Remote Monitoring of IoT Sensors and Communication Link Quality in Multisite mMTC Testbed

Seppo Horsmanheimo[1], Joonas Säe[2], Tero Jokela[3], Lotta Tuomimäki[1], Ethiopia Nigussie[4], Annemarie Hjelt[5], Sami Huilla[1], Tahsin Dönmez[4], Nicolas Le Bail[5], and Mikko Valkama[2]
[1] VTT Technical Research Centre, Finland
[2] Tampere University, Department of Electrical Engineering, Tampere, Finland
[3] Turku University of Applied Sciences, Finland
[4] University of Turku, Finland
[5] Digita, Finland
Contact e-mail: seppo.horsmanheimo@vtt.fi

***Abstract*—Massive Machine Type Communication (mMTC) technologies are key to addressing communication requirements of various emerging IoT applications. In this work, a multisite mMTC test network is designed and implemented in order to investigate the long-term communication quality and sensor data of LoRa and NB-IoT. This is essential for remote network maintenance operations, because it allows distinguishing communication quality defects from software/hardware failures. Moreover, it provides additional information about the communication link quality for network management. The test network is geographically scattered over a large area in Finland and experimented both in private and public networks. Measurements on LoRaWAN test networks revealed that higher SNRs and RSSIs are generally achieved for devices with lower spreading factors. Comparison of NB-IoT and LoRaWAN shows that NB-IoT has better communication quality performance. Overall, this paper provides first long-term multi-site and multi-technology mMTC measurements and corresponding performance analysis that are not available in the existing literature.**

***Index Terms*—mMTC, LoRa, NB-IoT, multisite testbed, QoS.**

I. INTRODUCTION

The forthcoming 5G mobile technology introduces massive Machine Type Communications (mMTC) as one of the service pillars [1]. 5G technology is considered as a system of systems and it exploits other technologies to fulfil end-users' requirements. Since mMTC has not yet been specified in 5G, we designed and implemented our multisite mMTC testbed using existing Low Power Wide Area Network (LPWAN) technologies to be a benchmark for the forthcoming 5G mMTC solutions.

LPWAN can be divided into two main groups: licensed and unlicensed technologies. The licensed version includes technologies developed by 3rd Generation Partnership Project (3GPP) such as Narrow Band Internet of Things (NB-IoT) and Long Term Evolution, category M1 (LTE-M), which are considered as cellular IoT technologies. They are especially interesting for mobile network operators, because they require mainly firmware updates for existing mobile network equipment, therefore enabling fast rollout of IoT networks.

The unlicensed version includes other IoT technologies, out of which Long Range (LoRa) and Sigfox can be identified as the most popular ones. Due to license free operations, they are much cheaper to deploy from the spectrum cost point of view. It makes them attractive to new telecommunications companies. However, they require their own infrastructure, which slows down the deployment across a geographically wide area. Overall, both of these technologies have their own pros and cons [2][3]. Some studies even suggest a combination of these two in order to utilize the pros of both technologies [4][5][6].

Typical mMTC use cases include different asset monitoring and smart metering. For water industries, remote water meter readings and pressure measurements of a water pipe on several test points can be used for assisting the detection of leakage points and other malfunctions. Electric power companies use mMTC sensors e.g. for tracking whether a door of a primary or secondary substation is open and for ensuring that the disconnectors used in high-voltage networks are open during maintenance work. Moreover, cable drums can be tracked with mMTC sensors and power line maintenance work can be supported by sensors attached to electric poles to sense if snow or ice load is too high for overhead cables or poles. Snow load is a problem especially in the northern and eastern parts of Finland. The smart building industry also benefits from mMTC use cases including metering of air quality, temperature, carbon dioxide, light conditions and detection of smoke, motion, and space utilization [7]. Sensors can also be sunk in wet concrete to monitor the drying process of the material by measuring the temperature and moisture. This has turned out to be a great aid for quality control in construction sites.

In this work, a multisite mMTC pilot system utilizing LoRa and NB-IoT technologies is designed and implemented. The aim is to study opportunities offered by both technologies for the remote monitoring of IoT devices. In addition to the metering information, communication quality data is collected to speed up the detection of communication quality related failures. The measurement covers two months of data from LoRaWAN and two weeks from NB-IoT networks. Both private and public test networks as well as stationary and mobile end devices are included in the trials. Such long-term multi-site and multi-technology measurements and associated performance analysis are something that is not available in the current open literature, forming thus the major contribution of the paper.

II. NATION-WIDE NB-IOT AND LORA NETWORKS

Our multisite testbed is designed to connect mMTC networks in the city of Espoo, city of Tampere, and city of Turku, all in the southern part of Finland. The testbed supports both public and private mMTC networks implemented with licensed NB-IoT and unlicensed LoRa technologies.

The licensed network part is built on top of Finnish 5G Test Network Finland (5GTNF) [8] presented in Fig. 1. It offers a 5G/NB-IoT core network to exchange information between the sites. Our sites are VTT Technical Research Centre of Finland Ltd (VTT) in Espoo, Tampere University (TAU) in Tampere, and University of Turku (UTU) and Turku University of Applied sciences (TUAS) in Turku. With minor modifications, our multisite testbed can also be extended to other 5GTNF pilot sites.

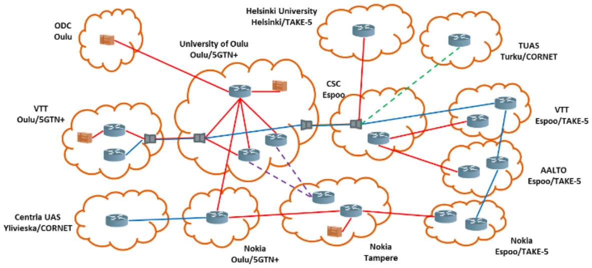

Fig. 1. 5G test network Finland (5GTNF) [8].

The unlicensed network part is built on top of Digita’s commercial nation-wide LoRa network [9]. Digita is a Finnish transmission and broadcasting network company that has implemented a commercial LPWAN using a combination of their high TV broadcasting masts, lower masts, rooftop sites, and two-way LoRa technology. The LoRa network’s outdoor population coverage is 92% and the area coverage is 51% in February 2019 and is continuously expanded based on customer needs.

In our testbed, both public and private LoRa networks are supported in the following way:

- The Espoo site (VTT) is connected to the nation-wide commercial LoRa network through Digita’s outdoor gateways and to a private LoRa network via one indoor LoRa gateway installed in the Micronova building.
- The Tampere site (TAU) is connected to the nation-wide LoRa network. One of the outdoor gateways is placed on the rooftop of the Kampusareena building, which is located at the center of the student campus in Hervanta, Tampere.
- The Turku sites (UTU and TUAS) are connected to the nation-wide LoRa network. The stationary LoRa terminals are connected to outdoor gateways located on the rooftops of the DataCity and ICT-city buildings. The site includes a private LoRaWAN network that was set up and deployed to conduct security research, which would not be possible in a commercial nation-wide network.

III. DATA PLATFORM AND VISUALIZATION TOOLS

Our goal for the platform is to support maintenance operations across a wide geographical area. The platform supports private, local, public, and nation-wide LPWANs. The core of our testbed is an application server (AS) that is located in Espoo. The server includes an InfluxDB database to store time series information. The server has dedicated interfaces to retrieve information: from public LoRa networks via Digita’s ThingPark, from private LoRa networks via open source The Things Network, and from commercial and NB-IoT networks via 5GTNF test networks. The overall structure of the data platform is presented in Fig. 2.

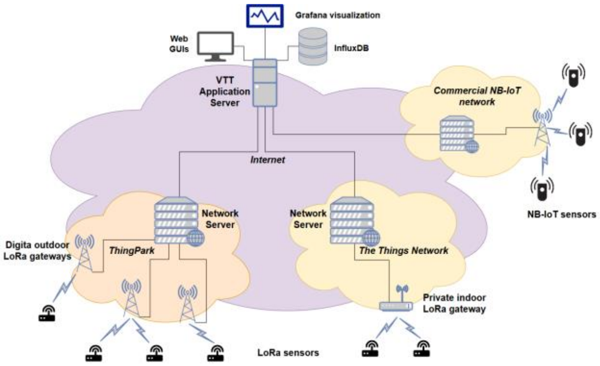

Fig. 2. mMTC multisite testbed.

Each of the four sites has its own characteristics and service needs to be fulfilled. The monitored data includes sensor and network quality information. The latter one is used to distinguish possible communication problems from sensor hardware or software failures and to help maintenance personnel to evaluate the performance of the data links.

Real-time visualization is important for management of distributed IoT systems. We used the Grafana tool to create real-time monitored data graphs. Separate dashboards for communication performance and sensor information have been implemented. Figure 3 illustrates in real-time received signal strength (RSSI) and signal to noise ratio (SNR) information from different sites.

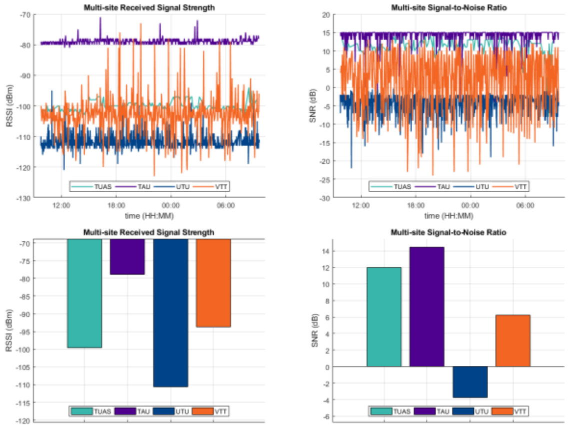

Fig. 3. Monitored multisite RSSI and SNR values.

Each site has its own sensors to be monitored. Figure 4 presents an example of sensor information collected from multiple end-devices at Turku site (UTU) including temperature, humidity, CO_2, and VOC levels.

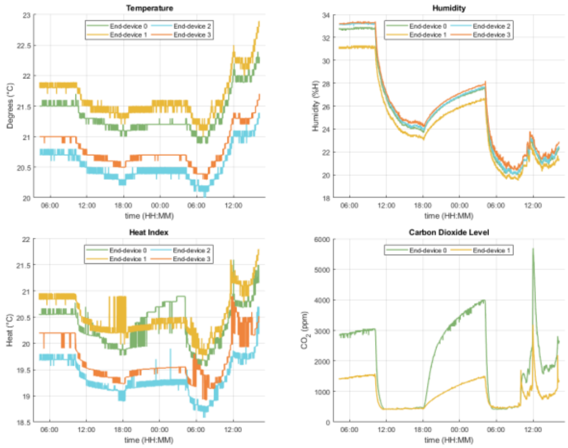

Fig. 4. Real-time sensor information collected from the University of Turku site.

The application server has also interfaces to 2D and 3D visualization tools. The data can be retrieved online or offline. For online scenarios, data is fetched directly from the InfluxDB database or delegated with MQTT protocol to registered subscribers. Figure 5 shows a snapshot of a 3D visualization tool that has been implemented on a Unity game engine. Locations for indoor samples are obtained from a mobile robot using a lidar or, alternatively, calculated by an indoor positioning server [10]. An mMTC device typically has a rather low sampling rate to reduce power consumption, so multiple identical devices are used in parallel to increase the sampling rate in case of mobile robot measurements.

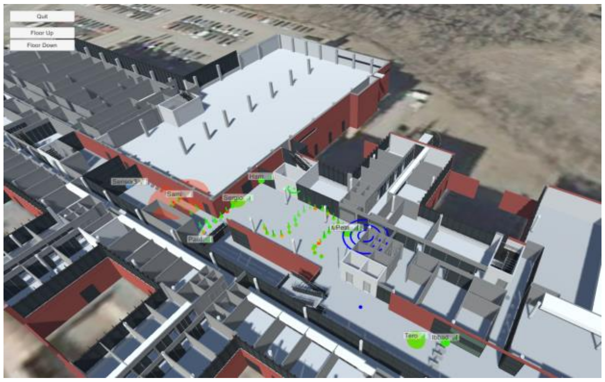

Fig. 5. A Unity based 3D visualization tool for assessing the performance of mobile mMTC sensors.

For offline scenarios, mMTC data is retrieved from InfluxDB in a table format for external tools like Excel, Matlab and QGIS. These tools are used for a more profound analysis e.g. to investigate effects of spreading factor on coverage, number of detected gateways, and available data rates. Similar analyses have been done by other research parties focusing on quantification and performance of LoRaWAN [11], LoRa coverage [12], and analysis of packet payloads, radio-signal quality, and spatiotemporal aspects [13].

IV. END-USER TERMINALS

The testbed supports stationary and mobile measurements. LoRa technology has matured over the years, so it offers a wide variety of end-devices. In contrast to LoRa, the availability of NB-IoT devices is significantly scarcer at the time of writing this paper. Therefore, the majority of end-devices used in our trials were LoRa end-devices. Figure 6 shows examples of LoRa and NB-IoT devices used in the field trials.

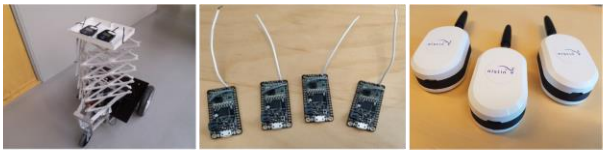

Fig. 6. Examples of mobile and stationary mMTC devices used in trials. The two left ones are LoRa and the right one NB-IoT devices.

The complete list of end-devices and sensors used in the trials is presented in Table I. All LoRa test networks used Type-A traffic compliant version of the LoRaWAN protocol. Confidentiality, integrity, and authentication of the messages were ensured using Electronic Code Book (ECB), Cipher based Message Authentication Code (CMAC), CCM* modes of operation of the Advanced Encryption Standard (AES) with a key size of 128 bits as specified in the specification of LoRaWAN.

TABLE I. LIST OF END-DEVICES USED IN THE MULTISITE TRIAL.

End-devices	**Sites**	**Indoor/ outdoor**	**Stationary/ mobile**	**Sensors**
Adafruit Feather 32u4	VTT	both	stationary	battery voltage
Adeunis	VTT	both	mobile	battery voltage, location, temperature
Sodaq	VTT[a]	indoor	stationary	battery voltage, temperature
Adafruit Feather 32u4	TAU	indoor	stationary	battery voltage
Adeunis	TAU	indoor	stationary	battery voltage
Elsys ERS	TUAS	indoor	stationary	temperature, humidity
Elsys ELT	TUAS	indoor	stationary	temperature, humidity
Elsys ESM	TUAS	indoor	stationary	temperature, humidity
Arduino + Libelium LoRaWAN Module	UTU	indoor	stationary	temperature, humidity, CO_2, VOC
Arduino + Libelium LoRaWAN Module	UTU[a]	indoor	stationary	temperature, humidity, CO_2, VOC
Exelonix NB|DESK	TAU[a,b]	indoor	stationary	temperature, humidity, pressure, accelerometer
iProtoXi Aistin Blue	TAU[a,b]	indoor	stationary	temperature, humidity, pressure, accelerometer

a. private network, b. NB-IoT

At Espoo site (VTT), Adafruit Feather 32u4 devices are used in stationary measurements. In the trials, the devices were placed in the same room to enable measurements with different spreading factors (SF). Adeunis LoRaWAN field test devices are used for both mobile indoor and outdoor measurements and Sodaq LoRa devices for private LoRa network measurements.

The user equipment at the Tampere site (TAU) consists of Adafruit Feather 32u4 LoRa Radios and Adeunis LoRaWAN. In the trials, the devices were placed in the same room. For NB-IoT measurements, NB|DESK NB-IoT devices manufactured by Exelonix and Austin Blue NB-IoT devices manufactured by iProtoXi were used. The results and analysis presented in this paper were conducted with NB|DESK devices placed in the same room. The private NB-IoT test network in Tampere utilizes Nokia base stations and the test network operates in Band 28 (700 MHz).

Both Turku sites (UTU and TUAS) consist of stationary indoor end-devices, which are located in two buildings in their premises.

V. MEASUREMENT DATA AND ANALYSIS

The measurement data was collected over a 2-month period between November 14, 2018 and January 14, 2019 from the four sites. Our main interest was to investigate network performance in terms of received signal strength (RSSI), packet error rate (PER), and signal quality (SNR) with different spreading factors. The documented capabilities and limitations of LoRaWAN [14] were taken into account by studying published performance analysis and measurement results [15][16][17].

Statistical data collected from the sites, more than 920 000 measurement samples, is presented in Table II. The table shows the averages and standard deviations of selected parameters over the 2-month measurement period. Packet error rate (PER%) is the ratio, in percent, of the number of packets not successfully received to the number of packets sent. The instant packet error rate means that the percentage is computed with a moving window of the last n packets: by default, the ten last uplink frames are taken into account. A value range as spreading factor in the SF column indicates that Adaptive Data Rate (ADR) is used. ADR is a dynamic mechanism for optimizing data rates, airtime and energy consumption in the network.

TABLE II. STATISTICS OF THE MULTISITE LORA MEASUREMENT.

Espoo site (VTT)						
Id	***SF***	***Inst. PER (%) / STD***	***RSSI (dBm) / STD***	***SNR (dB) / STD***	***Distance (km) / STD***	***Sample interval (s) / STD***
1	7-12	13.5 / 4.4	-91.9 / 5.6	5.8 / 7.4	2.1 / 1.9	156 / 58
2	12	13.1 / 2.8	-91.1 / 6.1	3.6 / 7.2	2.1 / 1.8	153 / 50
3	9	15.8 / 3.1	-97.8 / 4.4	8.4 / 6.2	1.7 / 1.2	146 / 54
4	7	23.3 / 5.4	-100.7 / 3.6	8.8 / 5.3	1.7 / 1.2	161 / 72
Tampere site (TAU)						
Id	***SF***	***Inst. PER (%) / STD***	***RSSI (dBm) / STD***	***SNR (dB) / STD***	***Distance (km) / STD***	***Sample interval (s) / STD***
1	7	9.1 / 2.7	-79.7 / 7.1	14.2 / 3.4	0.2 / 0.3	135 / 39
2	9	5.7 / 3.6	-77.9 / 8.9	14.2 / 6.1	0.3 / 0.6	129 / 32
3	12	2.8 / 3.9	-78.2 / 10.4	13.0 / 9.3	0.4 / 1.5	134 / 29
4	7	3.4 / 2.8	-69.4 / 8.4	14.3 / 4.7	0.2 / 0.3	126 / 24

<table>
<tr><th colspan="7">Turku site (TUAS)</th></tr>
<tr><th>Id</th><th>SF</th><th>Inst. PER (%) / STD</th><th>RSSI (dBm) / STD</th><th>SNR (dB) / STD</th><th>Distance (km) / STD</th><th>Sample interval (s) / STD</th></tr>
<tr><td>1</td><td>12</td><td>0.0 / 0.2</td><td>-77.1 / 5.0</td><td>14.9 / 1.5</td><td>0.2 / 0.7</td><td>302 / 39</td></tr>
<tr><td>2</td><td>7</td><td>8.5 / 7.1</td><td>-75.5 / 11.1</td><td>14.0 / 4.8</td><td>0.5 / 0.8</td><td>322 / 92</td></tr>
<tr><td>3</td><td>7-12</td><td>36.3 / 17.2</td><td>-99.2 / 7.2</td><td>10.8 / 10.9</td><td>2.9 / 4.7</td><td>319 / 91</td></tr>
<tr><td>4</td><td>7-12</td><td>5.3 / 7.6</td><td>-97.8 / 6.9</td><td>10.6 / 7.3</td><td>3.3 / 4.3</td><td>320 / 102</td></tr>
<tr><th colspan="7">Turku site (UTU)</th></tr>
<tr><th>Id</th><th>SF</th><th>Inst. PER (%) / STD[a]</th><th>RSSI (dBm) / STD</th><th>SNR (dB) / STD</th><th>Distance (km) / STD</th><th>Sample interval (s) / STD</th></tr>
<tr><td>1</td><td>12</td><td>- / -</td><td>-105.5 / 3.9</td><td>-0.5 /4.4</td><td>4.0 / 1.9</td><td>33 / 10</td></tr>
<tr><td>2</td><td>7-8</td><td>- / -</td><td>-109.8 / 2.9</td><td>-1.5 / 3.3</td><td>2.9 / 1.4</td><td>51 / 48</td></tr>
<tr><td>3</td><td>7-8</td><td>- / -</td><td>-103.5/ 4.3</td><td>6.2 / 4.8</td><td>3.1 / 1.7</td><td>34 / 12</td></tr>
<tr><td>4</td><td>10-11</td><td>- / -</td><td>-110.0 / 3.1</td><td>-4.6 / 5.0</td><td>3.1 / 1.6</td><td>33 / 10</td></tr>
</table>

a. PER values were not available from the University of Turku.

From Table II, a web graph is constructed to illustrate differences in network performance between devices, sites, and used spreading factors. Figure 7 shows that smaller SF values are used with higher SNR and RSSI values.

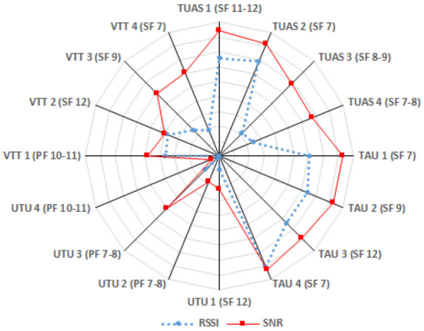

Fig. 7. Average RSSI and SNR values of end-devices at the four sites with different spreading factors. Values are not in scale.

To better understand long-term effects of weather and load conditions, Fig. 8 shows the average RSSI and SNR values of each device. Different sites are presented with different colors (TUAS in turquoise, TAU in purple, UTU in blue, and VTT in orange) and the size of the ellipse illustrates the standard deviations of measured RSSI and SNR values. SNR is defined as the ratio between the received power signal and the noise floor power level. Figure 8 shows that the highest deviations in SNR values per device are obtained from TUAS and TAU devices. The largest deviation between sensors in the same room can be found from the UTU site. The figure shows clear differences between devices in case of different SF values. When SNR is below 7 dB, it can be used as an overall quality indicator; otherwise RSSI value is preferable.

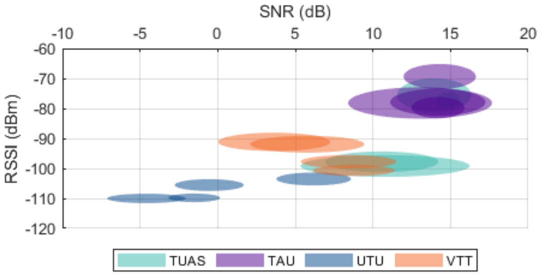

Fig. 8. RSSI vs. SNR at different sites.

Figure 9 shows the SNR vs. PER% values. The size of the ellipse shows the deviations in SNR and PER% values. High SNR value constitutes lower PER%. Differences between the devices are highest in TUAS site, but in all sites, the effects of different SF values on PER% are evident. The deviation in PER% values is the smallest at TAU and VTT premises. The lowest average PER% value was measured with TAU 4 (SF 7) device that was using repetition mode. It lowered the PER% value to one third compared to TAU 1 (SF 7) device.

In general, correlation between SNR and PER% should be better than between RSSI and PER%, since the SNR takes into account the current noise level. This means that when the SNR is low, more packets should be lost. The 2-month measurement indicated that this generalization does not always apply. The PER% depends also on other factors than SNR.

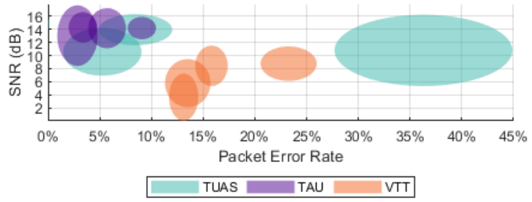

Fig. 9. SNR vs. PER% at different sites.

Deviations in RSSI and SNR values were high in all sites. The 2-month measurement gave us an opportunity to investigate how different loads and weather conditions affect the reporting gateway (the highest SNR). Figure 10 shows the locations of reporting gateways at Espoo site. The area of a reporting gateway is close to 100 km^2. Another observation was that the location of a gateway moved (a small picture in the figure) in some cases. This is likely due to the use of a GPS receiver at the gateway. Due to different satellite constellations, location of the gateway moves up to 200 meters. This has an effect on the positioning accuracy if multilateration is used.

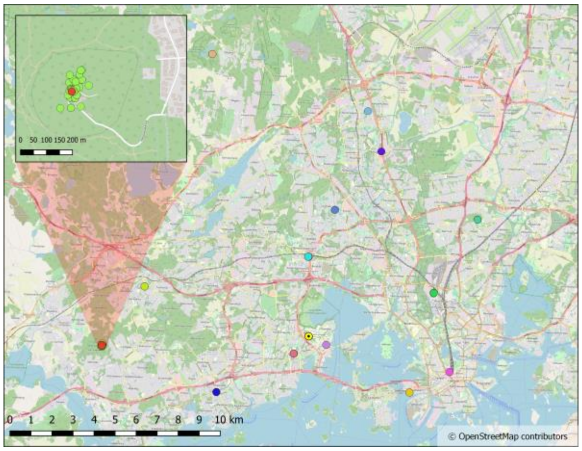

Fig. 10. Locations of a reporting gateway in Espoo site.

Figure 11 shows pie charts with two spreading factors. The chart shows how often a specific gateway was reporting the communication quality parameters. The figure shows that higher SF value (10-11) causes more variation in the reporting gateway than in the case of SF 7.

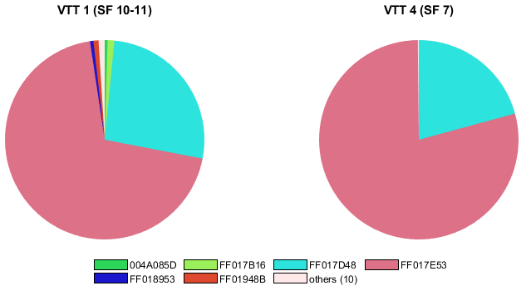

Fig. 11. Proportions of gateways' reporting times with SF 10-11 and SF 7.

Table III shows a comparison between LoRaWAN and NB-IoT test network measurements from Tampere University. The measurement data was collected between January 16 and January 24, 2019. As these two technologies have slightly different characteristics, only directly comparable measurement results are shown in the table.

TABLE III. TAMPERE UNIVERSITY NB-IOT AND LORA COMPARISON.

Device	**RSSI (dBm)**	**RSSI STD**	**SNR (dB)**	**SNR STD**	**Spreading factor**
LoRa #1	-77.6	7.4	14.5	3.0	7
LoRa #2	-70.2	10.4	14.5	5.7	9
LoRa #3	-75.5	9.5	13.2	8.5	12
NB-IoT #1	-65.5	0.9	28.5	0.6	-
NB-IoT #2	-63.7	1.5	27.6	1.3	-

Table III shows that NB-IoT measurements were performed closer to the base station antennas, as the RSSI is clearly stronger than in LoRaWAN network. This correlates also with higher SNR values, but that is not the only reason for higher SNR values. NB-IoT is utilizing licensed frequency bands and therefore it performs better in comparison to the unlicensed LoRaWAN network. This is due to careful frequency planning, which is performed for the licensed bands, whereas unlicensed frequency bands are free to use for anyone (under certain power restrictions). Figure 12 shows average SNR vs. RSSI values in the case of LoRa and NB-IoT with standard deviations. It can be noted, that NB-IoT has clearly smaller variation.

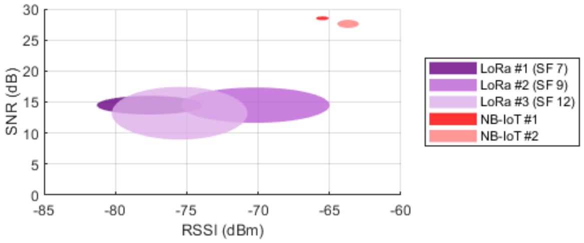

Fig. 12. Comparison of NB-IoT and LoRa SNR vs. RSSI values at the TAU site.

The importance of monitored IoT data security increases as monitoring is extended to all parts of the building, and more and more building automation is relying on real-time decision-making based on the collected IoT data. The private network in Turku site (UTU) was used for security research. Study results indicate that protocol vulnerabilities in major version v1.0 can be exploited to launch different kinds of attacks on the test network such as replay, denial of service (DoS), eavesdropping, and acknowledge spoofing. Study also revealed that some of these vulnerabilities, addressed in the latest major version 1.1, could be exploited in backward compatibility scenarios [18]. LoRaWAN provides end-to-end confidentiality for application data, but not end-to-end integrity protection. Therefore, it is crucial to have secure channels between the backend servers. In the multisite mMTC testbed, secure channels are established using Transport Layer Security (TLS).

VI. CONCLUSIONS

The paper presented the design of a multisite mMTC testbed consisting of both private and public test networks and results of a parallel long-term sensor and communication quality measurements conducted in the cities of Espoo, Tampere, and Turku. Monitoring of both sensors data and communication quality is important for remote maintenance operations to be able to distinguish possible communication related failures from software and hardware device failures. It also provides real-time communication link quality information for the managers of the networks.

The 2-month measurement indicated that the packet error rates in LoRa network were relatively high, so end-users need to design the remote monitoring system in such a way that the application is able to tolerate the loss of some measured samples. The repetition mode helped to reduce the packet error rate. The reduction was over 60% compared to measurements without the repetition.

The measurements in LoRaWAN network indicated that higher SNR and RSSI levels allows to use lower spreading factors, which constitute lower packet error rates. When higher SF values (10-11) were used, the area of the reporting gateways increased significantly. The reported distance from a specific gateway was also found to vary during a long measurement, which has a negative impact on IoT localization services. The comparison between NB-IoT and LoRaWAN showed that NB-IoT had higher RSSI and SNR values. Moreover, the deviations of both values were significantly smaller. This is due to fact that the NB-IoT base station in the pilot setup was relatively close to the devices and the careful network planning for the licensed band reduced the interference of other base stations. In addition, the number of other NB-IoT devices in the test network is still rather limited compared to LoRa devices, so the network load is smaller.

In the future, integration of LoRa and NB-IoT networks continues and more emphasis is put on security and remote control to complement remote IoT monitoring services.

ACKNOWLEDGMENT

This work was supported by the Finnish public funding agency for research, Business Finland, under the project “Wireless for Verticals (WIVE)” and “5G Vertical Integrated Industry for Massive Automation (5G-VIIMA)”. Both projects are part of 5G Test Network Finland (5GTNF) and multisite prototype was developed by industrial and research partners.

REFERENCES

[1] M. Shafi et al., “5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice,” IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, pp. 1201-1221, 2017.

[2] R. S. Sinha, Y. Wei, S.-H. Hwang, “A survey on LPWA technology: LoRa and NB-IoT,” ICT Express, vol. 3, no. 1, pp. 14-21, 2017.

[3] S. Popli, R. K. Jha, S. Jain, “A Survey on Energy Efficient Narrowband Internet of things (NBIoT): Architecture, Application and Challenges,” IEEE Access. doi: 10.1109/ACCESS.2018.2881533

[4] X. Zhang, M. Zhang, F. Meng, Y. Qiao, S. Xu, S. Hour, “A Low-Power Wide-Area Network Information Monitoring System by Combining NB-IoT and LoRa,” IEEE Internet of Things Journal, vol. 6, no. 1, pp. 590-598, 2019.

[5] K. Mikhaylov et al., “Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration,” 2018 IEEE International Conference on Communications (ICC).

[6] R. Yasmin, J. Petäjäjärvi, K. Mikhaylov, A. Pouttu, “On the integration of LoRaWAN with the 5G test network,” 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC).

[7] R. Yasmin, J. Petäjäjärvi, K. Mikhaylov, A. Pouttu, “Large and Dense LoRaWAN Deployment to Monitor Real Estate Conditions and Utilization Rate,” 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC).

[8] “5GTNF,” [Online]. Available: http://5gtnf.fi/

[9] “Digita’s IoT LoRaWAN network,” [Online]. Available: https://digita.fi/en/services/iot/iot_lorawan_network_coverage_map

[10] S. Horsmanheimo et al., “Indoor positioning platform to support 5G location based services,” unpublished.

[11] J. Petäjäjärvi, K. Mikhaylov, M. Pettissalo, J. Janhunen, J. Iinatti, “Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage,” International Journal of Distributed Sensor Networks, vol. 13, no. 3, 2017.

[12] A. Augustin, J. Yi, T. Clausen, W. M. Townsley, “A Study of LoRa: Long Range & Low Power Networks for the Internet of Things,” MDPI, Sensors, vol. 16, no. 9, 2016.

[13] N. Blenn, F. Kuipers, “LoRaWAN in the Wild: Measurements from The Things Network,” arXiv:1706.03086, 2017.

[14] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melià-Seguí, T. Watteyne, “Understanding the Limits of LoRaWAN,” IEEE Communications Magazine, vol. 55, no. 9, pp. 34-40, 2017.

[15] T. Petrić, M. Goessens, L. Nuaymi, L. Toutain, A. Pelov, “Measurements, performance and analysis of LoRa FABIAN, a real-world implementation of LPWAN,” 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC).

[16] E. D. Ayele, C. Hakkenberg, J. P. Meijers, K. Zhang, N. Meratnia, P. Havinga, “Performance Analysis of LoRa Radio for an Indoor IoT Applications,” 2017 International Conference on Internet of Things for the Global Community (IoTGC).

[17] P. Neumann, J. Montavont, T. Noël, “Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study,” 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob).

[18] T. C. M. Dönmez, E. Nigussie, “Security of LoRaWAN v1.1 in Backward Compatibility Scenarios,” Procedia Computer Science, vol. 134, pp. 51-58, 2018.