The Gigantium Smart City Living Lab

A Multi-Arena LoRa-based Testbed

Rodriguez Larrad, Ignacio; Lauridsen, Mads; Vasluiano, Gabriel; Poulsen, Anders Normann; Mogensen, Preben Elgaard

Published in:
15th International Symposium on Wireless Communication System (ISWCS 2018)

DOI (link to publication from Publisher):
10.1109/ISWCS.2018.8491077

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

The Gigantium Smart City Living Lab: A Multi-Arena LoRa-based Testbed

Ignacio Rodriguez[1], Mads Lauridsen[1], Gabriel Vasluianu[1], Anders N. Poulsen[1], and Preben Mogensen[1]

[1]Wireless Communication Networks Section, Department of Electronic Systems, Aalborg University, Denmark
{irl, ml, pm}@es.aau.dk

***Abstract*—The Wireless Communications Networks Section, from the Department of Electronic Systems at Aalborg University, Denmark, has successfully deployed, in collaboration with a number of Danish local industrial partners and the municipality of Aalborg, a LoRa network in the Gigantium multi-arena center. The initial aim of this network is to serve as an integrated multi-arena indoor environment monitoring wireless system, in contrast to the existing cabled solutions based on bus communication systems for each of the individual arenas. In addition, the network also enables usage monitoring of arenas and meeting rooms. The final setup is comprised of 33 multi-sensor nodes distributed across the multiple arenas, and 4 gateways, which provide macroscopic diversity to the wireless system, ensuring a high level of reliability. The setup is already operational, but still open for optimization. The deployed network will serve as a testbed for research in the wireless, and indoor environment domains.**

***Index Terms*—MTC, IoT, LoRa, testbed, indoor environment**

I. Introduction

Gigantium is a large sports and culture center located in the municipality of Aalborg, Denmark. This center, which extends over an approximate overall surface area of 33.000 m^2, consists on multiple arenas (two halls, two ice rinks, a swimming pool and an athletics hall), an administration area with offices and meeting rooms, and a conference area; all of them interconnected by a public foyer [1]. Each of the arenas is run as an independent arena, meaning that Gigantium can host multiple different activities at the same time. For the reader to get an idea on the size of the arenas, the main and auxiliary halls can host handball games, concerts, or exhibitions with a capacity of up to 8.500 and 1.500 people, respectively. The main ice rink, which hosts ice hockey games, has a capacity of 5.000 people. For visual reference, Fig. 1 illustrates a floor plan of the facilities. For further details on the distribution of the Gigantium center, there is an inside-building Google Street View tour available at [2].

The independence of the arenas that conform Gigantium, plays a role not only from the usability perspective, but also from a management point of view. Each of the arenas make use of an individual high-end indoor environment monitoring and control system. Each of these individual systems are based on a number of sensors and actuators wired to a central unit. Moreover, these systems use different bus protocols and technologies from each other and, as a consequence of this, the indoor environment information handled by each of them is, typically, not compatible with the others. The optimization of the general building performance requires the centralization of the overall indoor environment monitoring, which is a complex and costly task. Aggregating data from the different arenas would require a huge investment in an integration system (with proper drivers to each of the individual subsystems) to aggregate the data from the different arenas. In the view of this and the same potential issue when optimizing other public buildings, the local government in Aalborg (AaK Bygninger), in collaboration with Aalborg University, a number of industrial and technological partners (RTX A/S, Neogrid Technologies ApS, Trifork, and IBA System) and the North Denmark ICT cluster manager BrainsBusiness, decided to launch the ”SMART Aalborg” research project with the aim of mapping Internet-of-Things (IoT) technologies to different smart-building and smart-city use cases.

After exploring different possibilities, it was clear that the single integrated multi-arena indoor environment monitoring system would have to be wireless, which would allow to reduce the overall installation cost by eliminating the need for dedicated bus communication wires. The design of a wireless system in a huge indoor scenario like this would have been a very challenging task in the past but, nowadays, with the development of the new low-cost and long-range wireless IoT technologies, it has become more feasible. In this case, LoRa was selected as the candidate wireless technology due to its low-power and wide-area coverage capabilities as well as its full deployment flexibility [3]. Its 868 MHz (sub-GHz) frequency of operation, together with the 125 kHz bandwidth and +14 dBm transmit power, ensure large coverage - at expenses of the interference experienced in the selected unlicensed band of operation [4]. Moreover, the multiple radio configuration options (mainly in terms of spreading factor and coding rate) allow the optimization of the system in terms of scalability [5], reliability and power consumption.

The initial deployment of the wireless indoor environment monitoring system in Gigantium consists on 33 sensor nodes deployed at different observation positions. One of the keys of this deployment is that each of the nodes is a multi-sensor device tracking different indoor environment variables using 9 sensors. Therefore, a total of 9x33=297 sensors will be reporting periodic data via the LoRa network to a centralized monitoring back-end service. The network is fully operational in Gigantium since March 2018 [7], [8] and, apart from the

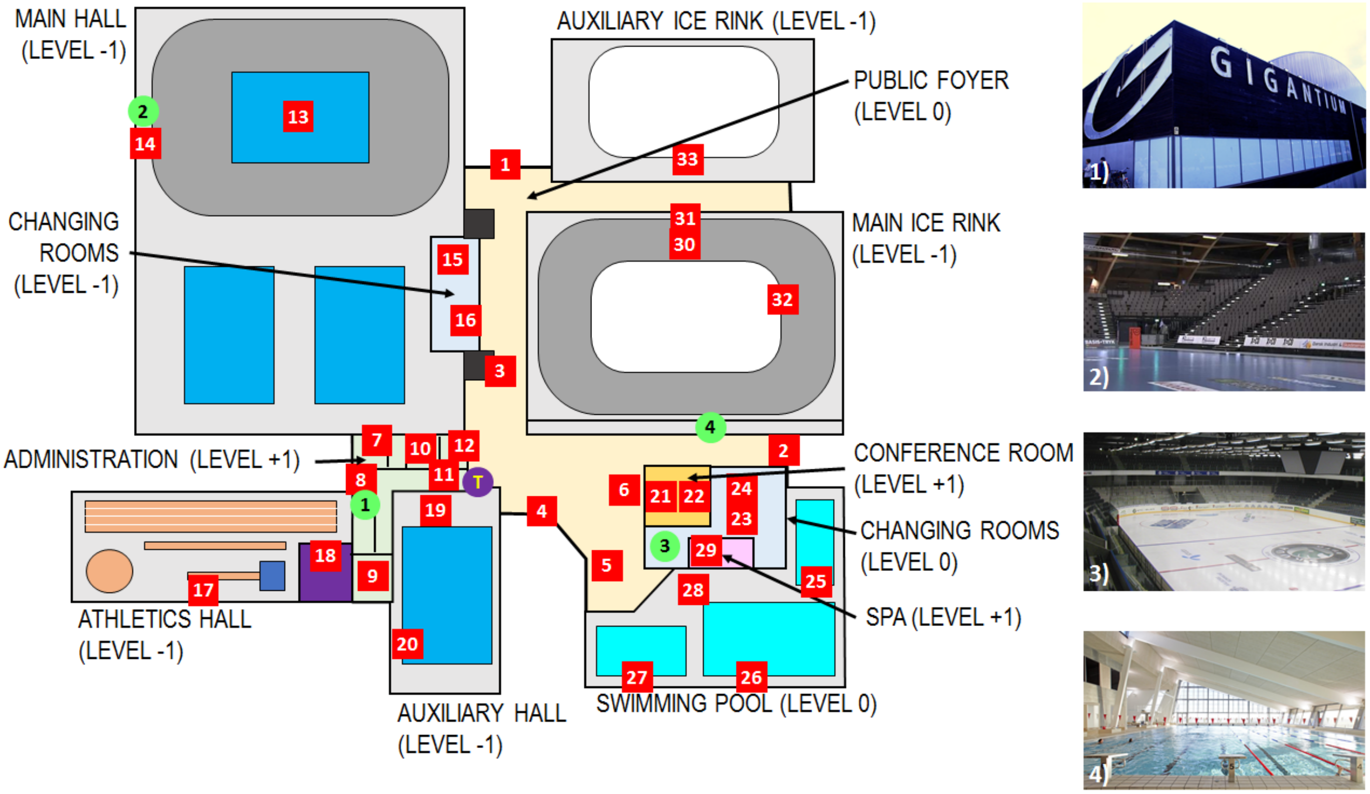

Fig. 1. Gigantium's floor plan and LoRa network layout: multi-sensor node (SN) locations (red squares), gateway (GW) locations (green circles), test gateway location (purple circle). Side pictures: 1) outside, 2) main hall, 3) main ice rink, and 4) swimming pool.

obvious use as environment monitoring system, the network serves now also as a research testbed. In its current shape, the LoRa-based network it is not a very challenging massive machine-type communication (mMTC) scenario [6] in terms of nodes and activation times. However, this is one of the very first end-to-end wireless IoT complex pilot networks ever deployed, and it will now be evolved and optimized, facing more complex radio access situations. The Wireless Communication Networks Section at Aalborg University, who was responsible for the deployment of the network, will now perform research on the radio performance and optimization of the LoRa network. The Department of Civil engineering of Aalborg University will have access to the sensor data and will perform research on the indoor environment dynamics of the building. The Department of Computer Science of Aalborg University will also have access to the sensor data and will develop, together with some of the technological company partners, data analytics techniques. This multi-disciplinary research will allow to create better processes and solutions and evaluate if similar solutions would be suitable for other smart-buildings.

The rest of the paper is structured as follows: Section II illustrates the layout of the LoRa network deployed in Gigantium; Section III summarizes the preliminary coverage and performance assessment; Section IV presents the settings of the final deployment and the macroscopic diversity analysis; and, finally, Section V concludes the paper and provides the guidelines for the near-future optimization of the network.

II. Gigantium Smart City Lab LoRa Network Layout

The deployed LoRa network consist on 33 battery-powered RTX4301 indoor environment multi-sensor nodes (SN) and 4 RTX4302 gateways (GW) [9]. Each of the SNs includes 9 different sensors - which have been selected by following a compromise between quality and price: a SENSIRION STS31 high accuracy temperature sensor; a MCP4726 DAC with external custom circuits for sound pressure sensing; a Broadcom APDS-9200 digital UV and ambient light sensor; a BOSCH BME280 combined humidity, pressure, and temperature sensor; an Ams CCS811 ultra-low power digital gas sensor, providing estimated CO_2 based on Volatile Organic Compounds (VOCs) measurements; a PaPIRs EKMB1 motion sensor (passive infrared-based), and a ST LSM9DS1TR magnetometer, accelerometer and gyroscope. Before deploying, the temperature, humidity, pressure and estimated CO_2 sensors have been tested and calibrated in a controlled environment. The temperature sensors provide very reliable indoor readings with a maximum error of 0.71°C. The pressure sensors work reasonable well with a maximum error of 2.5 hPa, but may not be able to measure pressure differences between rooms. Unfortunately, the humidity and estimated CO_2 sensors did not provide as reliable results as expected, and thus replacement of these latter sensors are considered for a next release version of SNs.

Both the SN and GW end devices are non-commercial prototypes, based on LoRa Semtech SX1276 transceivers [10].

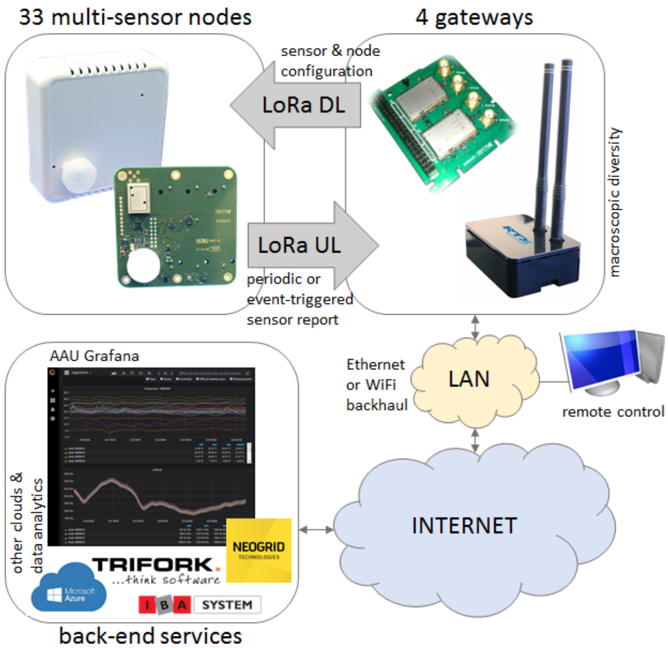

Fig. 2. Overall implemented system: data and control flows.

A picture of the devices is shown in the data and control flows diagram in Fig. 2. As illustrated in that figure, the GWs are connected to Internet either via Ethernet or WiFi in order to forward the periodic sensor data received from the SNs via the LoRa uplink channel to a cloud back-end server. At Aalborg University a back-end server was built for this particular Gigantium's LoRa system, and a visualization dashboard was created based on the Grafana open platform [14]. The data is also forwarded to other cloud services from the project partners, who are currently running analytics over the incoming data. The configuration of the SNs is done by logging in to the corresponding paired GW from the local network and making it send a configuration message via the LoRa downlink channel. In this setup, all 33 SNs are paired to the 4 GWs in order to ensure reliability via macroscopic diversity.

A description of the exact locations of the SNs and GWs in the Gigantium LoRa network is given in Tables I and II. The positions have also been plotted in Fig. 1. For non-indoor environment experts, it should be noted that the SN locations are not random. They have been selected by colleagues from the Civil Engineering department at Aalborg University to ensure readings are relevant when optimizing the indoor environment. By logging and analyzing the information from SNs deployed at approximately 1.75 m height at the 33 identified positions, it is possible to keep track of the usage/occupancy level and overall indoor environment dynamics at each of the different arena facilities. Note the 1.75 m height does not apply to SN locations 1 and 2 - where the SNs are deployed at a higher height, above the entrance door; and SN location 13 for obvious reasons - it is deployed right beneath the electronic scorer at the highest possible location inside the main hall. For a better understanding of the scenario and the deployment, observe that the ground heights of each of the arenas or

TABLE I
LIST OF SENSOR NODE LOCATIONS

area	level	description	SN #
public foyer	0	entrance north	1
	0	entrance east	2
	0	outside ticket sales box	3
	0	pillar external wall south	4
	0	middle pillar	5
	0	swimming pool entrance	6
administration	+1	administration 1	7
	+1	inside administration 2	8
	+1	inside meeting room 1	9
	+1	inside meeting room 2	10
	+1	inside meeting room 3	11
	+1	inside meeting room 4	12
main hall	+2	under electronic scorer	13
	-1	pillar external wall west	14
	-1	inside changing rooms	15
	+1	ceiling above changing rooms	16
athletics hall	-1	pillar external wall south	17
	0	gym	18
auxiliary hall	-1	entrance north	19
	-1	pillar external wall west	20
conference room	+1	pillar middle	21
	+1	pillar wall east	22
swimming pool	0	inside changing room males	23
	0	inside changing room females	24
	0	next to pool jump	25
	0	pillar external wall south	26
	0	pillar external wall south	27
	+1	beginning of waterslide	28
	+1	inside wellness spa	29
main ice rink	1	middle level stands	30
	0	upper level stands	31
	-1	Zamboni entrance	32
auxiliary ice rink	-1	middle lower level	33

TABLE II
LIST OF GATEWAY LOCATIONS

area	level	description	GW #
administration	+1	inside administration	1
main hall	0	inside control box east	2
swimming pool	0	inside staff room	3
main ice rink	+1	inside press room	4
public foyer	+1	initial test (Kerlink)	T

areas within Gigantium are not at the same level. To illustrate such difference and give idea on the different heights, a level indicator has been assigned to each of the SN positions in Table I by taking the reference of the public foyer as level 0. Each level has an approximate height of 6 m.

III. Initial Coverage and Performance Test

Before deploying the LoRa network, a small radio coverage and performance assessment was done. A measurement was carried out at each of the 33 intended SN positions in order get an insight on the overall radio propagation constraints in the scenario. For this test a different LoRa setup was used, with a Kerlink IoT Wirnet 868 Station [11] deployed at a test reference position (marked with a T in Fig. 1 and Table II). At each of the measurement points, a measurement was performed by using a LoRa Coverage Tester device. This device, based on a LoRa Microchip RN2483 transceiver [12]

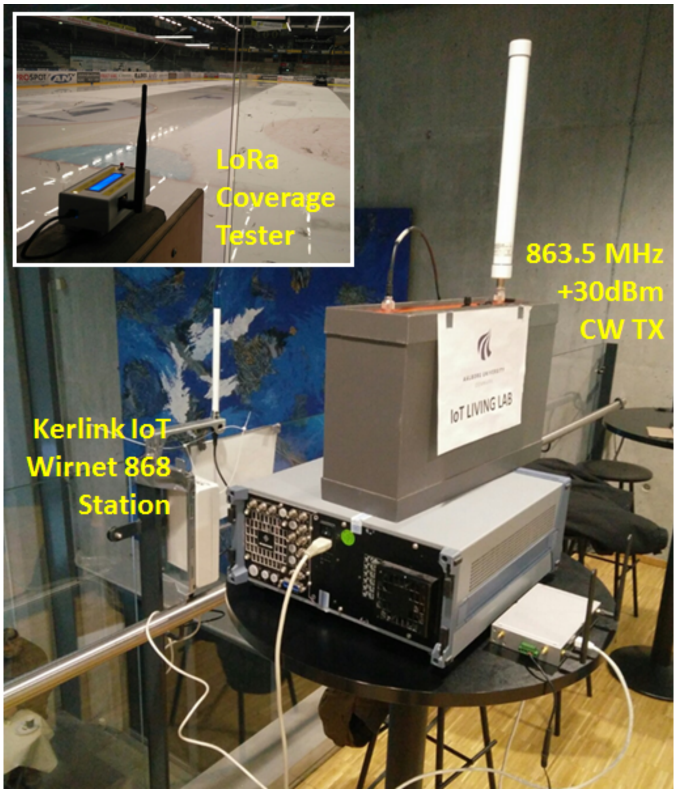

Fig. 3. Co-located Kerlink IoT Wirnet 868 Station and 863.5 MHz CW transmitter at GW position T, and LoRa Coverage Tester at SN position 32.

and an Arduino Uno, was configured to send 6 test messages with different spreading factor (SF) and coding rate (CR) configurations. In this case, CRs 4/8 and 4/5 were evaluated for SFs 7, 10 and 12. This LoRa test system was previously calibrated in [13] for the most robust LoRa configuration with CR 4/8 and SF 12, resulting in a maximum path loss (PL) of 155 dB for a minimum detected received signal strength indicator (RSSI) of -127 dBm and signal-to-noise ratio (SNR) of -20 dB.

In parallel with the LoRa test, a narrow-band continuous wave (CW) measurement was performed. A 863.5 MHz CW transmitter (TX) was co-located with the LoRa station and, at each of the 33 positions, a local average power measurement was performed by using a Rohde & Schwarz TSME scanner. To ensure the maximum dynamic range possible, and be able to detect potential positions in outage of the LoRa system, the CW was transmitted at +30 dBm. Both test system setups are shown in Fig. 3.

The results of this preliminary measurement test are presented in Fig. 4. The upper graph displays the cumulative distribution function (CDF) of the RSSI for the CW scanner and the Lora tester measurements at each of the 33 measurement positions. The lower graph displays the CDF of the SNR measured by the LoRa tester. The LoRa tester curves contains measurement data from all 6 combinations of CR and SF, as there was no significant difference in terms of RSSI or SNR at each individual position. Before going into further details, it should be remarked that there was no position in outage in

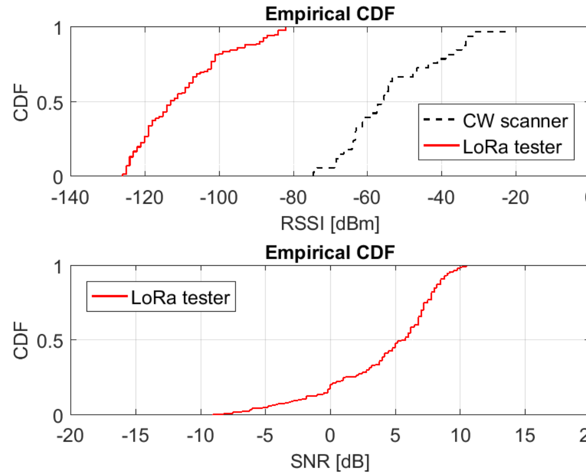

Fig. 4. Results of the initial coverage test.

the LoRa test system - at least one of the messages with any of the CR and SF combinations was always received; actually all messages for all combinations were received at all points except SN 33. At this location, the messages with the less robust configuration were not received (SF 7).

Interestingly, all points were in coverage of the LoRa system; larger losses were actually expected due to the fact that each of the arenas is structurally like a huge metal box with reinforced concrete walls. Position SN 33 was also the one with lower RSSI (-126 dBm) and SNR (-9 dB) as seen from the LoRa tester system perspective. At this position, the signal had to propagate along the open area of the public foyer, penetrate into the auxiliary ice rink and propagate to the sensor located in the middle of the lower level. Other positions with low coverage level were SN 28 (-125 dBm RSSI, -7 dB SNR) and SN 32 (-120 dBm RSSI, 4 dB SNR). The first one, despite propagation into the swimming pool area is through a low attenuation glass, was at a quite shadowed position close to the beginning of a waterslide on the upper level. For the second location, the signal has to penetrate into the main ice rink and travel to the far end close to the Zamboni entrance behind a heavy protection glass (see Fig. 3 for visual reference). Penetration at grazing angles and losses due to height level differences are main contributors to the overall signal attenuation in the Gigantium scenario. On the other hand, the positions with better coverage were, of course, the ones in the public foyer close to the LoRa test GW which were in a line-of-sight (LOS) or almost-LOS situation (around -85 dBm RSSI and 10 dB SNR).

The results obtained with the parallel CW setup were highly correlated with the ones from the LoRa test system in terms of RSSI. The average offset between both measurements is approximately 50 dB, due to the different TX powers and antenna gains of the systems. The overall PL experienced in the Gigantium scenario from the position GW T, estimated from the CW measurements and compensating for the antenna gains, was 63-118 dB.

In the view of the results, it was clear that, at least in terms of coverage, a single LoRa GW would be able to cover the entire Gigantium scenario and provide a good performance with a minimum configuration of SF 10 and CR 4/5.

IV. Final Deployment Performance Analysis

As explained earlier in Section II, for the final deployment, instead of a single LoRa GW, 4 units were installed. This was done to ensure the reliability of the system by applying macroscopic diversity i.e. letting multiple gateways receive and decode packets from a node. There were several uncertain factors at the moment of the deployment, which might have compromised the reliability with a single GW: 1) the performance of the deployed system could be different from our calibrated LoRa test system, 2) potentially, worst propagation conditions could happen when the arenas are full of people attending the different sport or cultural events, which might introduce some dynamics in the coverage.

The LoRa radio configuration[1] was set to SF 10, CR 4/5, and 125 kHz bandwidth as per the observations from the preliminary test. Initially, only 5 sensors are active at each SN (producing different temperature, pressure, humidity and CO2 data), resulting in an aggregated LoRa payload of 45 bytes. The sensor readings are transmitted in intervals of 310 s (approximately 5 min). This periodicity is sufficient for monitoring the indoor environment and for identifying and tracking unexpected events. Furthermore, the interval entails the European 868 MHz band duty cycle regulations [16] are not violated. Specifically, the utilized 868.0-868.6 MHz band has a duty cycle limitation of 1 % per hour. This means a device may only transmit $0.01 \cdot 3600\,\mathrm{s} = 36\,\mathrm{s}$ per hour. Given the 45 bytes payload and the aforementioned radio configuration the time-on-air t_{tx} is approximately 520 ms, according to Semtech's LoRa calculator [15]. Thus, the duty cycle DC_{sys} of the deployed system is:

$$DC_{\mathrm{sys}} = 100 \cdot \frac{3600\,\mathrm{s}}{t_{\mathrm{interval}}} \cdot \frac{t_{\mathrm{tx}}}{3600\,\mathrm{s}} \quad [\%] \tag{1}$$

$$= 100 \cdot \frac{3600\,\mathrm{s}}{310\,\mathrm{s}} \cdot \frac{0.52\,\mathrm{s}}{3600\,\mathrm{s}} = 0.17\,\% \tag{2}$$

In case all sensors are activated the payload is 128 bytes, resulting in a time-on-air of 1220 ms and a duty cycle of 0.39 %. Therefore, independently of the number of activated sensors the duty cycle regulations are not violated, and it is even possible to halve the transmission interval. However, the current interval of approximately 5 minutes is estimated to be a good trade-off between measurement resolution, power consumption and self-interference.

Note, the sensors were activated at random times during the installation, which translates into random transmission times within the 5 min intervals. This should randomize and thus reduce the chance of collision/interference in the system.

[1]The reader might have noted in Fig. 2 that the GWs are equipped with two radios. Effectively, in this setup, only one of them is used. Further radio research is ongoing to exploit, for example, the diversity benefits of having two radios with different LoRa settings or operating in different frequency bands.

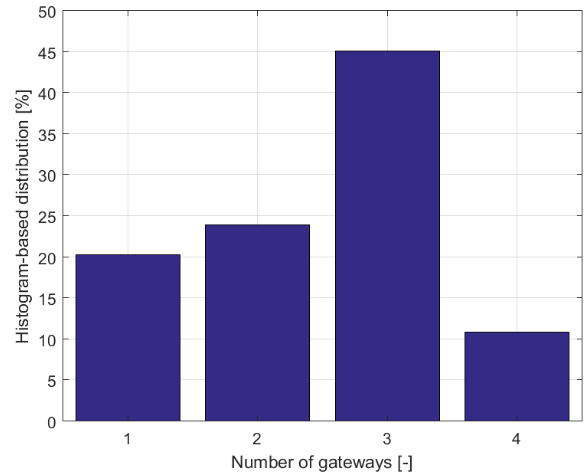

Fig. 5. Average number of gateways receiving a packet from a node.

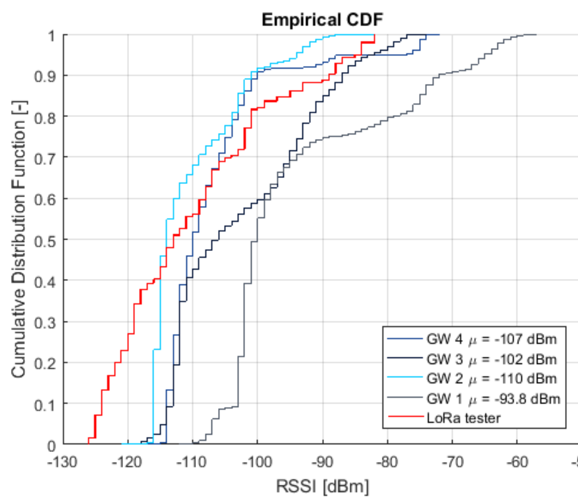

Fig. 6. RSSI for all received packets per gateway.

A. Macro-diversity Analysis

As illustrated in Fig. 1, the network utilizes 4 gateways to benefit from macroscopic diversity. Fig. 5 shows the distribution of how many gateways receive an individual packet. The data was collected during one week in March 2018 from 29 nodes, and contains approximately 55000 individual packets, which translates to more than 220000 duplicated received packets. The results show that more than half of the packets are received by at least 3 gateways and thus the average packet error rate across all nodes, based on the LoRa sequence number, is less than 1.2 %. It is for further study to observe the benefit of the macroscopic diversity, when thousands of people attend concerts, fairs, and sports events.

Since more than half of the packets are received by at least 3 gateways, it is no surprise that the observed RSSI is high. The average is about -95 to -110 dBm per gateway, as illustrated in Fig. 6. The RSSI from the initial measurement test was also plotted in the figure to serve as reference, but it should be noted that the curves for GWs 1-4 include the time variant dynamics of the coverage as they have been computed over the full one-week set of received data. In general, it can be seen how the GW RSSI statics are highly correlated with the concentration distance of SNs around them. GW1 is in a more SN-populated area than 2, and thus, despite of the time variations, in average experiences a better RSSI distribution due to the proximity of the nodes.

B. Multi-sensor Nodes Battery Life

The SNs are powered with 3 AA batteries (4.5 V). A calibration measurement was performed in order to find the cut-off voltage at which the nodes would stop working and would require the batteries to be replaced with new ones. The minimum voltage at which the nodes are still operational and sending trustworthy sensor data is 2.8 V. Based on the empirical discharge trends observed during the calibration, considering the same LoRa configuration set for the Gigantium's network, a SN battery life of 120 days (4 months) is expected. The battery status of each of the 33 SN is also monitored from the AAU Grafana back-end dashboard, so an alert will pop-up when a SN needs a battery replacement.

V. Conclusions and Future Work

This paper has presented one the first end-to-end wireless IoT pilot projects relying on the LoRa communication protocol. 33 multi-sensor battery-powered nodes have been deployed in a multi-arena in Aalborg, Denmark to monitor indoor environment and building usage. Even though the 33.000 m^2 complex is made with reinforced concrete and metallic surfaces, initial measurements showed one single LoRa gateway could provide coverage to all arena facilities. However, the final network is designed to utilize the macroscopic diversity capabilities of the LoRa protocol by means of the deployment of 4 gateways. The results show that more than half of the transmitted messages are received by at least 3 gateways, which thus entails very low packet error rates.

Future work includes replacement of the estimated CO_2 and pressure sensor, but more importantly the analysis and application of the collected data to optimize indoor environment, both to save water, heat, and electricity, but also improvement the welfare of employees and guests. From a radio research perspective, a more extensive end-to-end performance analysis will be performed, at the same time that the network is evolved and optimized to collect more data or operate with different radio configuration.

Acknowledgment

This study is part of the Aalborg University WCN IoT Living Lab research project, which was born under the umbrella of the SMART Aalborg municipal project. The authors would like to express their gratitude to Jørn Sørensen and Per H. Christensen, Living Lab Team Members, for their contribution to the development of the LoRa Coverage Tester; as well as to Kim T. Jønsson and Rasmus L. Jensen, from the Department of Civil Engineering at Aalborg University, for the detailed planning of node locations and for performing the study on the accuracy of the indoor environment sensors. The authors would also like to thank to Morten H. Larsen from Gigantium, for grating access to all facilities and his assistance throughout all the different testbed testing and network deployment stages.

References

[1] Gigantium,"Kultur og idrætscenter, haller, skøjtehal, svømmehal, koncerter", Internet: https://gigantium.dk/ [May. 1, 2018].

[2] Google Maps, "Gigatium's 360° virtual tour", Internet: https://gigantium.dk/360-inview [May. 1, 2018].

[3] A. Augustin *et. al*, "Study of LoRa: Long Range & Low Power Networks for the Internet of Things", Sensors, vol. 16(9), 2016.

[4] M. Lauridsen *et. al*, " Interference Measurements in the European 868 MHz ISM Band with Focus on LoRa and Sigfox", IEEE Wireless Communications and Networking Conference (WCNC), 2017.

[5] O. Georgiou *et. al*, "Low Power Wide Area Network Analysis: Can LoRa Scale?", IEEE Wireless Communications Letters, vol. 2(6), pp. 162-165, 2017.

[6] E. Dutkiewicz *et. al*, "Massive Machine-Type Communications", IEEE Network, vol. 31, no. 6, pp. 6-7, 2017. *et. al*,

[7] BrainsBussiness, "Gigantium bliver testsite for IoT-netvrk", Internet: http://www.brainsbusiness.dk/dk/nyheder/gigantium-bliver-testsite-for-iot-netvaerk.htm [May. 1, 2018]

[8] A.J. Jakobsen, and A. Falck, "Gigantium får taget temperaturen", Nordjyske Erhvevsliv (Mar.20, 2018), pp 8-9.

[9] RTX, "Wireless Wisdom", Internet: https://www.rtx.dk/ [May. 1, 2018].

[10] Semtech, "SX1276 transceiver", Internet: https://www.semtech.com/products/wireless-rf/lora-transceivers/SX1276 [May. 1, 2018].

[11] Kerlink, "Wirnet Station", Internet: https://www.kerlink.com/product/wirnet-station/ [May. 1, 2018].

[12] Microchip, "RN2483 transceiver", Internet: http://www.microchip.com/wwwproducts/en/RN2483 [May. 1, 2018].

[13] I. Rodriguez *et. al*, "Testing of Low-Power Wide-Area Technologies in Controlled Propagation Environments", Loughborough Antennas and Propagation Conference (LAPC), 2017.

[14] GrafanaLabs, "Grafana", Internet: https://grafana.com/ [May. 1, 2018].

[15] Semtech, "LoRa Modem Calculator Tool", Internet: https://www.semtech.com/uploads/documents/SX1272LoRaCalculatorSetup1_1.zip [May. 9, 2018].

[16] ETSI, "Electromagnetic compatibility and Radio spectrum Matters; Short Range Devices; Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW; Part 1", 300 220-1 V2.4.1, 2012.