COVER LETTER

To the attention of Professors Leopoldo Angrisani and Francesco Bonavolontà
Guest Editors of the Special Issue of Acta IMEKO

Dear Guest Editors,

first of all, we want to thank you again for the possibility to submit an extended version of our paper conference entitled "A novel experimental-based tool for the design of LoRa networks" to the Special Issue of Acta IMEKO.

According to the journal's Author Guidelines, please find in this cover letter the requested additional information about the submitted extended version of the original paper that appeared in the Proceedings of the 2019 IEEE International Workshop on Metrology for Industry 4.0 and IoT.

- Chose a different title for the full paper: the title chosen for the full paper is "A Field Measurements Based LoRa Networks Planning Tool" that is different from the title of the origina conference paper ("A novel experimental-based tool for the design of LoRa networks");
- Create a substantial extension and indicate the main points of extension:

With respect to the conference paper, the following additional contributions and changes (reported in blue text color) have been added to the full version:

- Initial part of the Abstract has been changed:

The Long Range (LoRa) transmission technology enables energy-constrained devices, like tiny sensor systems used in Internet of Things (IoT) applications, to be distributed over wide areas and still be able to establish affordable connectivity. This motivated an exponentially increasing amount of different solutions and services based on LoRa, either dedicated to long-term monitoring of distributed plants and infrastructures, and to human-centered applications, like safety-oriented sensor systems to be used in the workplace. In dense LoRa networks, predicting the number of supported nodes in relation to their position and the propagation environment is essential to ensure a reliable and stable communication and to limit costs. In this paper, after comparing different path loss models based on a field measurement campaign of LoRa Received Signal Strength Indicator (RSSI) values within a University campus, two main modifications of the LoRa Simulator tool are implemented. They are aimed at improving its accuracy in the prediction of the number of sustainable nodes, according to the target Data Extraction Rate set. Simulations based on field measurements show that by an improved path loss evaluation, and using three gateways, the number of nodes could increase theoretically from about 100 to about 6000.

- In the Introduction section, the following new lines and references have been added:

Many examples of IoT applications relying on LoRa transmission technology may be found in the recent literature. Addabbo et al. [5, 6] present a low-power IoT architecture for the monitoring of chemical emissions, to be employed to set up monitoring infrastructures in industrial plants or public buildings. In the context of smart cities, the use of LoRa provides the advantage of allowing for the deployment of a large quantity of sensor nodes while keeping the structure of the acquisition network relatively simple and flexible. A LoRa-based smart bin architecture for waste management in the smart cities' context is presented in [7], exploiting an ultrasonic sensor to check for the trash level inside the bin. Using a single-channel LoRa network, it is shown how a system composed by 5 sensor nodes was deployed in the historical centre of the city of Florence, in Italy. Another example, dealing with the problem of covering long distances among LoRa nodes and gateways in sensor networks deployed to monitor gas pipelines, has been recently presented in [8]. In order to overcome the limits of transmission coverage, the paper suggests a multi-hop linear topology supported by a properly adapted synchronization protocol. Other examples of distributed plants and systems monitored by means of a LoRa-based solution are given in [9, 10]. At the same time, LoRa has been chosen to support also sensor network solutions aimed at human monitoring, as presented in [11], where a wearable system for noise assessment in the workplace is proposed, according to which it is possible to notify a subject about a potentially dangerous exposure to high noise levels for a prolonged time.

[5] T. Addabbo, A. Fort, M. Mugnaini, L. Parri, S. Parrino, A. Pozzebon, V. Vignoli, "A low-power IoT architecture for the monitoring of chemical emissions," ACTA IMEKO June 2019, Volume 8, Number 2, pp. 53–61.

[6] T. Addabbo *et al.*, "An IoT Framework for the Pervasive Monitoring of Chemical Emissions in Industrial Plants," *2018 Workshop on Metrology for Industry 4.0 and IoT*, Brescia, 2018, pp. 269-273.

[7] T. Addabbo *et al.*, "A LoRa-based IoT Sensor Node for Waste Management Based on a Customized Ultrasonic Transceiver," *2019 IEEE Sensors Applications Symposium (SAS)*, Sophia Antipolis, France, 2019, pp. 1-6.
[8] A. Abrardo, A. Fort, E. Landi, M. Mugnaini, E. Panzardi and A. Pozzebon, "Black Powder Flow Monitoring in Pipelines by Means of Multi-Hop LoRa Networks," *2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0&IoT),* Naples, Italy, 2019, pp. 312-316.
[9] E. L. d. Medeiros, C. A. d. S. Filho, F. B. S. d. Carvalho, R. M. S. Cruz and C. d. S. Moreira, "Data Acquisition System Development for a Hydraulic Plant using Hybrid Communication Network based on LoRa," *2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Auckland, New Zealand, 2019, pp. 1-6.
[10] L. Lei, Z. H. Sheng and L. Xuan, "Development of low power consumption manhole cover monitoring device using LoRa," *2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC),* Auckland, New Zealand, 2019, pp. 1-6.
[11] L. Lombardo, L. Iannucci, M. Parvis, S. Corbellini and S. Grassini, "A Wearable System for Noise Assessment in Workplaces," *2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC),* Auckland, New Zealand, 2019, pp. 1-6.

LoRa is being used and evaluated in mobility conditions too, as presented in [13].

[13] S. Spinsante, A. Poli, S. Pirani and L. Gioacchini, "LoRa Evaluation in Mobility Conditions for a Connected Smart Shoe Measuring Physical Activity," *2019 IEEE International Symposium on Measurements & Networking (M&N),* Catania, Italy, 2019, pp. 1-5.

(This is the only self-citation present in this work).

- In Section 3. Experimental results, a new Table, which is now Table 1, has been added, that was not present in the conference paper, together with the following lines:

Table 1 reports the average RSSI values measured in each one of the 37 real positions selected within the campus, together with their corresponding variance.

- In Subsection 3.1, the following new paragraphs have been added, together with the new Figure 5:

Data about the number of packets lost during transmissions was collected too, by setting the number of transmitted packets at each measurement position, and then checking the number of packets received at the backend server, through the GW. In fact, each LoRa packet carries several data fields; among them, the Frame Counter field allows to associate a counter to each packet, which is incremented sequentially by the transmitter [4]. Once the transmission from a specific measurement site was finished, the sequence of received packets at the server was checked, to obtain the number of lost packets. Figure 5 shows the resulting percent packet loss at each measurement direction: direction no. 1 is the south-west one with respect to the GW in Figure 2, whereas direction no. 8 is the north-west one in the same Figure, identified in a clockwise fashion. As shown in the graph, on average the percent number of lost packets is under a 7% threshold, except for direction no. 6, along which the highest percent packet loss was measured, around 12%. Because measurements in the 37 different positions were carried out in a randomized fashion, during a single week, we assume that the highest loss value along direction no. 6 is motivated by the propagation environment, and not by occasional or sporadic conditions.

- A new Subsection 3.2 has been added, entitled "Comparison of path loss models to field measurements", together with new paragraphs and Figures 6 and 7:

Before implementing a modified version of the LoRaSim tool to improve the network planning performance, the results of RSSI field measurements were processed in order to check which theoretical model, among those presented in Section 2.1, can be considered more reliable in describing the LoRa signal propagation behaviour.

To this aim, the average RSSI values at each position, reported in Table 1, were considered, in relation to the corresponding distance d between the measurement position and the GW, assuming a fixed LoRa node height of 1 m. Two different polynomials were used to interpolate the available values, a 3rd degree polynomial and a 6th degree one, described by the following equations:

$$RSSI_3(d) = -5.49 \cdot 10^{-63} d^3 + 2.94 \cdot 10^{-32} d^2 - 0.50d + -70.75 \text{ [dBm]}, \quad (10)$$

and

$$RSSI_6(d) = 3.69 \cdot 10^{-12} d^6 + 5.99 \cdot 10^{-11} d^5 - 1.38 \cdot 10^{-6} d^4 + 5.13 \cdot 10^{-4} d^3 - 7.32 \cdot 10^{-2} d^2 + 4.25d - 171 \text{ [dBm]}. \quad (11)$$

Both the models are shown in Figure 6 together with the measured average RSSI values. Equation (10) is able to correctly describe 14.6% of the measured data, whereas the 6th degree model given by Equation (11) is able to correctly describe 23% of the measured data. Following the generation of the interpolation models based on the measured RSSI values, they

were compared to the theoretical models previously introduced, as shown in Figure 7.

As visible in Figure 7, in general the Log-Distance model over estimates the path loss, providing the lowest estimated RSSI values with respect to the measured ones. The 6th order polynomial model is not applicable for distances shorter than 35 m, whereas the 3rd degree polynomial model seems to better represent the measured RSSI trend. Both the 3GPP path loss models provide acceptable results, featuring a limited under estimation of the RSSI. Finally, all the Okumura-Hata models overestimate the RSSI, with an average excess of 60 dB with respect to the measured values.

Based on the experimental RSSI measurements carried out, the 3GPP path loss models (urban and suburban), provide the best approximation to predict the propagation behaviour of the LoRa signals within the campus. In any case, for the sake of completeness, all the theoretical models are implemented within the LoRaSim tool and used to predict the performance of the network.

- In Subsection 3.3 the following new lines have been added:

When, during a LoRa transmission, a signal arrives at the receiver while the previous packet has not been processed yet, the receiver is not able to decode one or both of them. Denoting this overlap between packets x and y as O(x,y), the condition according to which the LoRaSim tool decides about a successful packet decoding may be expressed as: $C = O(x,y) \wedge C_{freq} \wedge C_{sf} \wedge C_{pwr} \wedge C_{time}$, where the different symbols represent an overlap (leading to a collision) in frequency, spreading factor, power and timing, respectively. The use of the AND logic operators implies that a packet is suppressed at the receiver (i.e. lost) if and only if all the overlapping conditions occur. Each overlap is represented by an independent random variable, so, according to the central limit theorem, their sum tends toward a normal distribution.

- A total of 22 References are present in the full paper.

Please do not hesitate to contact the corresponding author, Susanna Spinsante, should any other action be requested about this submission.

Best Regards,

Susanna Spinsante