9€	12€	20€
annual subscription cost	-	10€	1-2€	-
Device availability	++	0	+	- -

* depending on the frequency of use, + without antenna gain (0dBi)

5. EXPERIMENTAL EVALUATION OF LPWAN TECHNOLOGIES

5.1. Experimental setup

An area of the campus consisting of several challenging buildings for building penetration was chosen as the experimental environment (see Fig 1 (a)). We use several off-the-shelf devices for the experiments (see Table 2). Since there are no end-user Wi-SUN® devices available, we use a development kit from Silicon Labs. This equipment does not provide an accurate measurement of RSSI, but is intended to provide an estimate of building penetration with real devices.

Table 2. Devices used in experiments

Device	LPS8	DLOS8	LoRa E5 mini	SIM7020E	MKR FOX	SLWSTK6007A
type	GW	GW	device	device	device	dev kit
manufacturer	Dragino	Dragino	Seeed	Simcom	Arduino	Silicon Labs
radio chip	SX1308	SX1301	STM32WLE	MT2625	ATAB8520E	EFR32MG12
technology	LoRa	LoRa	LoRa	NB-IoT	Sigfox	Wi-SUN®
band MHz	868	868	868	900 / 800	868	868
Tx pow. / dBm	14 / 20	14 / 27	14	23	13	14
Rx sen. / dBm	-140	-140	-136.5	-131	-132	-120

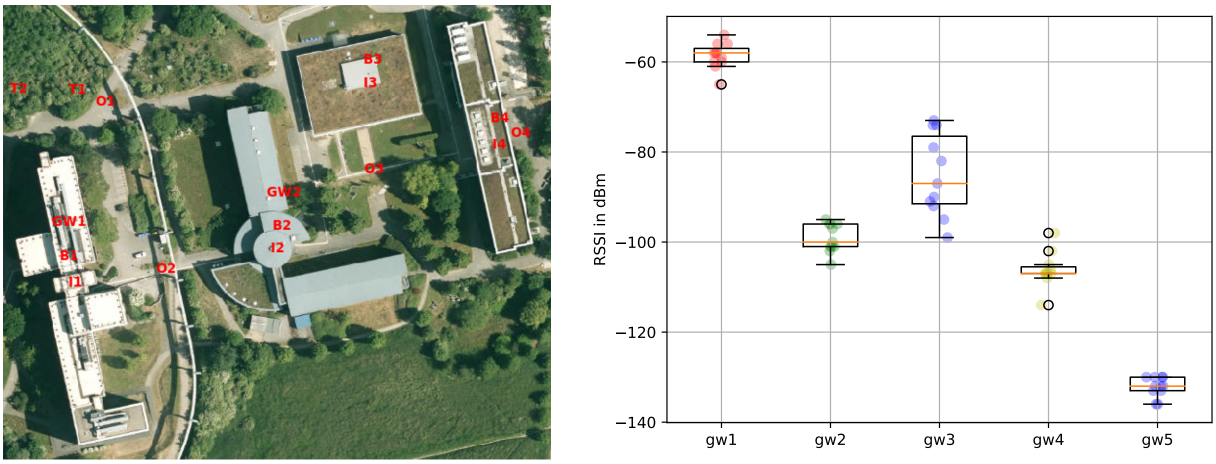
5.2. Indoor experimental evaluation of LoRaWAN® and Wi-SUN®

In the first measurement campaign, we compare LoRaWAN® with Wi-SUN®. The experiments are performed in building 2, where the LoRaWAN® gateway GW2 (LPS8) is placed on the first floor near a window. Measurements are made on different floors and in the basement to measure the penetration loss of the ceilings. With LoRaWAN® it is possible to reach every floor of the building up to the 3rd floor and even the basement. Penetration loss is 10 dB for each ceiling upstairs and 55 dB to the basement.

With Wi-SUN® it was only possible to penetrate two ceilings. The basement could not be reached with this technology. In general, it was not possible to establish a stable connection when the RSSI was lower than -95 dBm. Due to the relatively low link budget, building penetration is not Wi-SUN®'s strength. Rather, its strengths lie in high data throughput and low latency.

5.3. O2I penetration of LoRaWAN®, Sigfox OG and NB-IoT

Fig. 1 (a) shows the experimental area at the campus Emil-Figge-Str. in Dortmund. The outdoor MPs are named O1, O2, O3 and are located between the buildings. The indoor MPs I1-I4 are located on the first floors in the entrance halls of the buildings. The MPs in the basements of the buildings are labeled B1-B4. There are two MPs in the energy supply tunnel, T1 and T2. T1 is placed under an emergency manhole of the tunnel, T2 is placed directly at the heat meters. Two LoRaWAN® gateways are placed in the area. The outdoor gateway GW1 (DLOS8) is placed on the roof of building 1, while the indoor gateway GW2 (LPS8) is placed inside on the first floor near a window. Both gateways are preinstalled and not placed for this work.



(a) (b)

Figure 1. (a) Experimental area at campus Emil-Figge-Str. with measurement points marked in red (b) LoRaWAN®RSSI values of Gateways at measurement point O2

At each MP, several measurements are made for each radio technology except Wi-SUN®. The results are shown in Table 3. For LoRaWAN®, the reported RSSI fluctuates a lot. Fig. 1 (b) shows the fluctuation of the RSSI reported by the gateways. The values are not normally distributed and have outliers. The RSSI values in the figure are reported by four gateways receiving the messages from a device at O2. The RSSI values in the Table 3 are the medians of the measurements at the indicated MP. In this challenging environment, Sigfox 0G was unable to reach the basements of the buildings (except B2 and B4) and the energy supply tunnel. LoRaWAN® can reach the basements and the tunnel except for MP T2, which has a greater distance to the emergency manhole than T1. Two MNOs with different frequency bands are evaluated. Vodafone (NB Vo) uses band 20 (800 MHz) for NB-IoT, while Deutsche Telekom (NB DT) uses band 8 (900 MHz). The RSSI values for NB-IoT are measured DL and are obtained directly from the NB-IoT modem using AT commands. The UL RSSI values for LoRaWAN® are obtained from the TTN back-end. The DL RSSI is obtained from the device using AT commands. The Sigfox 0G RSSI values are measures UL at the BS and reported by the Sigfox back-end system.

Table 3. RSSI values in dBm for LoRaWAN® (LW), NB-IoT (NB) and Sigfox

MP	LW UL	LW DL	NB DT	NB Vo	Sigfox
O1	-72	-68.5	-66	-77	-96.5
O2	-58	-61	-66	-74	-94
O3	-57	-55	-63	-73	-101
O4	-83.5	-84	-64	-74	-100
I1	-81	-78.5	-74	-84.5	-111
I2	-87	-90	-85	-90	-116.5
I3	-102	-102.5	-90	-99	-127
I4	-93	-94	-77	-81	-114
B1	-101	-106	-95	-116	-
B2	-111	-110	-97	-112	-137
B3	-114	-115	-110	-111	-
B4	-111	-106	-85	-94	-124
T1	-116	-112	-107	-114	-
T2	-	-	-112	-118	-

To compare the BPL of different LPWAN technologies, the RSSI of the indoor MPs is subtracted from the RSSI of the nearest outdoor MP. Table 4 compares the BPL for each indoor MP.

Table 4. Calculated O2I BPL from nearest outdoor MP to indoor MP in dB

	I1	B1	I2	B2	I3	B3	I4	B4	T1	T2
LoRaWAN® UL	23	43	29	54	45	57	9.5	27.5	44	-
LoRaWAN® DL	17.5	45	29	55	47.5	60	10	22	43.5	-
Sigfox 0G	14.5	-	22.5	43	26	-	13	23	-	-
NB-IoT DT B8	8	29	22	34	27	47	13	21	41	48
NB-IoT Vo B20	10.5	42	17	39	26	38	7	20	39	45

Due to measurement inaccuracies, these values are not exact and it is not possible to rank the performance of the technologies in terms of BPL. In addition, the LoRaWAN® GWs adjust the transmit power depending on the RSSI, so the BPL in the DL may be too low.

The BPL depends more on the signal path than on the LPWAN technology used. The LoRaWAN® GW1 is placed on top of building 1, the signal has to travel through all ceilings to reach the first floor and the basement. Therefore the BPL of I1 and B1 is much higher for LoRaWAN®compared to NB-IoT and Sigfox 0G. The basement of building 4 is underground on the west side and above ground on the east side. The signal of LoRaWAN® comes from the west, that of NB-IoT and Sigfox 0G come from the east, so the BPL of LoRaWAN® is much larger than that of NB-IoT and Sigfox 0G. The Sigfox 0G BS is much further away than the LoRaWAN® GWs. The angle of entry into the buildings is therefore significantly flatter compared to LoRaWAN® and the BPL is in a similar range to NB-IoT.

From the measured values it can be concluded that the angle at which the signal enters the building, and therefore the position of the GW and BS, has a greater influence on BPL than the technology used. This means that if the LPWAN infrastructure is unknown, the suitability of a LPWAN technology must be determined by measurements. However, the measured values can be used to determine the order of magnitude of BPL to be expected. It is clear to see that the MPs in the basements have a very high BPL of up to 60 dB for LoRaWAN®, which means that the signal is attenuated by a factor of 10^6.

6. LPWAN ARCHITECTURE

There are many reasons to choose a LPWAN technology. In addition to range and building penetration, cost, availability of devices and infrastructure play a major role. In addition, technologies are constantly evolving. Technologies such as Wi-SUN®, which are not widely used today, may become more prevalent in the future, while other technologies such as Sigfox may become less important. In particular, the market for LPWAN energy monitoring devices is changing rapidly. Even if a separate LoRaWAN® infrastructure is operated, it is usually cheaper to use an NB-IoT device than to install a separate LoRaWAN® gateway for a single device if there is no LoRaWAN® coverage at the device's location. For this reason, a hybrid and modular

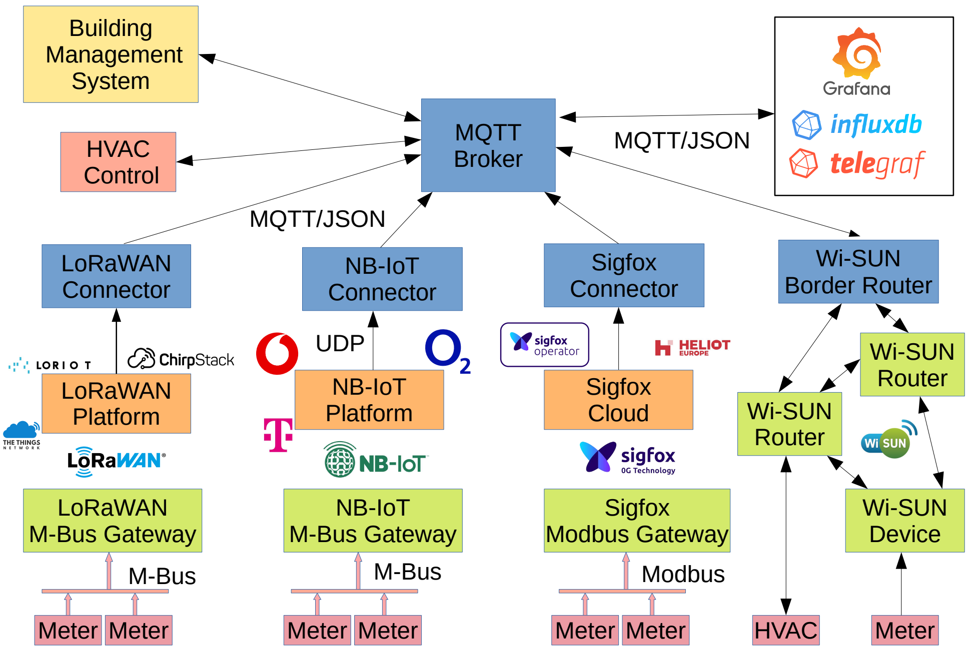


Figure 2. Proposed architecture for energy monitoring and control

architecture is proposed in which multiple LPWAN technologies can be integrated (see Fig. 2). The communication is message based and uses the publish-subscribe messaging pattern. It is implemented using the MQTT protocol. Multiple devices such as meters are connected to a MQTT broker via software connectors. The software connectors provide an abstraction layer for LPWAN technologies with a common interface based on MQTT and JSON.

The architecture connects existing energy meters and sub-meters with different interfaces to the IoT middleware via multiple LPWAN radio technologies. The district heating and cooling meters provide an M-Bus interface, while the gas meters provide only pulses to be counted. Energy data from different sources and technologies is transmitted over different wireless technologies. A connector for each technology receives the energy data over the Internet, decodes the binary data, and converts it to a normalized JSON format. The energy data is then published to a MQTT broker, which acts as a central hub in the system. The data is stored in a time series database for later analysis and visualization in a web front-end.

7. CONCLUSIONS

The paper presents an experimental evaluation of four LPWAN technologies in deep indoor environments. LoRaWAN® and NB-IoT show better building penetration than Sigfox 0G and Wi-SUN®. By using licensed radio bands and automatic retransmission in case of packet loss, NB-IoT offers higher reliability compared to other LPWAN technologies. Compared to NB-IoT, LoRaWAN® has the advantage of lower power consumption, greater flexibility in the choice of infrastructure, and a wider range of devices available for energy monitoring. Wi-SUN® may become more important in the future due to its mesh topology. However, there are currently no energy monitoring devices available for use in Europe. Furthermore, Wi-SUN® has the lowest building penetration compared to the other LPWAN technologies considered. Sigfox 0G generally offers a high link budget and therefore the potential for high building penetration, but only two out of four basements are reached in the experimental evaluation. This is likely due to the low density of Sigfox BSs in the area studied.

A hybrid and modular architecture for energy monitoring has been proposed that can integrate multiple LPWAN technologies. The architecture has been implemented and tested for LoRaWAN® and NB-IoT. It is successfully used for energy monitoring in several buildings at the Dortmund University of Applied Sciences and Arts.

REFERENCES

3GPP, 2024. Study on channel model for frequencies from 0.5 to 100 GHz. 3GPP TR 38.901 version 18.0.0.

Hoo F., Lim Tan F. S., Ching Bon Chan R., Waszecki P., Keoh S. L., Kiat Seow C., Li M., Cao Q., and Sum C. S., 2023. 5G-Wi-SUN for Building Management System. Proceedings of 2023 6th International Conference on Applied Computational Intelligence in Information Systems (ACIIS), 1–6.

ITU-R, 2015. Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz. P Series Radiowave propagation, Recommendation ITU-R.

Kadusic E., Ruland C., Hadzajlic N., and Zivic N., 2022. The factors for choosing among NB-IoT, LoRaWAN, and Sigfox radio communication technologies for IoT networking. Proceedings of 2022 International Conference on Connected Systems & Intelligence (CSI), 1–5.

Malarski K. M., Thrane J., Bech M. G., Macheta K., Christiansen H. L., Petersen M. N., and Ruepp S., 2019. Investigation of Deep Indoor NB-IoT Propagation Attenuation. Proceedings of 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 1–5.

Naumann H. and Oelers W., 2021. *LPWAN Comparison – Low Energy Consumption with NB-IoT, LoRaWAN and Sigfox.*

Persia S., Carciofi C., and Faccioli M., 2017. NB-IoT and LoRA connectivity analysis for M2M/IoT smart grids applications. Proceedings of 2017 AEIT International Annual Conference, 1–6.

Roosipuu P., Annus I., Kuusik A., Kändler N., and Alam M. M., July 2023. Monitoring and control of smart urban drainage systems using NB-IoT cellular sensor networks. Water Science and Technology 88, 339–354.

Tangsunantham N. and Pirak C., 2022. Experimental Performance Analysis of Wi-SUN Channel Modelling Applied to Smart Grid Applications. Energies 15.

Thrane J., Malarski K. M., Christiansen H. L., and Ruepp S., 2020. Experimental Evaluation of Empirical NB-IoT Propagation Modelling in a Deep-Indoor Scenario. Proceedings of GLOBECOM 2020 - 2020 IEEE Global Communications Conference, 1–6.

Wan L., Dai X., Welfonder T., Petrova E., and Pauwels P., Sept. 2023. Semi-automated thermal envelope model setup for adaptive model predictive control with event-triggered system identification. Proceedings of Building Simulation 2023: 18th Conference of IBPSA. Vol. 18. Building Simulation. IBPSA, Shanghai, China, 3664–3671.