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Comparison of Indoor/Outdoor, RSSI-Based Positioning Using 433, 868 or 2400 MHz ISM Bands

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***Abstract*—This paper compares accuracy of indoor positioning systems using one of three selected ISM bands: 433, 868 or 2400 MHz. Positioning is based on Received Signal Strength Indication (RSSI), received by majority of ISM RF modules, including low-cost ones. Investigated environment is single, indoor space (e.g. office, hall) and personal use, thus 2-dimensional (2D) coordinate system is used. Obtained results, i.a. average positioning error, are compared with similar measurements taken at outdoor, open space environment. The system is local, i.e. its operational area is limited by range of used RF modules – typical a few tens of meters. The main focus is research of how much accuracy (and usefulness) can be expected from standard RF modules working at typical ISM frequencies.**

***Keywords*—indoor location, personal location, RSSI measurement, ISM bands**

I. Introduction

INDOOR positioning is still a missing piece in the jigsaw puzzle of the true global personal navigation service. Although outdoor positioning already become mature and widely available: GPS and Glonass (with Galileo and Beidou in future). These systems have enough accuracy for most applications in their free/civilian versions. Constant progress in electronics made them affordable and truly portable: small, light and less power-hungry devices. On the other hand, there are still missing effective alternatives for indoor use. Although there has been proposed a variety of location methods, based on various physical phenomena (e.g. video, ultrasound, MEMS dynamics, UWB pulses), none of them became dominating [1-12].

System which is a subject of this paper uses RSSI (Received Signal Strength Indication) values to compute distances between user and corresponding *beacons*. It must be noted that RSSI is not a Received Signal Power Indication (RSPI) – a true received signal power measurement. Such systems are much more expensive and impractical in scope of consumer electronics.

The used RSSI is assumed to be time-invariable function of a RSPI, defined (with some accuracy) by manufacturer of a selected RF IC. It is further altered by receiving path (antenna, PCB transmission line, impedance mismatch etc.). However, it is assumed that the total relation between RSSI and a received signal is similar and constant for all used devices.

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The main difficulties, with the greatest influence on system accuracy are:

- reflection, diffraction and dissipation of electromagnetic waves in a building environment,
- existence of interfering signals.

There have been used three RF modules: RFM69CW-433S2 (for 433 MHz band), RFM69CW-868S2 (for 868 MHz band) and ESP8266-12E Wi-Fi IoT (for 2.4 GHz band). The two first have been selected for their high dynamics of the RSSI read-out: 115 dB. The last module has been chosen for its low cost, low power consumption and acceptably high RSSI dynamics: approx. 90 dB.

II. Theoretical Background

The first step of position calculation is estimation of distances from located object (receiver) to number of transmitters (beacons), placed at known locations. This estimation is based on the RSSI read-out. The modified *Friis* formula (the *log-model*) is used [13]:

$$RSSI\ [dBm] = -10 \cdot n \cdot log_{10}\left(\frac{d}{d_0}\right) + RSSI_0 \qquad (1)$$

where:

- $RSSI$ – read-out returned by the receiver, in [dBm],
- d – distance between receiver and transmitter (beacon), in [m],
- N – propagation constant,
- d_0 – reference distance: 1 [m],
- $RSSI_0$ – RSSI read-out at reference distance d_0, in [dBm].

Simple transformation makes possible calculation of unknown distance d, based on measured RSSI from particular beacon, assuming known (estimated) values of $RSSI_0$ and n:

$$d = d_0 \cdot 10^{\frac{RSSI_0 - RSSI}{10 \cdot n}} \qquad (2)$$

Notice all measured and estimated parameters in power, therefore their uncertainty has got large impact on d uncertainty.

In both indoor and outdoor cases, values of $RSSI_0$ and n have been calculated based on measurement of $RSSI$ = f(d) relation. Finally, least-square error non-linear fitting (trust region reflective method) has been used to fit $RSSI_0$ and n.

The second step of positioning calculation is 2-dimensional (2D) trilateration. A flat coordinate system has been used for three reasons:

1. it covers most common scenario of personal location at home/office/public/commercial facilities, where users are at similar and constant height. Therefore, distinction

among users crawling, walking or climbing the walls is not needed;
2. high location error for 3-dimensional (3D) trilateration occurs, when all beacons and receiver are at (or near) common horizontal plane [14];
3. simplicity. Proposed case can be easily extended to 3D coordinate system.

Based on well-known circle formulas, set of non-linear equations can be written (fig. 1):

$$\begin{cases} d_1^2 = (x-a_1)^2 + (y-b_1)^2 \\ d_2^2 = (x-a_2)^2 + (y-b_2)^2 \\ d_3^2 = (x-a_3)^2 + (y-b_3)^2 \end{cases} \tag{3}$$

where:

- x, y – unknown coordinates of the receiver,
- a_i, b_i – known coordinates of i-th beacon transmitter, i = 1, 2, 3;
- d_i – measured distance to i-th beacon, i = 1, 2, 3.

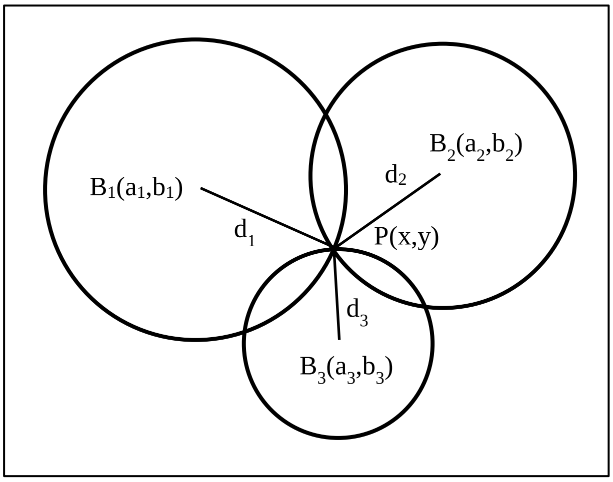

Fig. 1. 2D-trilateration geometry.

Above set of equations can be transformed e.g. into matrix form and solved using standard methods. Unfortunately, this set equations is contradictory in the real world, because measured distances d_i are always altered by unknown measurement error - thus point of intersection cannot be directly found. On the other hand, more than N = 3 beacons can be used, e.g. to improve location accuracy. Therefore, again, non-linear fitting has been applied using trust region reflective method [14].

For given assumed position $P(x,y)$, the exact distances r_i to particular beacons B_i (i = 1, 2, …, N) can be expressed as:

$$\begin{cases} r_1^2 = (x-a_1)^2 + (y-b_1)^2 \\ r_2^2 = (x-a_2)^2 + (y-b_2)^2 \\ \vdots \\ r_i^2 = (x-a_i)^2 + (y-b_i)^2 \\ \vdots \\ r_N^2 = (x-a_N)^2 + (y-b_N)^2 \end{cases} \quad \begin{matrix} i = 1,2,\dots,N \\ N \geq 3 \end{matrix} \tag{4}$$

where N is total number of beacons B_i. Then, distance error e_i from i-th beacon B_i is computed using measured distance d_i:

$$e_i = d_i - r_i \quad i = 1,2,\dots,N \tag{5}$$

Finally, coordinates (x,y) are fitted such that sum of squared errors is minimal:

$$\sum_{i=1}^{N} e_i^2 \rightarrow min \tag{6}$$

III. Wave Propagation Environment

Geometry of propagation space is an elongated rectangular room with dimensions 15 x 4.8 m. N = 5 transmitters (beacons) have been placed at particular coordinates (tab. I). All RSSI measurements have been taken at static location of the receiver P (tab. I). All beacons and point P were placed at height of 1.3 m. Indoor environment is a standard office/university construction from 70’s: concrete ceilings, 3 full-brick walls, fully windowed 4-th wall and 3 m of height (fig. 2). Outdoor environment is open area of a grass airport without any constructions or obstacles at close distance. Locations of beacons and point P are the same as for indoor case.

Table I.
Beacons and P-Point Coordinates

	B1	B2	B3	B4	B5	P
***X* [m]**	0.60	14.55	8.40	14.55	0.65	7.00
***Y* [m]**	0.35	0.35	0.40	3.60	3.60	2.50

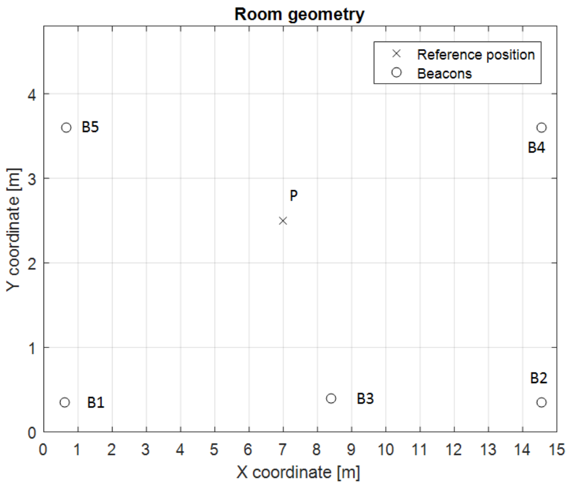

Fig. 2. Room geometry.

The first step was estimation of $RSSI_0$ and n parameters for the given environment. There have been recorded 10 RSSI measurements, in 1 m steps, at each distance d = 2 ÷ 11 m from each beacon (towards center of the room). The RSSI read-out for corresponding distances have been averaged. Then, best values of $RSSI_0$ and n have been estimated (with least square error), fitting (1). Fig. 3 presents averaged RSSI values and fitted function for indoor room and 868 MHz band.

Tab. II presents estimated values of $RSSI_0$ (for reference distance d_0 = 1 m) and n (propagation factor) for selected ISM bands at indoor environment.

Table II.
$RSSI_0$ and N for Indoor Environment

***f* [MHz]**	**433**	**868**	**2400**
***RSSI₀* [dBm]**	-54.8	-53.8	-37.9
n	2.19	2.31	1.34

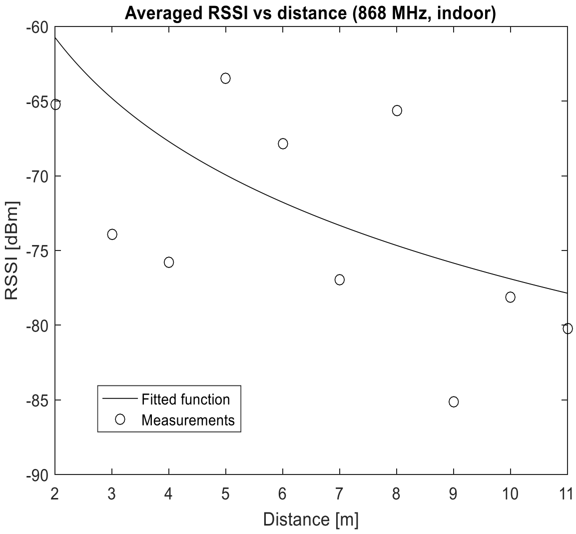

Fig. 3. Example of averaged RSSI vs distance read-outs (indoor, 868 MHz).

Tab. III presents estimated values of $RSSI_0$ (for reference distance d_0 = 1 m) and n (propagation factor) for selected ISM bands at outdoor environment.

TABLE III.
$RSSI_0$ AND N FOR OUTDOOR ENVIRONMENT

f **[MHz]**	**433**	**868**	**2400**
RSSI₀ **[dBm]**	-53.2	-53.1	-34.9
n	3.34	3.35	2.48

It should be strongly emphasized, that estimated parameters $RSSI_0$ and n strongly depend on low precision RSSI measurement, environment and also vary in time. Therefore, their special and temporal uncertainty is main source of positioning error.

IV. INDOOR AND OUTDOOR MEASUREMENTS

There have been recorded at least 500 RSSI read-outs from each beacon. Full measurement set (5 RSSI read-outs from all 5 beacons) has been repeated every 700 ms.

Fig. 4 presents statistics of indoor positioning error as function of frequency, at which RSSI has been measured.

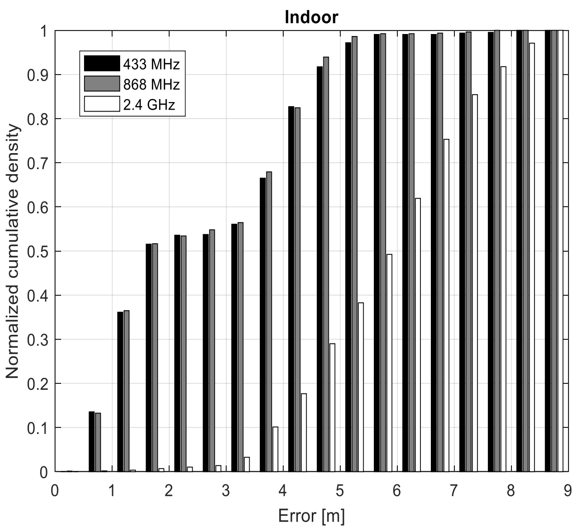

Fig. 4. Positioning error for indoor environment.

It can be observed that positioning using 433 or 868 MHz ISM bands outperforms positioning using 2.4 GHz band. Possible reason is weaker influence of propagation environment on longer radio waves. Notice shape of the density function envelope far from standard distribution.

Based on indoor measurements, a there have been calculated following parameters expressing positioning accuracy:

- CEP - circular error probable (also circular error probability or circle of equal probability), 50% of hits (position estimates) is placed within given radius (error);
- CEP70 – non-standard quantity, equivalent to CEP, but for radius of 70% positions. This quantity is used in place of standard RMS (root mean square) precision parameter (covering 63% to 68% position hits), but defined only for standard probability distribution of positioning error;
- R95 – radius of 95% of all position estimates.

Average position error, values of the CEP, CEP70 and R95 parameters for indoor case are presented in tab. IV.

TABLE IV.
AVERAGE POSITION ERROR, CEP, CEP70 AND R95 FOR INDOOR ENVIRONMENT

f **[MHz]**	**433**	**868**	**2400**
Average error [m]	2.85	2.79	6.49
CEP [m]	2.0	2.0	6.5
CEP70 [m]	4.5	4.5	7.0
R95 [m]	5.5	5.5	8.5

Again, positioning using 433 and 868 bands is equivalent, outperforming positioning using 2.4 GHz bands.

Fig. 5 presents statistics of outdoor positioning error as function of frequency, at which RSSI has been measured.

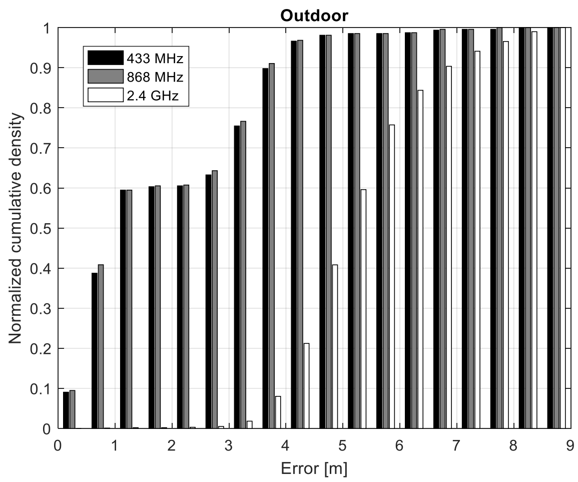

Fig. 5. Positioning error for outdoor environment.

Average position error, values of the CEP, CEP70 and R95 parameters for outdoor case are presented in tab. V.

TABLE V.
AVERAGE POSITION ERROR, CEP, CEP70 AND R95 FOR OUTDOOR ENVIRONMENT

f **[MHz]**	**433**	**868**	**2400**
Average error [m]	2.01	1.98	5.55
CEP [m]	1.5	1.5	5.5
CEP70 [m]	3.5	3.5	6.0
R95 [m]	4.5	4.5	8.0

Again, positioning using 433 and 868 bands is equivalent, outperforming positioning using 2.4 GHz band. However, for all three frequencies, outdoor positioning is slightly more accurate than indoor. Possible reason is weaker influence of propagation environment (more similar to "free space"). Notice shape of the density function envelope far from standard distribution.

Fig. 6 and 7 present location of beacons ('o'), real position ('x') and spread of calculated positions ('+'). Spread of the calculated positions confirms that positioning error does not have typical probability distribution.

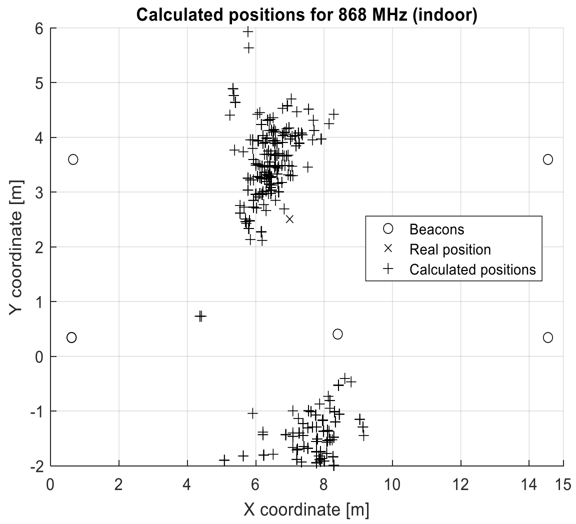

Fig. 6. Positioning spread for indoor environment.

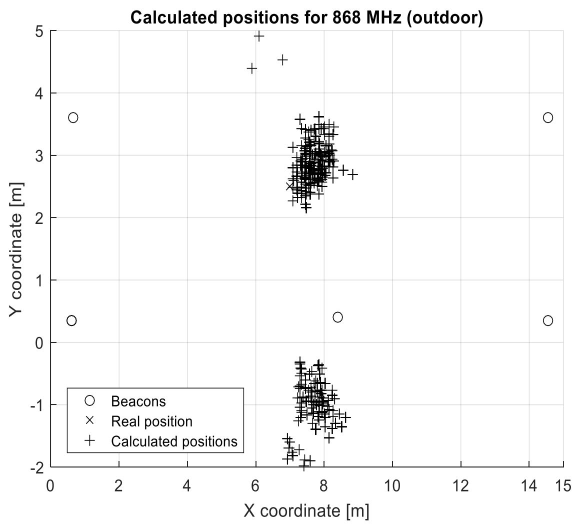

Fig. 7. Positioning spread for indoor environment.

V. Reducing Number of Beacons

It is unknown *a priori* which distance measurement has greatest uncertainty. It is possible, that some beacons (or their combination) actually increase positioning error. Tab. VI contains measured indoor average positioning errors for all combinations of 3 and 4 beacons used. The results are compared with average positioning errors for case when all 5 beacons are used.

TABLE VI.
AVERAGE INDOOR POSITIONING ERROR [M] VS NUMBER OF BEACONS (B)

***f* [MHz]**	**433**	**868**	**2400**
1-2-3-4-5 (all beacons)	*2.85*	*2.79*	*6.49*
1-2-3-4 (without B5)	7.44	7.29	**5.58**
1-2-3-5 (without B4)	**1.84**	**1.81**	**5.35**
1-2-4-5 (without B3)	3.75	3.68	7.26
1-3-4-5 (without B2)	3.67	3.56	6.94
2-3-4-5 (without B1)	**2.10**	**2.08**	7.41
1-2-3	6.57	6.48	**4.45**
1-2-4	9.30	9.09	**6.24**
1-2-5	**2.67**	**2.63**	**5.78**
1-3-4	7.51	7.36	**5.31**
1-3-5	**2.21**	**2.13**	**5.54**
1-4-5	6.86	6.59	8.76
2-3-4	5.39	5.35	6.61
2-3-5	**1.05**	**1.06**	**6.34**
2-4-5	**2.21**	**2.20**	9.06
3-4-5	3.03	2.97	7.47

Tab. VII contains the same measurements repeated for outdoor environment.

TABLE VII.
AVERAGE OUTDOOR POSITIONING ERROR [M] VS NUMBER OF BEACONS (B)

***f* [MHz]**	**433**	**868**	**2400**
1-2-3-4-5 (all beacons)	*2.01*	*1.98*	*5.55*
1-2-3-4 (without B5)	2.02	1.94	**3.96**
1-2-3-5 (without B4)	4.23	4.19	**4.84**
1-2-4-5 (without B3)	**1.83**	**1.76**	6.03
1-3-4-5 (without B2)	2.29	2.16	6.12
2-3-4-5 (without B1)	2.33	2.29	6.73
1-2-3	4.42	4.38	**3.17**
1-2-4	**1.64**	**1.58**	**4.16**
1-2-5	4.41	4.38	**4.81**
1-3-4	2.85	2.86	**4.01**
1-3-5	3.99	3.97	**5.45**
1-4-5	**1.82**	**1.79**	7.50
2-3-4	**1.25**	**1.24**	5.66
2-3-5	4.03	4.01	5.69
2-4-5	3.39	3.48	8.10
3-4-5	2.38	2.41	6.99

It can be observed improvement for specific number and combination of used beacons. The results are comparable for indoor 433 and 868 MHz bands: elimination of beacons 1 and 4 significantly reduces average positioning error. Situation is different for 2.4 GHz band: the best result is obtained after elimination of beacons 4 and 5.

Outdoor case is different: beacons 1 and 5 should be eliminated for the highest accuracy in 433/868 MHz bands – beacons 4 and 5 for 2.4 GHz band.

Notice, that these results can only be valid for the investigated point *P* and be far different for other locations.

VI SUMMARY

Positioning based on RSSI measurement performs better for 433 and 868 MHz ISM bands, which performance is comparable. Notice this result is dependent on used RF modules. There also have been observed strong dependence on number and combination of used beacons, however 433 and 868 MHz bands still outperformed 2.4 GHz band.

All solutions suffered from similar problems: high uncertainty of transmitter ($RSSI_0$) and propagation (n) parameters are the main factors of location uncertainty.

Outdoor positioning performs better, which is not a surprise: less obstacles and interference makes propagation closer to free space model.

Low overall positioning accuracy for all frequencies is result of no filtering or data processing used. This has been done by purpose, in order to investigate "raw" positioning accuracy. Other Authors have proposed many techniques (i.a. RSSI fingerprinting, Kalman filtering, Markov chains) able to significantly reduce location error – down to several cm. Also, multiple utilization of two or more bands is possible. Summarizing: there exists possibility for acceptable and useful indoor positioning system, especially using 433 and/or 868 MHz ISM bands.

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