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# LocURa4IoT - A testbed dedicated to accurate localisation of wireless nodes in the IoT

Adrien van den Bossche, Réjane Dalcé, Thierry Val

**Abstract**—LocURa4IoT (Localisation and UWB-Based Ranging testbed for the Internet of Things) is a testbed dedicated to the evaluation of ranging and synchronisation protocols in wireless networks. The platform is also equipped to support the study of indoor localisation using the Time of Flight of radio signals to evaluate the distance between nodes. Although initially designed around the Ultra-Wide Band (UWB) technology, LocURa4IoT now embarks Bluetooth Low Energy (BLE) and LoRa transceivers which are co-located with the UWB nodes. This opens the way to the study of network approaches taking advantage of heterogeneous physical layers. This paper describes the architecture of the LocURa4IoT testbed and introduces 2 datasets collected on the platform: one is centered on the UWB physical layer and the other exploits the embedded BLE transceiver. Key results regarding the ranging error and the impact of walls are highlighted.

**Index Terms**—Bluetooth Low Energy, Localization, Ranging, Testbed, Ultra-Wide Band



## I. INTRODUCTION

THE process of protocol engineering has recently undergone significant development within the scientific community. While a few years ago, the common tools offered to engineers and researchers wishing to evaluate and validate their new protocols were mainly formal methods and network simulators, it is now more and more common to use testbeds. At the same time, new research areas have emerged, such as indoor localization of connected objects, taking advantage of distance measurements by radio time-of-flight for optimal performance. This article introduces LocURa4IoT, a testbed dedicated to the localization of connected objects using Ultra-Wide Band (UWB) transmissions. After a presentation of the objectives and the existing platforms, LocURa4IoT will be detailed, from both the hardware and software points of view. A public and free to use dataset will also be presented.

## II. OBJECTIVES

Testbeds are quickly becoming a preferred means for the evaluation of the many proposals in the field of Wireless Sensor Networks (WSNs) and the Device Layer (DL) of the Internet of Things (IoT). Some testbeds, like FIT IoT-LAB [1], give access to a large population of nodes on which

to run experiments, through a web interface which manages multi-user access and resource reservation. Other initiatives place the user at the heart of the implementation of his own testbed: in the case of WiSH-WaIT [2], a set of software tools are offered to build a testbed based on RaspberryPi. Other platforms are deployed outside as the first step towards a smartcity type solution: this is the case of CityLab [3] which deploys boxes on the facades and roofs of the city of Antwerp in Belgium. Table III gives a brief overview of existing testbeds which are linked to research facilities.

Although the existing testbeds allow the study of various facets of networking problems, they are not suitable when it comes to precise indoor localization. As a matter of fact, the technologies deployed (WiFi [4], LoRa [1] [7] [9], Bluetooth [8], IEEE 802.15.4/ZigBee [12] [13] etc.) do not support fine-grained distance estimation in indoor environments. Some testbeds offer communications via Software Defined Radios (SDR) [8] [9]: although these devices support a variety of physical layers via software libraries, the large bandwidth required by Ultra-Wide Band signals is still a challenge for them. In addition, other testbeds dedicated to computer networks, such as [11], have an entirely different focus and are thus not suitable.

The LocURa4IoT testbed has been designed and deployed to meet the demand for an evaluation platform for distance estimation (ranging) protocols between UWB nodes as well as communication paradigms using this physical layer. The ranging function is specified in the IEEE-802.15.4 standard and is found in Real Time Location Systems (RTLs) solutions offered by UWB component manufacturers like Qorvo. This function is now being integrated into next-generation smartphones. UWB nodes must have 64GHz timers in order to

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TABLE I: Comparison of various testbeds

Testbed (size)	Technologies	Strengths	Weaknesses
W-ilab.t [4] +200 nodes	Wi-Fi, Bluetooth, ZigBee, USRP	+GUI + Accessible via EmuLab	-Reservation contention
TutorNet [5] 104 nodes	802.15.4		- Website not maintained
MoteLab [6] 190 nodes	IEEE 802.15.4	+ GUI + Database	- No web-based access - Website not maintained
LoRa FABIAN [7] size unavailable	LoRa 868MHz (PHY), 802.15.4 (MAC)	+Git +Internet integration	-Information availability
NITOS [8] +100 nodes	802.15.4/ZigBee, Wi-Fi, Bluetooth, LTE, SDR, SDN; envt. sensors, GPS (bike network)	+ Diverse testbed + Accessible via OneLab	- Reservation contention
FIT IoT-LAB [1] 2728 nodes	802.15.4, Bluetooth Low Energy, LoRa, sub-GHz (868MHz et 433MHz); envt. sensors, accelerometres	+ Large and diverse testbed	- requires lab authorization for students
Orbit [9] [10] 400 nodes	Wi-Fi, Bluetooth Low Energy, 802.15.4/ZigBee, SDR, SDN, LTE, WiMAX	+ Ergonomic GUI	- Reservation contention
PlanetLAB [11] +1000 nodes	Linux VM	+ Linux-compliant + Accessible via OneLab	- US version no longer maintained
Twist [12] 90 nodes	Wi-Fi, 802.15.4/ZigBee, Bluetooth	+ Diverse testbed	-Complex subscription process
Wisebed [13] +500 nodes	802.15.4 2.4GHz, 868 MHz; Wi-Fi, Ethernet; envt. sensors	+Multiple locations +Mobility (Roomba..)	-Website accessibility

accurately timestamp transmission and reception of frames. Several protocols can be used, such as the well-known TWR (Two-Way Ranging) [14] involving two nodes, a TWR client node and a TWR server node, exchanging 3 messages.

Ever since its launch in 2016, LocURa4IoT has been successfully used in the evaluation of several *ranging* and fine-grained synchronization protocols such as [15].

In the next chapter, we will present the architecture and the special features of the testbed.

### III. LOCURA4IOT

Like most testbeds, LocURa4IoT can be broken down into three layers: the *nodes* and *controllers* layers, which constitute the first two material layers of the testbed; and *data and algorithms* layer, which allows the processing of data during or after the experiment.

- The *nodes* layer is a wireless sensor network (WSN) used for experiments. Each node is equipped with several wireless interfaces (UWB, BLE, LoRa), making it possible to address the localization problem via the most popular technologies in the IoT.
- The *controllers* layer includes the equipment used to configure, activate/deactivate and interact with the WSN nodes. The data collected from the nodes is presented live via an MQTT broker.
- The *data and algorithms* layer is dedicated to the processing and exploitation of data. This is made up of agents who, via the MQTT bus, directly exploit the data coming from the nodes and generate intermediate or final data.

A central server is responsible for running experiments on the testbed. Those experiments are described through Python scripts.

#### A. Wireless nodes layer

All nodes of the LocURa4IoT testbed are based on a DecaWave DWM1001-DEV board. This hardware centers on a

Nordic nRF52832 microcontroller (ARM Cortex-M4) which is used to pilot a BLE transceiver, an IEEE 802.15.4 compatible UWB transceiver and an accelerometer. A LoRa / LoRaWAN HopeRF RFM95 transceiver and I2C sensors, among which an atmospheric pressure sensor, are also added. The node may use a variety of wireless technologies to address the problem of location determination via different physical layers and compare the performance of one technology to the other. Finally, a GNSS receiver (D-GPS) completes the set: this provides an additional source of location information as well as a reference synchronization via the 1-PPS signal. This synchronization, of the order of a microsecond, can be used as a reference for MAC protocols. This granularity is not suitable for indoor distance measurements using radio time of flight.

The firmware executed by the nodes is not constrained by a particular OS; the user can implement a basic C/C++ code in a bare-metal approach, or deploy a system or a richer protocol stack via an embedded OS like FreeRTOS or Apache MyNewt, which are the two systems that have been tested so far.

To date, the testbed comprises 64 nodes spread over 3 sites. On all sites, node deployments have been conducted using laser rangefinders. Regular verification indicate a precision under 2 cm for the fixed positions. Therefore, the real position of each node, fixed or mobile, can be used in the results to calculate a ranging / localization error. In view of the layout of the walls on the different sites, some radio links are NLOS (Non Line-of-Sight).

The sites (figures 1, 2 and 3) are as follows :

- Site 1: this sites consist in 50 nodes deployed in the offices, open space and meeting rooms of the laboratory, over a 300 square meter area and on one level. The walls are either terracotta bricks or drywall. Most nodes are deployed on a horizontal plane 2.65m above the ground and positioned using a PVC or aluminum structure. Some are placed very close to the ground, at an antenna height of 3cm. Two rails with respective lengths 7m and

2m make it possible to move two mobile nodes: the linear position (millimeter precision), the speed and the acceleration of the mobiles can be controlled from the experimental scenarios. When the researcher is on site, he benefits from several devices for viewing the results in real time (video projector and virtual reality headset). This first site has very good radio repeatability properties, especially at night when all doors are shut and no human movement is present. Figure 1 illustrates the main room (North room) of this deployment.

- Site 2: this deployment consists in 10 nodes deployed in the furnished apartment of the *Maison Intelligente de Blagnac*, over a 70 square meter area and on one level. In this environment, the nodes are arranged in a variety of ways, generally near furniture or appliances (oven, coffee maker, television, etc.); this proximity allows the association of any node with a *Semantic Description of the Position* (DSP). The DSP opens up new ways to express position which do not solely rely on traditional *n*-lateration. This site is dedicated to the study of usages and facilitates studies involving end-users and collaborations with research teams and manufacturers outside the networking community.
- Site 3: the third site consists in 4 nodes deployed in a 20 m<sup>2</sup> anechoic chamber in the laboratory premises. The nodes are mounted on a PVC structure with an inter-node distance that depends on the experiment. The chamber isolates the experiment from signals generated by devices that are outside and also keeps the signal coming from the nodes in the room from radiating outside.

Site P3 can be used for initial evaluation of a protocol in an isolated environment. The implementation is then tested on P1 with a larger number of nodes in a more challenging environment. In some cases, the solution can also be evaluated through its usage: this is done on P2 and involves human-machine interactions.



Fig. 1: Testbed site P1

## B. Controllers layer

As is usually the case with testbeds, the experiments are managed by a central server which allows programming of remote nodes and log centralization. The nodes are managed by around forty controllers based on Raspberry-Pi boards connected to a wired network. The controllers are in charge of

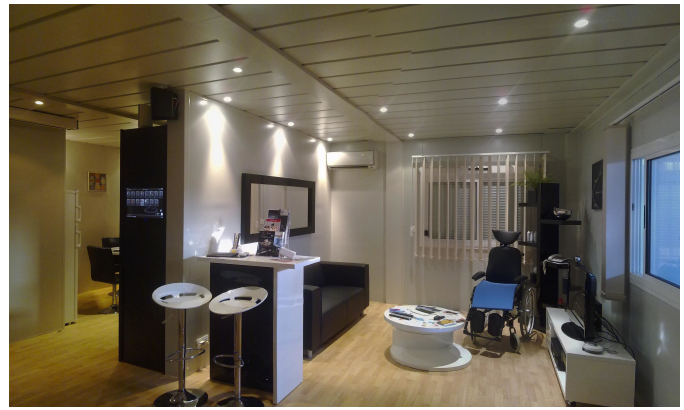


Fig. 2: Testbed site P2

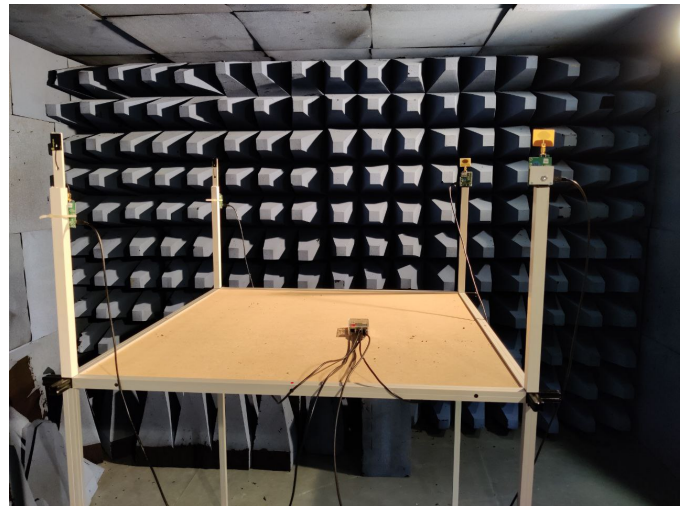


Fig. 3: Testbed site P3

reprogramming the devices as well as capturing the serial console output. They also offer a command sending service to the serial console of the attached wireless device. The controllers are synchronised via PTP / IEEE1588 protocol over Ethernet. The timestamps that are added to the console messages during the capture process can be used to properly merge the logs. These logs are then collected through an MQTT bus, with a *topic* organization facilitating data exploitation, both in live and offline mode. Examples of topics are given below:

- `testbed/node/173/in` : console input of node 173
- `testbed/node/156/out` : console output of node 156
- `rail/1/course/request` : set the node mounted on rail n°1 at a specific distance passed as an argument
- `rail/1/course/indication` : get the distance from the reference extremity of rail n°1 to the node mounted on said rail.

The experimental scenario (flashing, start-up and control of nodes, movements of mobiles via the rails, etc.) is described by a Python script, allowing a simple implementation of iterations.

### C. Data and algorithms layer

Another originality of the LocURa4IoT testbed relates to the use of data from nodes. The pub/sub approach in MQTT makes developing software agents that process the data live or interact with the nodes during the experiment easy. For example, knowing the position of each fixed node by installation and of each mobile via the instantaneous position of the rails, an agent constantly searches for *ranging* data on the console outputs to compute the instantaneous *ranging error*, a key performance parameter in this type of study. Once the agent detects that the payload is a ranging result, it updates it with the computation results and publishes the new payload on the MQTT *ranging/#* topic. This operation takes place regardless of the signal (UWB, BLE ...) or protocol (TWR, SDS-TWR ...) used to generate the ranging. Likewise, it is possible to implement *n*-lateration algorithms to calculate mobile positions on the fly according to known positions (anchor nodes) and rangings, or even agents allowing the representation of data on maps: the top of figure 4 shows the floor plan of site P1. The bottom part represents ranging errors measured between node pairs: the red segment corresponds to distance over estimations and the blue ones to underestimations.

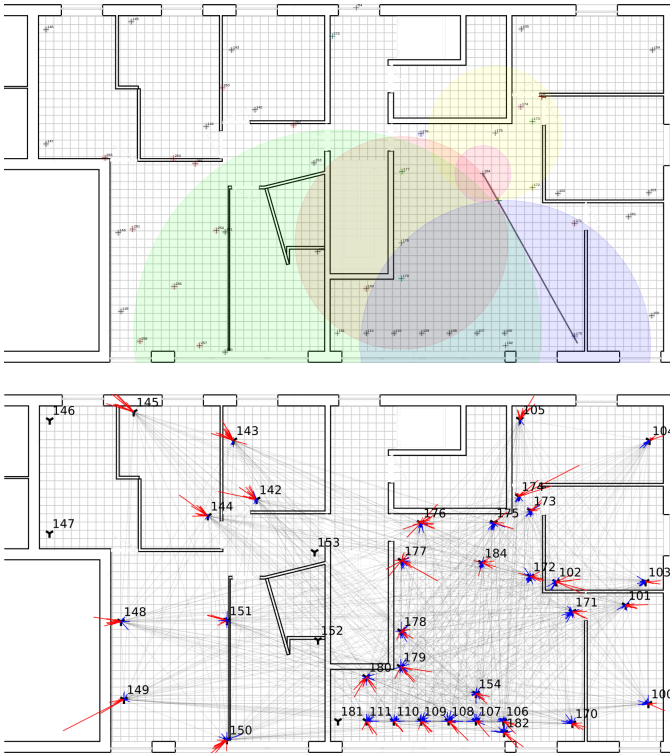


Fig. 4: Data visualization; top: ranging results between one mobile and five anchors as circles; bottom: positive (red) and negative (blue) ranging errors among 34 nodes

Finally, the ability to process the data via MQTT agents opens the door to collaborations with researchers from the Artificial Intelligence (AI) field. For instance, many studies have been conducted on obstacle detection using either channel models [16] or real-world datasets [17]. Being able to plug for instance a python agent to the broker will allow for continuous

learning on the deployment environment without requiring the AI specialist to master all the PHY, MAC and NWK aspects.

### D. Comparison to existing platforms

LocURa4IoT is currently taking its place in the existing testbed panorama. In terms of size, it is relatively small with less than a hundred nodes at the time. Still, the variety of environments makes up for the limited scale. In terms of technologies, although the initial focus was on indoor localisation using UWB, the platform also supports Bluetooth Low Energy and LoRa links. Instead of having hardwired sensors on every node, the approach chosen in LocURa4IoT consists in deploying custom sensor shields. The current set of sensors matches what is available on platforms such as FIT IoT-Lab [1] and NITOS [8] but they may be modified easily to suit specific experiments. LocURa4IoT's main weakness is linked to large-scale use of the platform. So far, only a few research teams in France have been to exploit it but public access is expected to be fully functional by the first quarter of 2022 thanks to a collaboration with FIT IoT-Lab. [1]

## IV. EXPERIMENTS AND RESULTS

In order to illustrate the capabilities of the testbed and before its upcoming opening for public use, two open datasets are made available to the scientific community [18] [19]. These datasets, under ODBL license, can be used freely by the reader. The following section introduces the scenario used to generate the datasets as well as a few results.

### A. Experimental scenario

The first step in experiment planning is to select the appropriate LocURa4IoT site as each one has its strong points. For this experiment, we used site P1 as it guarantees good radio repeatability properties at night and provides NLOS links. Unfortunately, site P2 does not guarantee radio repeatability as it is an experimentation site for various types of research, from telecommunications to human-machine interactions: the presence of humans during those experimentation is an interesting factor to take into account but it is out of the scope of the current study. In addition, objects in site P2 may be moved at anytime: this affects repeatability, especially for RSS-based ranging (BLE). Site P3, due to its radio insulation, would also be a good candidate but it does not allow NLOS links due to its structure.

The implementation scenario involves 12 nodes (11 anchors and 1 mobile) from site 1 (figure 5). The mobile on the rail goes from 0m to 7m at a speed of about 3.4mm/s. The experiment lasts 33 minutes and generates nearly 94969 BLE samples and 21214 UWB samples. For both technologies, the dataset only contains the results for successful rangings: messages were lost in both cases. Investigating the cause of these losses is out of the scope of the current study. Most of the links are in line of sight (LOS): when it comes to nodes 100 and 101, they are separated from the mobile by a drywall.

When collecting samples via UWB [18], the mobile executes the "3-message TWR" protocol (figure 6). It targets each

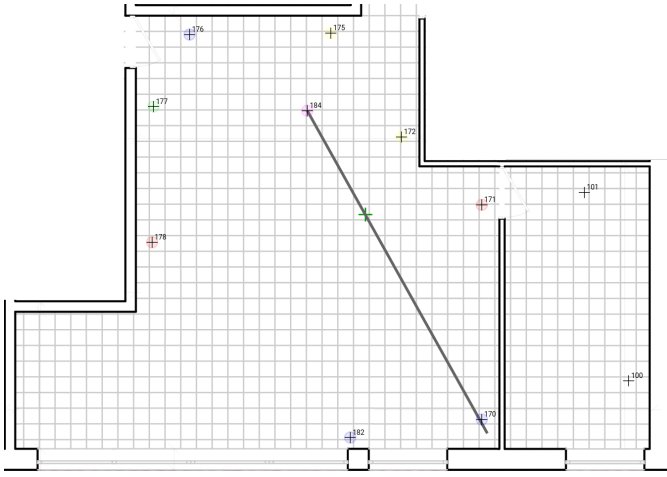


Fig. 5: Node placement in the room for this experiment

anchor in turn every 720ms. The first two messages create the timestamps that are used to estimate distance. The third message brings the timestamps collected by the anchor back to the mobile for computation. The network topology is a star, centered on the mobile. No rangings are done between the anchors. Since the rangings are initiated by the mobile and there is no other protocols running during the experiment, we suppose that there is no collision on the medium. No MAC mechanisms such as carrier sensing or retransmission are enabled; if a message is lost, the ranging fails and the next anchor is targeted. The physical layer is configured as follows: PHY UWB IEEE 802.15.4, channel 5 ( $f_c=6500\text{MHz}$ ,  $\text{BW}=499\text{MHz}$ ), preamble code 4,  $\text{PRF}=16\text{MHz}$ .

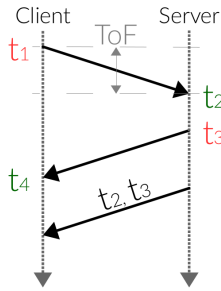


Fig. 6: 3M-TWR protocol sequence

In the BLE-RSSI approach [19], anchor nodes generate beacon messages every 200ms. Upon reception of a beacon, the mobile extracts the Received Signal Strength Indication (RSSI) and computes an equivalent distance. This transformation is done using a model derived from experiments conducted in the same environment. Another possible exploitation of RSSI measurements relies on the fingerprinting approach [20] and is outside the scope of this paper as we present a comparison of the ranging capability of both signals.

Figure 7 shows the original data used to develop our model. In order to counter the fluctuations of RSSI, we computed the mean of the RSSI value over a sliding window with a width of either 5, 20 or 100 samples. The raw RSSI values are also plotted in blue. The same structure can be found in the final dataset [19].

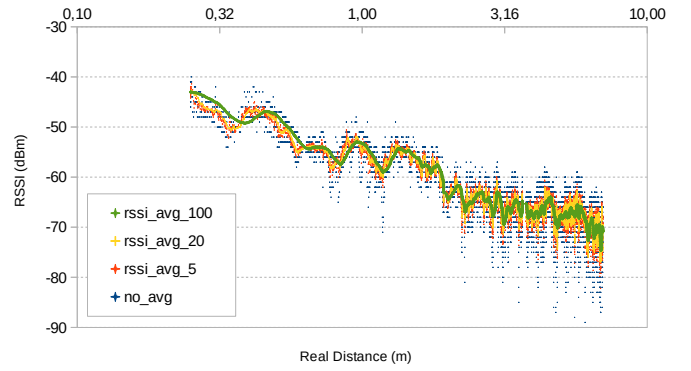


Fig. 7: RSSI vs real distance

TABLE II: Parameters of the log distance path loss model

Parameter	Value
$P_t$	0dBm
$G_t$	-7.5dB
$G_r$	-7.5dB

The green curve corresponds to a sliding window of 100 samples. Given the very low speed of the rail and the beacon period, the position of the mobile varies by 6cm over a 20s interval. The uncertainty introduced by the movement is therefore negligible. The exponential regression model obtained from the green curve is given in equation 1.

$$r = 0.001671 \times \exp(-0.1168 \times \text{RSSI}) \quad (1)$$

The model in equation 1 has been obtained using real data. In order to validate the results obtained, we compared it to the well-known Log Distance Path Loss Model (equation 2) [23] [24].

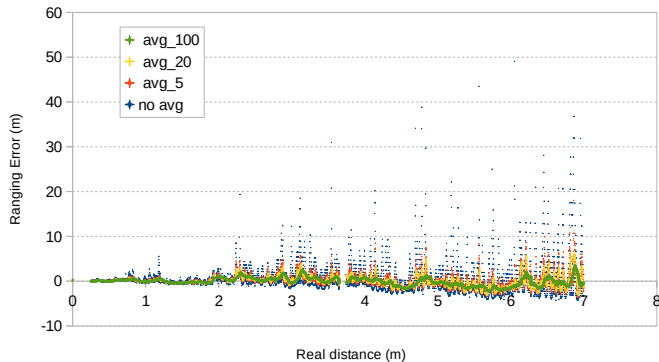
$$\log D = \frac{1}{10\eta} (P_t - P_r + G_t(\theta, \phi) + G_r(\theta, \phi) - X(\sigma) + 20 \log \frac{\lambda}{4\pi}) \quad (2)$$

The parameters used to configure the model are given in table II. The gain values were determined using the radiation pattern of the antenna [22] and the relative positions of the radio devices. The received power corresponds to the RSSI value which is expressed in dBm. Various values of  $\eta$  were tested and the best fit was obtained with  $\eta = 2$ , which corresponds to a Free Space/LOS environment. This is in line with the test conditions as no obstacles were present during data collection. Table III compares the results from both models. As they have similar performance, we will use the regression model in the remainder of the article.

Figure 8 and figure 9 show the ranging error observed after using the model on real RSSI data. As expected, the ranging error grows with the distance due to the path loss effect. On figure 9 gives a clear view on the error distribution for each distance class. It also shows the benefit from applying the moving average to the data, especially on the presence of outliers.

**TABLE III:** Comparison of ranging error (m) using the two models

	pathloss log distance model	our model
average	-0.278	-0.068
stdev	0.853	0.863

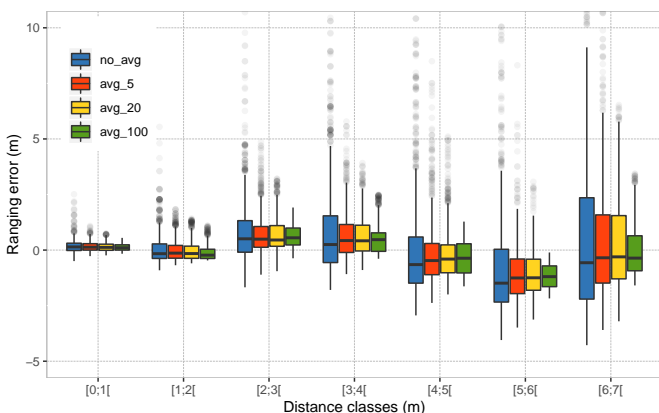


**Fig. 8:** BLE-RSSI: ranging error vs Real Distance

## B. Dataset presentation

The dataset is presented as a series of samples in JSON format. Each sample encapsulates a ranging result enriched by the agents of the testbed. A ranging may be generated either by UWB-TWR or by BLE-RSSI. A ranging result consists of:

- The addresses of the nodes involved and their 3D coordinates,
- In the case of UWB-TWR, the timestamps generated by TWR ( $t_1$ ,  $t_2$ ,  $t_3$  and  $t_4$ ), a sequence number, the measured clock skew, the NLOS indicator, the raw and the skew-aware distance estimates,
- In the case of BLE-RSSI, several RSSI values: raw (instantaneous) value, and 3 values from 3 moving averages (5, 20 and 100 values), and corresponding rangings,
- Environment information such as node temperature for both nodes. This data is systematically collected but has not been exploited so far,
- The true distance between the nodes and the ranging



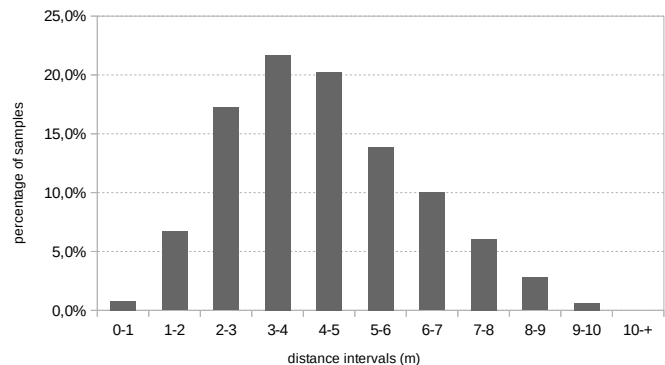
**Fig. 9:** BLE-RSSI: ranging error distribution per distance classes

error.

The UWB data show the impact of clock drift which is a main drawback of the TWR protocol. The skew is estimated by the transceiver for every incoming message and its value is stored in a register. Its effects can be countered with the method presented in [14]. In the dataset, we provide the raw distance estimate as well as an estimate where the impact of the clock difference has been mitigated using the method described in [21]. In addition, the dataset can also be exploited for the evaluation of localization algorithms based on  $n$ -lateration (with  $n \leq 11$ ): for instance, the precision can be studied based on the true values of the distances and positions as well as the estimated distances. The UWB data also includes an NLOS indicator. As defined by the chip manufacturer, it is computed as the ratio between the power of the first path and the total power detected. The closer the ratio is to one, the more the energy is concentrated on the first path. Although limited, this approach provides an initial estimate of the nature of the radio link. In depth study of NLOS detection using UWB signals is therefore an active research subject but is out of the scope of the current paper. The BLE-RSSI values can be used to feed both distance estimation models and fingerprinting methods, although in the latter case, the real positions of the mobile are constrained (limited to the line represented by the rail).

## C. Results and discussion

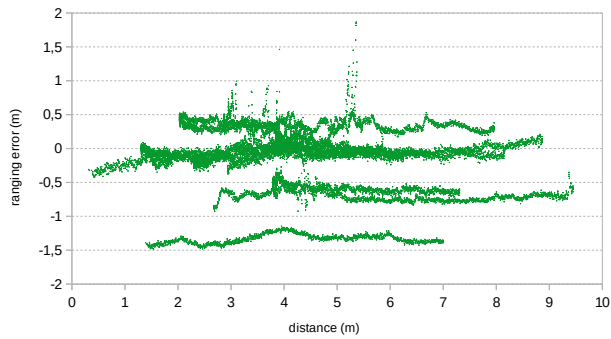
1) *Environment:* The current setup creates variety in inter-node distances. Figure 10 shows the distribution of the distances.



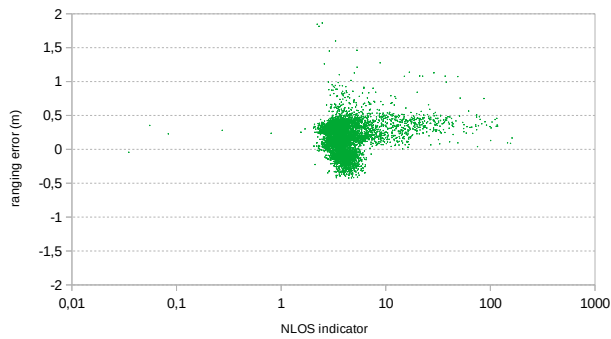
**Fig. 10:** Distance distribution in the experiment

2) *UWB-TWR ranging error analysis:* This section studies the ranging error resulting from UWB-TWR measurements and the impact of the clock differences between nodes (skew) on the estimated ToF.

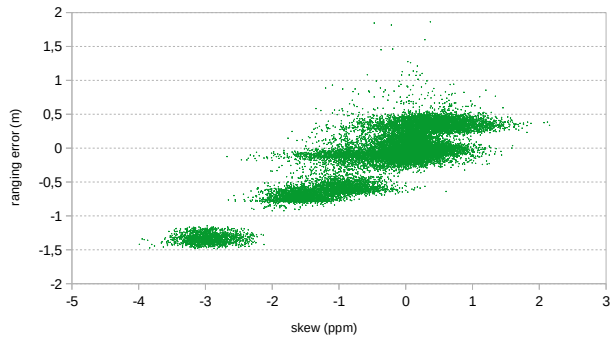
Figure 11a through 11d depict the raw situation: the skew is not taken into account. The ranging error is significant for ToF-based indoor ranging (figure 11a). The few samples of the NLOS Indicator over 10 do not justify this situation: most samples of the signal indicate a LOS situation (figure 11b). On the other hand, the ranging error seems to clearly be linked to the skew, with minimal absolute error coinciding with perfectly matched clocks (figure 11c). The interested reader



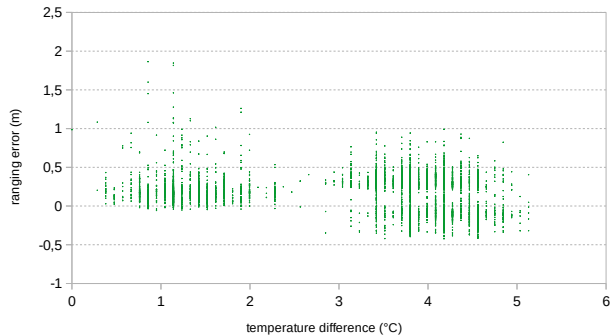
(a) Ranging error vs true distance



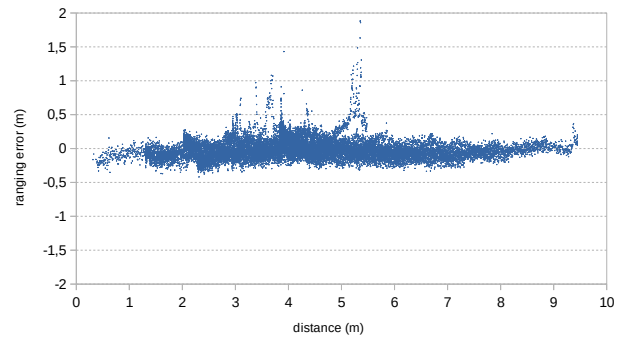
(b) Ranging error vs NLOS indicator



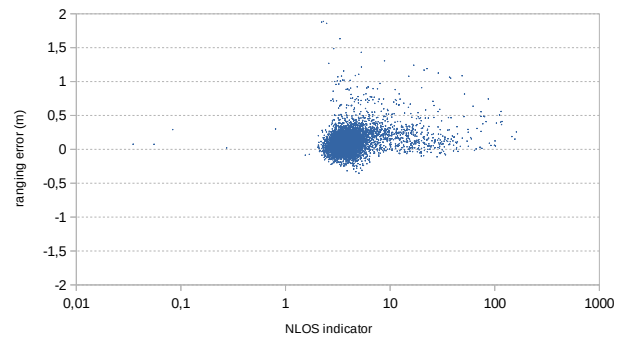
(c) Ranging error vs skew



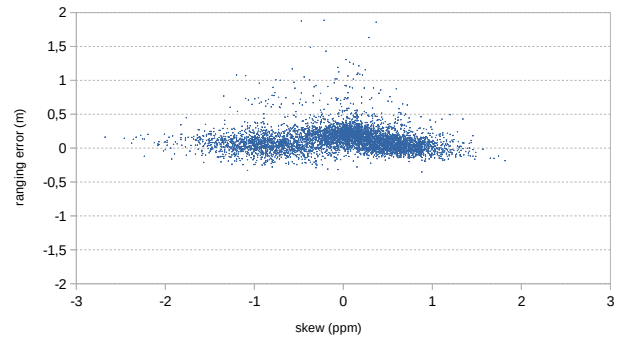
(d) Ranging error vs temperature difference



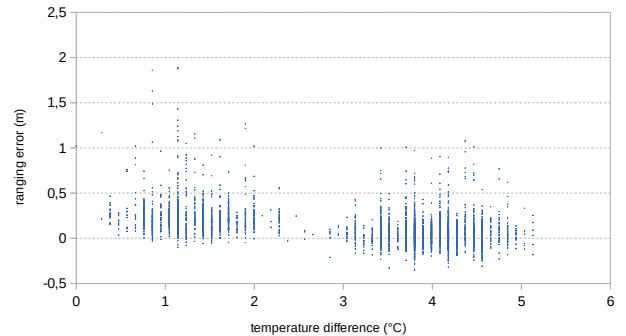
(a) Ranging error vs true distance



(b) Ranging error vs NLOS indicator



(c) Ranging error vs skew



(d) Ranging error vs temperature

**Fig. 11:** Representation of the raw ranging error using UWB-TWR

**Fig. 12:** Representation of the ranging error with 3messages based skew correction using UWB-TWR

may attempt to model the relationship between temperature, skew and ranging error (figure 11d).

Figure 12a through 12d illustrate the results with the skew taken into account, as recommended in [14]. In our case, the skew is computed as the average of the skew measured for all three messages of the protocol. The skew sample collected by the anchor is sent back to the mobile in the last message. This approach significantly improves ranging precision.

A key issue in the field of indoor localization is the detection of obstacles between an antenna pair. Figures 13a and 13b show the ranging error and NLOS indicator value for measurements involving node 184 which is at one end of the rail. The NLOS indicator value ( $\text{value} \leq 10$ ) indicates a LOS link. On the other hand, figures 13c and 13d correspond to an NLOS situation: the measurements involve node 101 which is most of the time behind a simple dry wall. At the furthest point, node 101 and the mobile are separated by a wall angle which is thicker than the drywall and causes a severe degradation of the ranging error. The same behavior can be observed on the NLOS indicator.

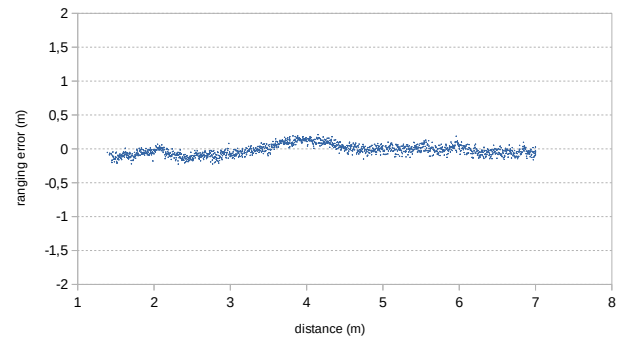
### 3) Comparison of BLE-RSSI and UWB-TWR performance:

In this section, we compare the ranging error obtained through both ranging methods over a distance class. In the case of BLE, we represent the results with a moving average over a 20-sample window. We have chosen to focus on the samples pertaining to classes 3-4m and 4-5m as they are the most prevalent in our dataset, according to figure 10. For both BLE (figures 14a through 14c) and UWB (figures 15a through 15c), we present the ranging error for 3 node groups: the first group contains only node 184: this anchor is positioned at one end of the rail and is therefore always in the same relative orientation. The second group contains all other LOS nodes and the third group contains nodes 100 and 101 which are in another room. In all situations, the impact of the drywall can be seen when comparing figure 14b to 14c, and figure 15b to 15c: the mean ranging error shifts to 4.25m for BLE and to 0.154m for UWB. This confirms the superiority of the UWB-TWR approach in indoor environments where obstacles will attenuate the power of the radio signal. Although this difference in performance is to be expected, the dataset is highly valuable as the real world data can be used as an input to algorithms combining both sources of ranging information for localization, obstacle detection, error mitigation and so on.

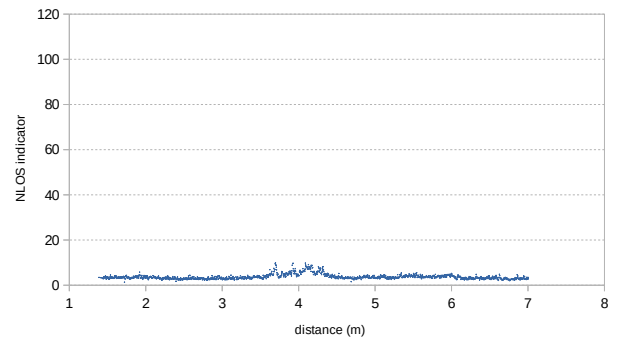
## V. CONCLUSION AND PERSPECTIVES

This article introduced LocURa4IoT, a testbed originally dedicated to studying the performance of ranging protocols and the precise location of IoT nodes. An open dataset, along with a description notice, accompanies this article. The dataset contains the ranging results for BLE-RSSI and UWB-ToF. As expected, ToF-based ranging outperforms RSSI-based distance estimation. In NLOS situations, the performance in terms of ranging error is of 15cm for UWB and 4.25m for BLE. The dataset allows the reader to appreciate the capabilities of the testbed while giving the opportunity to exploit real ranging data.

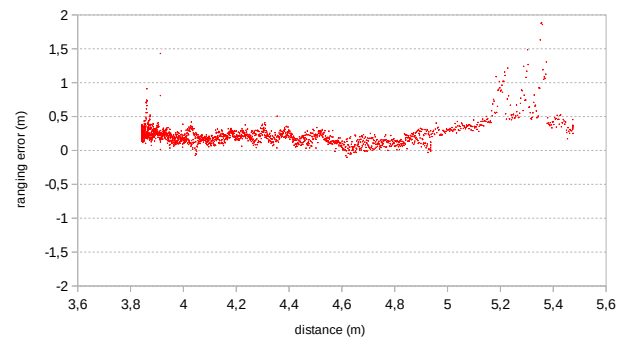
In addition to providing access to the research community, the next steps concern the study of the scalability of ranging



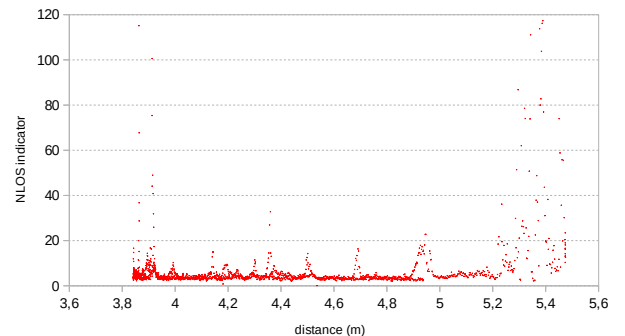
(a) Ranging error vs true distance for 184 (LOS)



(b) NLOS indicator vs true distance for 184 (LOS)

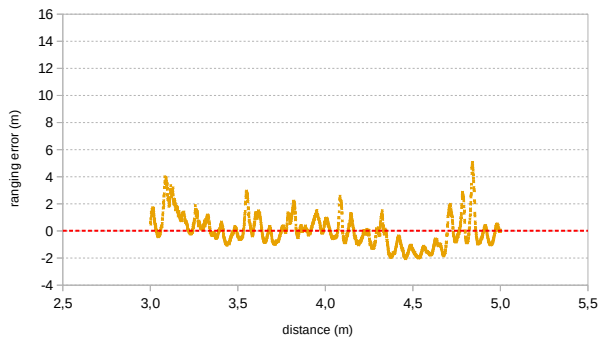


(c) Ranging error vs true distance for 101 (NLOS)

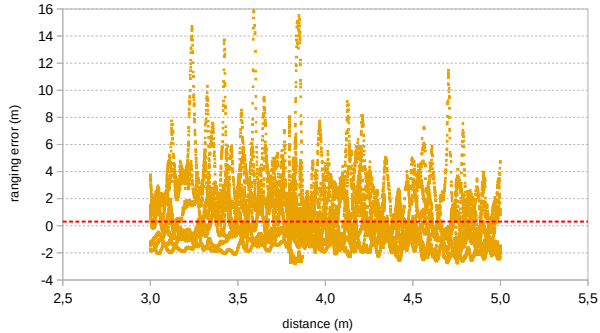


(d) NLOS indicator vs true distance for 101 (NLOS)

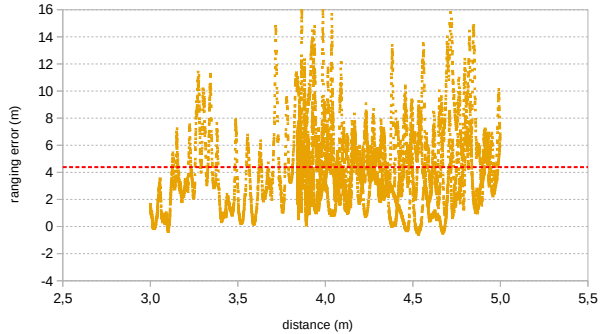
Fig. 13: Representation of the NLOS indicator using UWB-TWR



(a) Reference node (184)

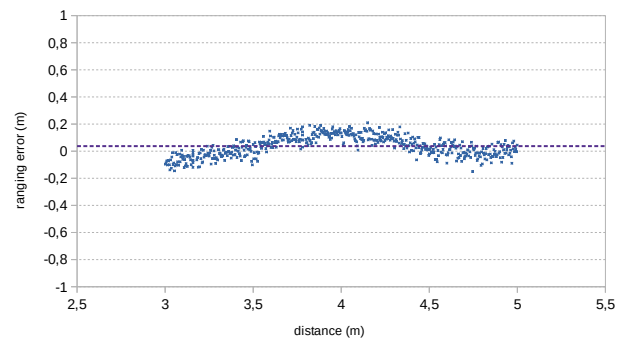


(b) LOS nodes (170, 171, 172, 175, 176, 177, 178, 182)

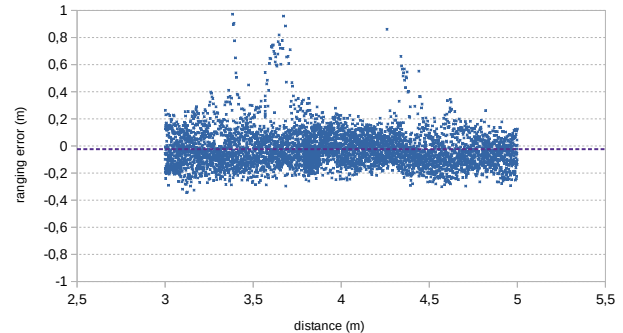


(c) NLOS nodes (100, 101)

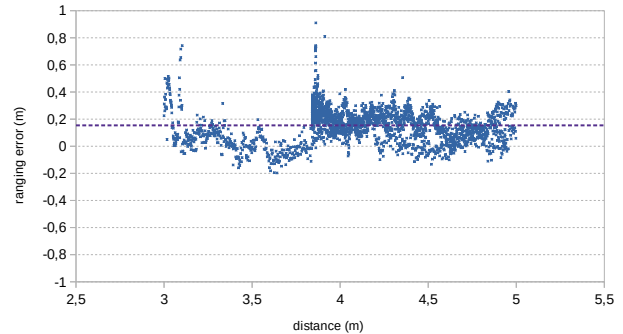
Fig. 14: Ranging error vs true distance using BLE-RSSI



(a) Reference node (184)



(b) LOS nodes (170, 171, 172, 175, 176, 177, 178, 182)



(c) NLOS nodes (100, 101)

Fig. 15: Ranging error vs true distance using UWB-TWR

and node location protocols, the mitigation of the impact of non-line of sight on ranging results, as well as the performance comparison of UWB with other popular radio technologies from the IoT ecosystem. Aside from localization related experiments, the testbed may also be used to study MAC-level and Network-level protocols over UWB. In this case, a richer dataset containing relevant timing and packet loss information could be generated. Thanks to the various sites of the testbed, it is also possible to finely evaluate proposed protocols and algorithms in the real world. In particular, running tests at different times of the day on sites 1 and 3 (open space and anechoic chamber) will allow the researcher to quantify the impact of both the environment and the implementation on the performance.

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