On the RSSI-Based Indoor Localization Employing LoRa in the 2.4 GHz ISM Band

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Abstract. *Demand for systems and technologies ensuring indoor localization or tracking of an object with high and stable accuracy is continuously increasing. There are several wireless technologies, for instance Bluetooth or Wi-Fi, which can be employed for indoor positioning. In the future, Long Range (LoRa), originally developed for long range communication with high link budget, can extend the family of these technologies. This paper focuses on the LoRa technology and its employing for Received Signal Strength Indicator (RSSI) based indoor localization in the licence free 2.4 GHz band. To measure and collect the values of RSSI, a simple measurement setup is proposed. The RSSI values are used to calculate the position of an object according to the principle of trilateration. Measurements are conducted in three different indoor environments for different signal configurations of LoRa. The recorded dataset is available online for future research purposes. The results show average localization error below 2.2 m. However, the performance of LoRa in terms of localization accuracy is highly depending on the signal configuration of LoRa, on the position of nodes and on the nature of indoor environment.*

Keywords

LoRa, 2.4 GHz ISM band, RSSI, indoor localization

1. Introduction

In the last decade, demand for systems to provide indoor localization or tracking of a device or subject with high and stable accuracy has been rapidly increasing. Thanks to advances in electronic devices and localization technologies, especially indoor ones, the number of fields and related use cases, in which indoor localization or tracking of an object is very important (e.g. healthcare, industry), has been continuously growing. Nowadays, among others, Bluetooth Low Energy (BLE), Local Area Networks (LAN, also called as Wi-Fi) and Radio Frequency Identification (RFID) are the most employed wireless technologies for such purposes [1–3]. In the future, the list of these technologies can be extended by Long Range (LoRa) [4], nevertheless it was not primarily developed for the field of localization.

LoRa belongs to the family of Low Power Wide Area Network (LPWAN) technologies [5]. It was developed to create a low data rate wireless communication link with high link budget in the license free sub-1 GHz bands. Its physical (PHY) layer is based on the chirp spread spectrum (CSS) modulation, but it also offers a special configuration enabling to use GFSK modulation. Support of different narrow bandwidths (dominantly 125, 250 and 500 kHz) and spreading factor (SF) values (from 6 to 12) makes LoRa a flexible system for the fields related to LPWAN [4].

Since 2017, a LoRa-based wireless link can be also created in the 2.4 GHz Industrial, Scientific and Medical (ISM) band. For this band, the PHY layer of LoRa supports new bandwidth (BW) values $\{200, 400, 800, 1600\}$ kHz and SF can also have a value of 5. Higher values of bandwidth are associated with higher data rates. Compared to sub-1 GHz bands, requirements on the duty cycle [4] are less strict at 2.4 GHz. Thanks to this and more flexible signal configuration, LoRa-based protocols can be employed in more application fields (e.g. industry machines) [6].

LoRa primarily targets on the field of Internet-of-Things (IoT) [5], [6]. However, in the future, the LoRa technology, thanks to its features, can be also used for localization or tracking of an object in different indoor or outdoor environments. Among others, this work focuses on the performance study of LoRa-based indoor localization at 2.4 GHz.

1.1 Related Work

Recently, attention of researchers focuses on the performance study of LoRa-based communication links in the 2.4 GHz band [7–9]. On the other hand, the number of works targeting on the LoRa-based localization is gradually increasing. In this work, studies focusing on the Received Signal Strength Indicator (RSSI) based indoor localization are in the spotlight [10–15]. In the following paragraphs, we briefly elaborate the outputs of these research and application-based studies.

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Comparison-based performance study of BLE, Wi-Fi and LoRa technologies for indoor localization was presented in [10]. The measurements were conducted in a long corridor (23 m) and large open room (25 m × 23 m) having both line and non-line-of-sight (LOS and NLOS) conditions. The localization accuracy for all technologies were evaluated in terms of packet drop and RSSI. In this study, LoRa achieved the best results. However, in contrast to BLE and Wi-Fi, it utilized the sub-1 GHz band. Probably, it is one of the main reasons of such an excellent performance. Unfortunately, details about the used system and signal configurations are not presented.

Sadowski and et al. [11] provided a set of RSSI-based measurements to explore and compare the features of BLE, Wi-Fi, ZigBee and LoRa wireless technologies for indoor localization. In the case of LoRa, once again, the sub-1 GHz band (915 MHz) was utilized. The measurements were performed in two indoor offices, located on a university campus, having different natures: research lab (contains several computers and wireless devices) with dimensions of 10.8 m × 7.3 m and meeting room (contains some tables and chairs) with an area of 33 m^2. The location estimation results (provided for distance up to 5 m) were obtained by the using of trilateration technique. It was shown that LoRa has high transmission range and very low power consumption. However, compared to other wireless technologies, LoRa achieved slightly lower localization accuracy (estimation error was $\approx$ 1.19 m), especially in an environment rich on the reflections. Information about the used signal configurations is not presented, on the other hand, the dataset obtained from the measurements is publicly available.

Similar study, as in the case of [11], was introduced in [12]. However, only one hardware equipment, namely Pycom's Lopy v1.0, containing Wi-Fi, BLE and LoRa communication modes was used. The measurements were realized in three different indoor environments (graduate lab, class room and corridor) located at a university in a time, when only a few students were available in these environments. Results revealed good performances of a LoRa (the second best in the measurements) utilizing the sub-1 GHz band. However, only one signal configuration of LoRa was considered in the measurements (signal level of 14 dBm and $SF = 7$).

RSSI-based localization with LoRa for indoor and outdoor environments were explored in [13]. To suppress the influence of noise caused by obstacles and multipath fading, six different RSSI-based localization algorithms were created. Indoor localization measurements were conducted in one large room. This work was mainly focused on the evaluation of the accuracy of the proposed algorithms while the LoRa-based indoor localization, utilizing RF band 433 MHz, has received lower attention.

In [14], simulation and measurement-based comparison of different RSS algorithms for BLE (2.4 GHz) and LoRa (868 MHz) indoor localization is presented. The measurements were conducted only in one large open hall, rich on LOS conditions, with sizes of 69 m × 69 m. A LoRa signal with high data rate and with a power of 18 dBm was employed. Both BLE and LoRa anchors were located at a height of 2 m. The outputs of simulations showed better performance for LoRa than for the BLE-based localization system. However, measurements showed minimal difference between the localization accuracy of both systems.

Feasibility of LoRa for smart home indoor localization at 915 MHz was investigated in [15]. The values of RSSI were obtained by using of the Adafruit Feather 32u4 RFM95 LoRa module. In the measurements, conducted in a furnished two-bedroom apartment with an area of 114.4 m^2, LoRa with signal bandwidth of 125 kHz, $SF = 8$ and coding rate of 4/5 was used. The transmit power was varied between 5 and 23 dB. There were used five tags and three anchors. Altogether, 2000 RSSI values at each five tags from each three anchors were collected. The offline processing of RSSI data showed localization accuracy around 1.6 m and 3.1 m for LOS and NLOS conditions, respectively.

From the above briefly elaborated state-of-the-art we can conclude the following:

1. Extensive performance study of an RSSI-based indoor localization with LoRa at 2.4 GHz has not been provided so far. Only authors of the report [16] have partly focused on LoRa and its ranging capabilities (to measure a distance between two points) at 2.4 GHz.

2. Dominantly, only one system or signal configuration of LoRa is considered. In numerous cases, the system parameters of LoRa are not presented in detail.

3. Except of [11], dataset from measurements is not available to support reproducibility of the research.

1.2 Contribution

The main contributions of this paper are the follows:

1. We introduce a simple RSSI-based measurement setup to provide repeatable performance studies of LoRa at 2.4 GHz in terms of localization accuracy. LoRa starter kit SK-iM282A (with radio module iM282A-L[1]) is employed to create a LoRa-based wireless link at 2.4 GHz.

2. We provide an extensive performance study of RSSI-based indoor localization with LoRa at 2.4 GHz. To create a comprehensive view of the performance of LoRa, we provide extensive indoor measurements for different LoRa system configurations including options of Fast Long Range Communication (FLRC) and GFSK modulations. Measurement campaigns, described in detail, are conducted in three indoor environments having different conditions for transmission.

[1] https://wireless-solutions.de/products/lora-solutions-by-imst/radio-modules/im282a-l/

3. For future research purposes, we provide a re-usable RSSI dataset obtained from the measurement campaigns. For instance, such a dataset can be utilized in the training process of different machine learning models. These can be used to improve the accuracy of indoor location estimation [17]. The dataset is available for download for other research purposes from: https://github.com/xsimka/LoRa-Localization.git.

1.3 Organization

The rest of this paper is organized as follows. The measurement campaigns and the experimental setup for LoRa-based indoor localization are described in Sec. 2. Evaluation of the obtained results are presented in Sec. 3. Conclusion remarks and outline of future research directions conclude this paper in Sec. 4.

2. Measurement Campaigns

To provide a comprehensive performance study of RSSI-based indoor localization for LoRa at 2.4 GHz, extensive measurements in different indoor environments must be performed. In this section, the measurement setup, used for this purpose, and the conducted measurement campaigns are presented in detail.

2.1 Experimental Setup

To collect RSSI-based values in indoor environments with different features, a measurement system with high reliability and simple setup is required. In this work, the WiMOD iM282A starter kit is used to create a LoRa-based wireless communication link at 2.4 GHz. It consists from two separated modules serving as transmitter (TX) and receiver (RX). Both of them are established with iM828A radio module. The iM828A is a bidirectional radio module, containing SX1280 RF module, to realize a LoRa-based wireless link in the 2.4 GHz band. Among others, it supports three different modulation options, namely: LoRa (main), FLRC and GFSK. The installed experimental setup in an indoor environment is captured in Fig. 1.

To configure the iM828A radio module, the WiMOD LR Studio[2] program with a support of graphical user interface (GUI) is used. It allows for the user to set the system parameters of LoRa, manage and monitor the whole wireless communication comfortably.

The wireless link is created as follows. The TX module is connected to a notebook via USB cable. The notebook has an installation of WiMOD LR Studio. In a form of battery-powered device, the RX module is placed from the TX at a defined position. After the set of system parameters, including carrier frequency and signal power, the TX module starts to transmit LoRa packets.

[2]https://wireless-solutions.de/downloadfile/lr-studio/

Fig. 1. Equipment used in the measurements.

The RX module receives these packets and sends back to the TX an ACK message (`Ack-Msg`) containing the measured radio parameters (RSSI, number of packets, air time, etc.) completed by time stamps. The received data in a form of `log` files are saved in the notebook for further offline processing. For this purpose (read-out of RSSI values and calculation of the coordinates of the target node), a MATLAB-based program was created and used.

2.2 Methodology of Localization

As it was mentioned above, the ACK message is completed by time stamps. These time stamps are expressed in the order of seconds, which represent insufficient resolution of values to calculate the propagation time for the Time of Arrival (ToA) method [1]. For this reason, the RSSI distance method providing information about the strength of the received signal (based on channel characteristics) was adopted. A logarithmic path loss model is used to determine the location distance based on the RSSI values [18].

In order to obtain the path loss model for the indoor environment, experimental measurements were provided in each indoor environment (see Sec. 2.3). For each point of the considered distance between TX and RX, 50 values of RSSI were collected and the median was subsequently calculated to remove the effect of step-changing values. The RSSI-based logarithmic path loss model was calculated as [18]:

$$RSSI\ [\mathrm{dBm}] = -10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + A + X_\sigma \quad (1)$$

where d is the distance between TX and RX, n is the path loss exponent and its value varies depending on the nature of the transmission environment, A denotes the RSSI value measured at distance $d_0 = 1$ m and X_σ represents the Gaussian normal distribution with zero mean value and standard deviation σ^2.

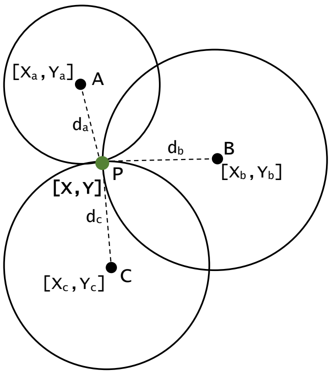


Fig. 2. Illustration of the principle of trilateration.

The trilateration geometric-based technique [11] is used to determine the position in a 2D space. For such a technique, minimally three reference (known) points for TX (reference node) are required. The TX in its reference position via RSSI estimation measures its distance from RX as a circle around the RX. Location of the RX (target node) can be determined according to the place, where three circles (three reference points) are intersected (see Fig. 2).

Let mark the range of RSSI-based measurements by d_a, d_b, d_c and the position of reference nodes by A, B and C. The position of the target node can be determined on the basis of the solution of two unknowns representing the coordinates (X and Y) of position of the target node as:

$$(X - X_a)^2 + (Y - Y_a)^2 = d_a^2, \quad (2)$$

$$(X - X_b)^2 + (Y - Y_b)^2 = d_b^2, \quad (3)$$

$$(X - X_c)^2 + (Y - Y_c)^2 = d_c^2. \quad (4)$$

2.3 Indoor Environments

Measurement campaigns were conducted in the building of grammar school of Zdar nad Sazavou, Czech Republic. Overall, three indoor environments having different natures for wireless transmission were selected for our study. The RSSI values were recorded at conditions when both TX and RX modules are mounted on a tripod at a height of 1 m above the floor level. Such a height approximately corresponds to the situation when a person holds a terminal device in his hands or it is placed in his pocket. During the measurements, the movement of people in all indoor environments was minimal.

The first set of measurements were provided in the **hall** of the grammar school. Its floor plan is shown in Fig. 3. Green and red circles denote places where TX and RX were installed, respectively. The hall has an approximate area of 200 m^2. It is made of concrete and its brick walls are complemented by supporting concrete columns. The ceiling material is mineral wool with paint finish. High wooden cabinets with a glass display case can be found on the left corner of the hall. Five windows, eight rows of wooden chairs and a ping-pong table are located on the right side of the hall. In this environment, it is possible to realize wireless transmission under both LOS and NLOS conditions.

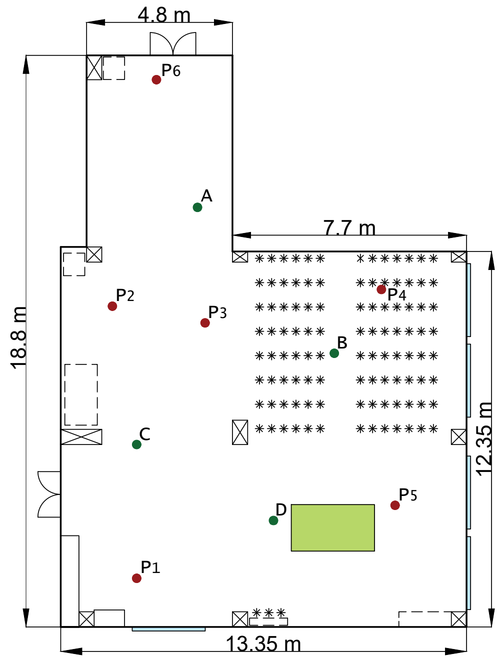


Fig. 3. Floor plan of Hall (• Tx, • Rx, ∗ chairs, - high cabinets, - - objects up to 1.2 m, windows, pingpong table).

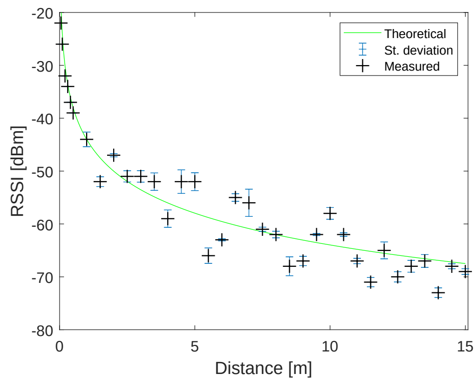


Fig. 4. Path loss model of the environment Hall based on the obtained RSSI values with 95% confidence intervals.

The path loss model of this environment is shown in Fig. 4. To obtain the path loss model of an environment, RSSI-based measurements were conducted in all indoor environments before the starting of real measurements to reveal the dependence of the signal strength on the increasing distance between TX and RX. In the hall (see Fig. 5 a)), the distance between TX and RX was varied in a range of 0 and 15 m. After the processing of the RSSI samples, the curve fitting function from MATLAB was used to estimate a model for the environment according to (1). The value of path loss exponent (n) was determined to 1.997. Next, A = –44 dBm was calculated as the median of the measured RSSI samples (see 95% confidence intervals in Fig. 4), whereas the mean value of all RSSI samples was $\mu = -62.77$. According to the coefficient of determination (R^2), the model corresponds to 92% with the measured characteristic.

a) Hall **b)** Locker room **c)** Corridor

Fig. 5. Indoor measurements environments.

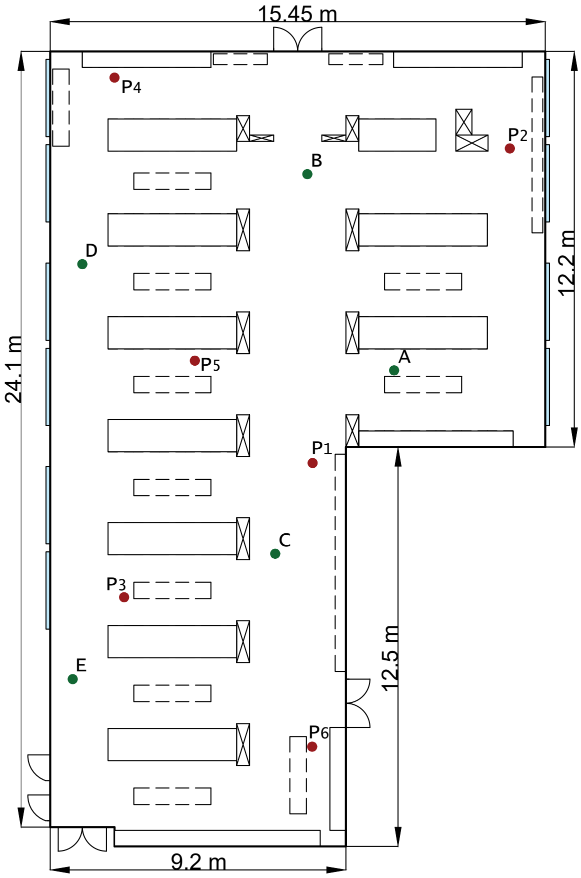


Fig. 6. Floor plan of Locker room (• Tx, • Rx, - wardrobes, - - benches, windows).

The second indoor environment, were the measurement campaigns were performed, is the **locker room** off the grammar school (see Fig. 5 b)) and its floor plan is captured in Fig. 6. It has an approximate area of 300 m^2. The walls of the room are made of bricks, the floor is covered with tiles and the ceiling together with columns are made of concrete. There are several metal wardrobes placed in rows through the entire room. Larger size of the room, numerous obstacles and rich conditions for NLOS-based transmission were the main reasons for involvement of this indoor environment in our study.

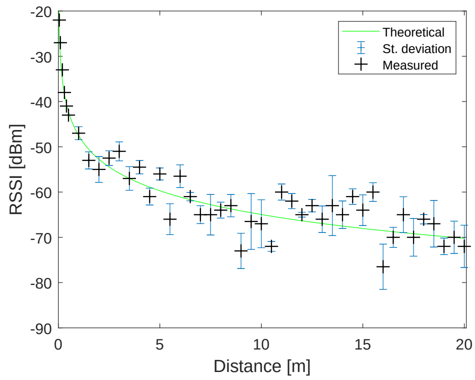


Fig. 7. Path loss model of the environment Locker room based on the obtained RSSI values with 95% confidence intervals.

To determine the path loss model (see Fig. 7), the values of RSSI were collected for distance up to 20 m. Next, the following parameters were obtained: n = 1.746, $A = -47.5$ dBm and $\mu = -61.55$. The coefficient of determination (R^2) is 90%.

The **corridor** of the grammar school (see Fig. 5 c)) was the third and final indoor environment, were the RSSI-based measurements were performed. It is a long narrow corridor with dimensions of 18.9 m × 3.0 m (see Fig. 8). The floor and ceiling partitions are made of concrete with mineral wool. The walls are made of bricks. Next, there are some wooden doors and no obstacles. From this point of view, there are strong conditions for LOS transmission. The path loss model for the corridor is shown in Fig. 9.

To extend our study, we provided additional measurements in this environment for the case when the distance between TX and RX is one and two storeys (i.e. the TX is placed in the first floor and the RX is in the third one). To obtain an appropriate path loss model, Equation (1) was extended by the floor attenuation factor (FAF), representing the attenuation between the floors, and parameter n_{FF} denoting the exponent of the initial (first) floor was used instead of n [19]. Parameter FAF has a value of –21 dB and –35 dB for one floor and two floors, respectively. The remaining parameters have the following values: $A = -47.4$ dBm, $n_{\mathrm{FF}} = 1.598$, $\mu = -59.51$ and R^2 = 92%.

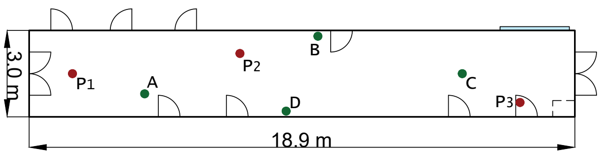


Fig. 8. Floor plan of Corridor (● Tx, ● Rx, - - locker, ■ glass partition).

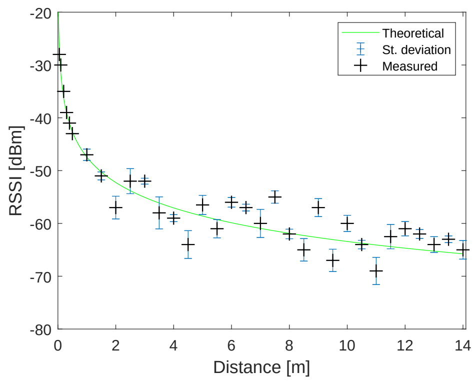


Fig. 9. Path loss model of the environment Corridor based on the obtained RSSI values with 95% confidence intervals.

Measurement scenario	**System option**	**BW** [kHz]	**SF**	$\mathbf{P_{Tx}}$ [dBm]
1.	LoRa	1600	5	8
2.	LoRa	200	12	8
3.	FLRC	1200	–	8
4.	FLRC	300	–	8
5.	(G)FSK	2400	–	8
6.	(G)FSK	300	–	8

Tab. 1. The LoRa system parameters used in the Hall.

Measurement scenario	**BW** [kHz]	**SF**	$\mathbf{P_{Tx}}$ [dBm]
1.	200	12	8
2.	200	5	8
3.	1600	5	8
4.	1600	8	8
5.	1600	10	8
6.	1600	12	8
7.	1600	12	0
8.	1600	12	–8
9.	1600	12	–18

Tab. 2. The LoRa system parameters used in the Locker room.

Measurement scenario	**BW** [kHz]	**SF**	$\mathbf{P_{Tx}}$ [dBm]	**Floor**
1.	200	12	8	–
2.	1600	5	8	–
3.	1600	12	8	–
4.	1600	12	8	1
5.	1600	12	8	2

Tab. 3. The LoRa system parameters used in the Corridor.

3. Results

This section deals with the analyze of the obtained results. As it was noted, in each indoor environment, the RSSI-based measurements were repeated at different signal configurations of LoRa. Thanks to this, it is possible to better explore the influence of the system parameters of LoRa and the nature of environment on the localization accuracy. The complete list of the used LoRa signal configurations is shown in Tabs. 1–3. In all measurement scenarios, the carrier frequency was set to 2.45 GHz and code rate (*CR*) of 4/5 was used. Dominantly, the selected values of parameters *BW* and *SF* and their combination represent the settings for RX with the highest (low *BW* and high *SF*) and lowest (high *BW* and low *SF*) sensitivity. Such configurations have direct impact on the localization accuracy (see Figs. 10-12).

The RSSI-based measurements were performed for randomly selected positions of RX. In all floor plans (see Sec. 2.3), these positions are marked by red circles. To better understand the influence of the nature of indoor environment, we worked with different positions of TX (e.g. see the green circles in Fig. 3). Thanks to this, it is possible to obtain a different set of equations (see Sec. 2.2) to determine the position of RX. It results in higher number of possible combinations of reference nodes (e.g. 'ABC', 'ABD', 'BCD', etc.) characterized by different signal coverage. These lead to different location coordinates differing in error of location estimate. In this work, the most accurate results are shown and analyzed.

3.1 Hall

Results from the measurements, conducted in the hall of grammar school, are shown in Fig. 10. They were obtained by the using of reference nodes (their *xy* coordinates are in units of m) A [4.5 ; 13.8], C [2.5 ; 6.0] and D [7.0 ; 3.5] (see Fig. 3). Horizontal axis marks the positions (P1, P2, etc.) at which the RX was installed (see floor plan in Fig. 3) while the vertical one marks the error between the real and estimated positions of RX. The Mean Squared Error (MSE) [11] was used to calculate the error between the real and estimated coordinates. Bar graphs correspond to the used LoRa signal configuration (see the legend in Fig. 10).

As it is visible, in terms of localization accuracy, different signal configurations result in different performances of LoRa. In the case of basic (LoRa) operation mode, differences between the signal configurations corresponding to the lowest and highest sensitivity level, in general, is not significant. Only at positions P4 and P5 are visible higher errors when $BW = 1600$ kHz and $SF = 5$ signal configuration is used. It is caused by the reflections due to a set of chairs and ping-pong table located close to the windows.

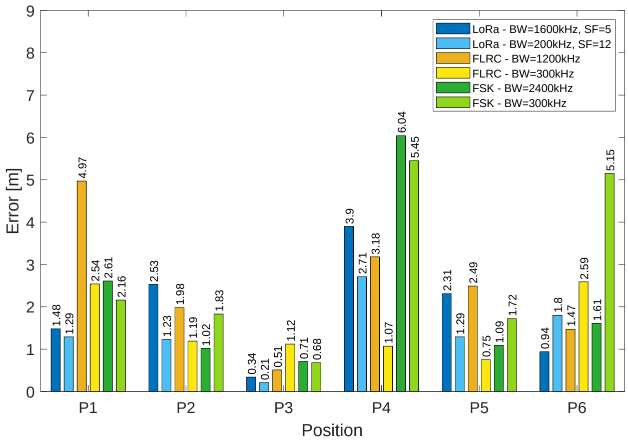


Fig. 10. Localization errors in the environment Hall.

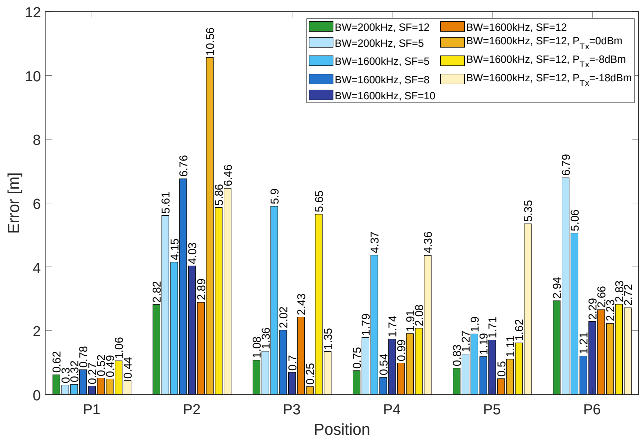


Fig. 11. Localization errors in the environment Locker room.

The FLRC operation mode employs coherent GMSK demodulation in combination with higher Forward Error Correction (FEC) protection (interleaving is included) [20]. In the measurements, one narrow and one wide signal bandwidth was used. In general, the performance of this mode is similar to the basic (LoRa) one. On the other hand, the localization errors are lower at positions P2, P4 and P5 when $BW = 300$ kHz.

The FSK operation mode allows for us to use conventional GFSK modulation. At this operation mode, the LoRa signal has the lowest resistance against multipath reflections (see localization errors for P4 and P6). In other cases, the performance of this mode is comparable with the FLRC mode. The average localization error for operation modes LoRa, FLRC and GFSK is 1.67 m, 1.98 m and 2.51 m, respectively.

3.2 Locker Room

Locker room of the grammar school was the second place, were the measurements were conducted. In this environment (see Fig. 6), the TX was placed at five reference positions due to large sizes of the room with nature rich on NLOS conditions. The most accurate results were obtained by the using of reference nodes 'ABD' having xy coordinates A [10.7 ; 14.2], B [8.0 ; 20.3] and D [1.0 ; 17.5].

Results in Fig. 11 show that the localization accuracy is mainly influenced by two factors. First one is given by the signal configuration of LoRa while the second one is given by the position of RX. The highest localization errors were recorded at positions P2 and P6, which are characterized by many obstacles. Low localization accuracy was examined in the case of $BW = 1600$ kHz. Overall, the lowest localization errors were achieved for signal configurations having low BW and high SF values. We explored the influence of transmission power on the localization accuracy for the LoRa signal having $BW = 1600$ kHz and $SF = 12$.

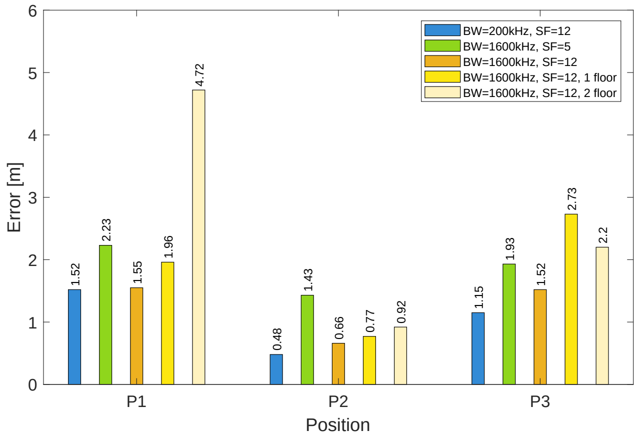
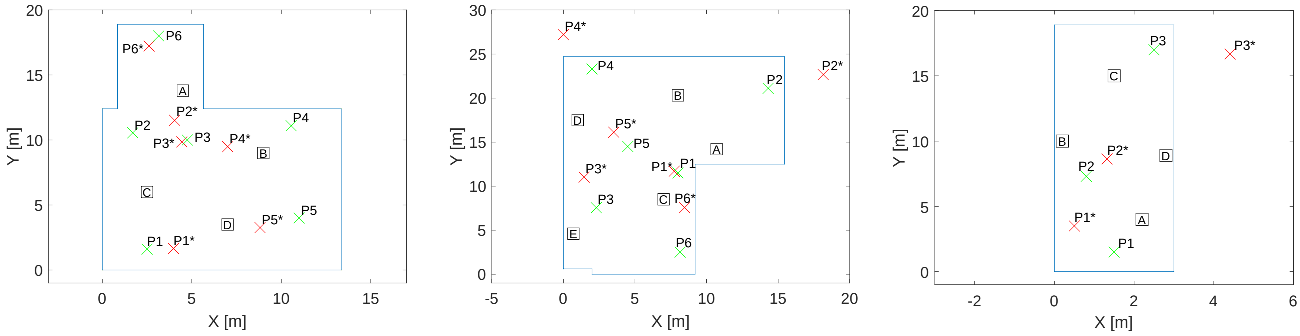


Fig. 12. Localization errors in the environment Corridor.

The following transmission powers of the LoRa signal were considered: 0 dBm, –8 dBm and –18 dBm. Overall, theoretical assumptions were fulfilled, i.e. the lower is the power level of the signal, the higher is the estimation error. On the other hand, as it is visible at position P2, the localization accuracy is the lowest for $P_{\mathrm{Tx}} = 0$ dBm. Repeated measurements excluded invalid RSSI data as a reason. Such a phenomenon, according to [21], can be occurred in a case when at trilateration technique two circles do not intersect. At $P_{\mathrm{Tx}} = 8$ dBm, the average localization error for configurations $BW = 200$ kHz and $SF = 12$ and for $BW = 1600$ kHz and $SF = 12$ is 1.45 m and 1.67 m, respectively.

3.3 Corridor

The corridor was the last environment, were the localization-based measurements were performed. The TX was placed at four different positions (see Fig. 8) and nodes A [2.2 ; 4.0], B [0.2 ; 10.5] and D [2.8 ; 8.9] were used to calculate the position of RX. The results in terms of localization error are plotted in Fig. 12.



a) Hall **b)** Locker room **c)** Corridor

Fig. 13. A visualization of localization accuracy (× – real position, × – localized position) in a two-dimensional space. The results, shown in the figures, were obtained at the following LoRa signal configuration: $BW = 1600$ kHz, $SF = 5$, $CR = 4/5$, and $P_{\mathrm{Tx}} = 8$ dBm.

In Tab. 3 is visible that we worked with two signal configurations of LoRa corresponding to low and high sensitivity level of RX. The measurements were divided into two parts. In the first one, both TX and RX were placed in corridor. Results show that there is not significant difference between LoRa signals having low or robust configuration. The difference between the considered configurations in terms of localization error is lower than 1 m. It is mainly caused by LOS conditions dominating in this environment.

The second part of the measurements employing LoRa signal with $BW = 1600$ kHz and $SF = 12$ was provided for the scenarios, when TX is placed in the corridor of the third (highest) floor of the building, but RX is placed on the second and then first floor with the same transmission environment (below the corridor). From this point of view, the lowest localization accuracy was recorded at position P1. The average localization error in the corridor, on the first and second floors was 1.39 m, 1.82 m and 2.6 m, respectively.

In Fig. 13, we visualize the localization accuracy in a two-dimensional (2D) space. For this purpose, we have created a custom MATLAB program. As it is visible, such a simple 2D visualization of results can help to better imagine the difference between the real and localized positions in terms of distance.

4. Conclusion

This paper dealt with the exploring of LoRa technology utilising 2.4 GHz ISM band for indoor localization purposes. To provide such a study, a simple RSSI-based measurement setup was proposed and the trilateration geometric-based technique was adopted to determine the location of an object. Measurement campaigns were conducted in different environments, all located in a grammar school, having different conditions for transmissions. In each measurement scenario, a LoRa signal with different configuration was employed. The time length of measurement for one signal configuration was average 30 minutes.

RSS-based measurements were provided in three indoor environments, namely: hall, locker room and corridor. Firstly, path loss model for these environments was estimated. At these measurements, the LoRa signal had the following configurations. For the hall and locker room: $BW = 1600$ kHz, $SF = 5$, $CR = 4/5$, and $P_{\mathrm{Tx}} = 8$ dBm and for corridor: $BW = 200$ kHz, $SF = 12$, $CR = 4/5$, and $P_{\mathrm{Tx}} = 8$ dBm. In all cases, the coefficient of determination was higher than 90%. Secondly, a set of RSSI-based measurements were provided in each environment. The recorded dataset is available online for future research purposes.

The evaluation of the obtained results shown that LoRa operating at 2.4 GHz can be a potential radio technology for indoor localization or tracking purposes in the future. However, the performance of LoRa, in terms of localization accuracy, is influenced by several factors. The signal configuration of LoRa and the used operation modes (e.g. FLRC) have a direct impact on the level of localization error. In an environment rich on NLOS conditions (e.g. locker room) it is recommended to use a robust signal configuration of LoRa (low BW and high SF values). In the locker room, the difference between the using of robust and low signal configuration (high BW and low SF) in terms of localization error is around 1.72 m. In the case of hall and corridor, this difference is around 0.49 m and 0.82 m, respectively.

In the future, the study in this paper can be extended by several ways. From the viewpoint of localization accuracy, an extensive investigation of possible influence of LoRa by other systems, for instance its coexistence with Wi-Fi [8], [22], will be important. Among others, outputs of these studies can help to better understand the connection between the used system configuration of LoRa and the nature of transmission channel [23], [24]. Next, similar studies as in this paper should be provided in outdoor environments. Finally, but not least, employing of machine learning approaches to improve the localization accuracy [17] is also among potential research topics.

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