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Analysis of the influence of radio beacon placement on the accuracy of indoor positioning system

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***Abstract*—This paper discusses factors influencing accuracy of estimating localization of radio networks terminals in indoor environment. It introduces parameters that can be useful to describe the quality of localization of radio landmarks. The paper presents a software for computer aided reference radio stations placement inside the buildings and shows the results of exemplary simulations carried out with the use of proposed algorithms.**

***Index Terms*—indoor positioning systems, Location Based Services, wireless local area networks, radiolocation**

I. Introduction

NOWADAYS many telecommunication systems use information about location of mobile terminal from GPS and GSM/UMTS systems to estimate user terminal location. But these systems have common defect, both do not work indoors. These limitation results from strong signal attenuation introduced by the outer walls of buildings and from the strong multipath propagation effects present in indoor areas. To overcome these problems there are created dedicated systems like sensor networks and used dedicated networks like WLAN, Bluetooth, ZigBee, RFID, UWB to work in a small area by having a lower signal strength which causes smaller signal interference in comparison to outdoor solutions. Many of these network systems are used in daily life to exchange information between terminals. But due to the growing interest in localization in indoor environment, a problem arises how to fast and correct locate reference landmarks, taking into consideration size of the area in which localization is possible, number of reference nodes and desired localization accuracy. If we place reference nodes correctly we can use these systems for example to help a blind or visually impaired person to move inside the building, or to help a disabled person to reach the medical room. Another important field of application of positioning systems includes navigation in industrial and manufacturing facilities [1].

This article discusses the factors influencing on location accuracy in indoor environment based on the RSS (Received Signal Strength). Then, it explains how to evaluate the quality of the reference station distribution based on the aforementioned factors. Next, it presents an algorithm which improves quality of placement of the reference nodes taking into consideration the aforementioned assessment methods. Then it deals with the results of the simulations in exemplary rooms with obstacles.

II. Factors Influencing Localization Accuracy

A. Lack of signals from minimum three reference radio stations

This is the most important factor that influences the possibility to estimate unknown position of the mobile terminal. When we have information about the distance from one reference station, we can only say that the terminal is somewhere around the circle with radius being equal to this distance. If we have information on the distances from two reference stations, we can limit our searching to two points resulting from intersection of two circles. To obtain unambiguous information about position of the terminal, information from at least three reference stations is required.

B. Adverse reference nodes geometry

Distance measurements between reference stations and localized terminal is not noiseless. The size of noise depend on the strength and types of signal used and environment surrounding reference station. All it caused a distance measurements error, that is shown as ring around the station, Fig. 1. As a result of imposition of three rings, we can indicate common areas where the terminal is likely to be localized in. This area is called the area of uncertainty, Fig. 1.

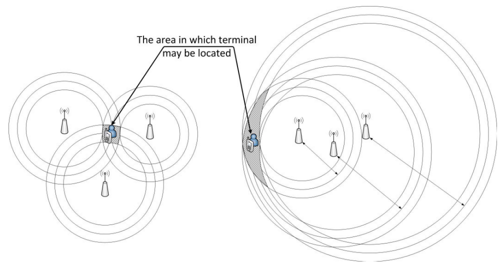

Fig. 1. Localization error for different geometry of reference nodes a) nodes located in an equilateral triangle b) nodes located on straight line.

The size of the area of uncertainty represents, in a sense, the error of localization. The uncertainty area is the smallest when the localized terminal is placed between the reference stations and the angles between adjacent stations are equal. On the contrary, the biggest area of uncertainty is created when the reference stations are placed along the line. This results in the highest error of unknown terminal localization.

C. Multipath propagation of radio signals

Multipath propagation results in imposition of several copies of the same signal reaching the receiver. The signal components travel along different paths and exhibit different power levels and phase shifts. This leads to the strong fluctuations of signal power, depending on the distance between the transmitter and the receiver [2], [3]. This factor has a particular importance in the localization methods based on the received signal strength and phase measurements [4], [5]. A graph shown in Fig. 2 presents the level of signal attenuation as a function of the distance between the antennas. Fluctuations of the signal power result from interfering of two waves: direct and reflected ones.

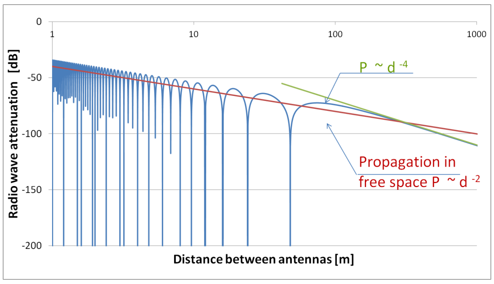

Fig. 2. Signal attenuation as a function of transmitter and receiver antennas separation

However, in a real indoor environment, the transmitting and receiving antennas are surrounded by walls and furnishing. In such conditions signals reflected from the obstacles reach the receiver, propagating along many different paths, thus having different phases. The number of interfering waves can be very high and difficult to estimate. In fact, there is no visible relationship between received signal strength and the distance, which makes difficult to determine the distance using the RSS method correctly. As a result, the calculated position shows significant errors. Another problem is the correct estimation of reflection coefficient of the radio wave for the obstacle. A huge coefficient variation dependent on the material which the obstacle is made of prevents from the accurate calculation of the radio wave reflected from the obstacle attenuation.

D. Radio signal attenuation in non line of sight case

If a line of sight (LOS) between localized object and reference station exists, we can assume that the measurement of signal strength is not affected by additional errors resulting from unspecified signal attenuation and delays due to reflections. In indoor environment it is often not possible to provide the LOS conditions in the entire room. In non line of sight case (NLOS), the signal reaches the receiver with additional attenuation resulting in the increase of the localization error.

E. Incorrect or inaccurate signal propagation model

Incorrectly chosen model of radio wave propagation, based on RSS method, can be a source of significant errors in terminal position calculation. The choice of appropriate propagation model should strictly depend on indoor environmental conditions. In practice, there is no ability to ensure that we choose the proper model, corresponding to temporary environmental conditions. For this purpose there are commonly used empirical models, based on a large number of measurements and statistical surveys.

III. Assessing the Distribution of Reference Stations

A. Evaluation of reference nodes geometry

To evaluate reference stations geometry in relation to the localized point we used two factors have been used: the first factor we propose is a simple formula determined on the trigonometric formulas. The second one is a modified factor HDOP (Horizontal Dilution Of Precision) used in GPS system to assess the layout geometry of satellites [6], [7], [8]. Fig. 3 shows the case where the terminal position is determined based on signals coming from four reference stations (according to [1]).

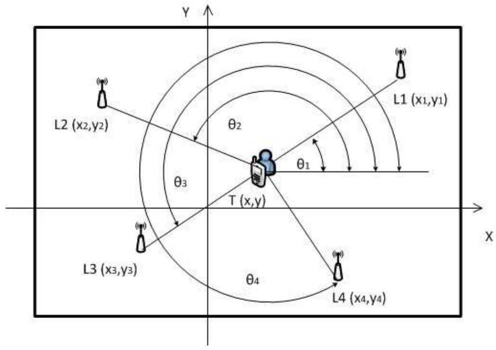

Fig. 3. Two dimensional localization schema.

In Fig. 3 the angle θ formed between the straight line passing through the localized terminal and a line parallel to the x axis are marked.
We assume that α is the angle between neighboring reference stations:

$$\alpha_1 = \theta_2 - \theta_1\,, \quad \alpha_2 = \theta_3 - \theta_2\,, \quad \alpha_3 = \theta_4 - \theta_3\,; \qquad (1)$$

The factor g(l) is obtained on the basis of trigonometric formulas:

$$g(l) = \frac{\sin^2\varphi_1 + \sin^2\varphi_2 + \sin^2\varphi_3 + \ldots + \sin^2\varphi_n}{n} \qquad (2)$$

where:

$$\varphi_n = \alpha_n - \left(\frac{2\pi}{n} - \frac{\pi}{2}\right) \qquad (3)$$

and:
α_n - the angle between the straight lines connecting the localized terminal with neighboring reference stations,
n - number of stations within the range of the terminal being localized.

The classification of the assumed geometry indexes is presented in Table I. This index measures the effect of the

TABLE I
EVALUATION OF GEOMETRY INDEX VALUES

Value of g(l) index	Evaluation of the geometry of the reference stations placement
0,5<g(l)≤1	Very good
0,35<g(l)≤0,5	Good
0,2<g(l)≤0,35	Sufficient
g(l)≤0,2	Bad

geometric configuration of the reference points on the position estimation [8].

The second factor that can be used to evaluate the distribution of radio stations is HDOP index, which is typically used to assess the potential localization error of GPS satellite navigation systems. HDOP factor for the three-dimensional case can be derived from matrix A:

$$\mathbf{A} = \begin{vmatrix} \frac{(x_1-x)}{R_1} & \frac{(y_1-y)}{R_1} & \frac{(z_1-z)}{R_1} & -1 \\ \frac{(x_2-x)}{R_2} & \frac{(y_2-y)}{R_2} & \frac{(z_2-z)}{R_2} & -1 \\ \frac{(x_3-x)}{R_3} & \frac{(y_3-y)}{R_3} & \frac{(z_3-z)}{R_3} & -1 \end{vmatrix} \tag{4}$$

where,

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{5}$$

and:
R_i - the distance between the coordinates (x_i, y_i, z_i) of the reference station and coordinates (x, y, z) of object to be localized. Introducing matrix Q:

$$\mathbf{Q} = (\mathbf{A}^T\mathbf{A})^{-1} \tag{6}$$

$$\mathbf{Q} = \begin{vmatrix} d_x^2 & d_{xy}^2 & d_{xz}^2 & d_{xt}^2 \\ d_{xy}^2 & d_y^2 & d_{yz}^2 & d_{yt}^2 \\ d_{xz}^2 & d_{yz}^2 & d_z^2 & d_{zt}^2 \\ d_{xt}^2 & d_{yt}^2 & d_{zt}^2 & d_t^2 \end{vmatrix} \tag{7}$$

the HDOP index for two dimensional case is determined.

$$HDOP = \sqrt{d_x^2 + d_y^2} \tag{8}$$

Based on the HDOP index, we can specify geometry index factor according to Table II [8].

TABLE II
EVALUATION OF HDOP INDEX VALUES

Value of g(l) index	Evaluation of the geometry of the reference stations placement
<1	Measurements error or redundancy
1	Ideal
1-2	Very Good
2-5	Good
5-10	Medium
10-20	Sufficient
>20	Bad

B. Quality of radio signal in non line of sight case

To evaluate the quality of radio signals reaching the receiver, we additionally assumed the criterion of maximum acceptable additional signal attenuation due to the presence of obstacles between the localized terminal and a reference station. We assumed the following classification of radio propagation conditions:

- conditions are considered to be ideal when there is no additional attenuation in radio path caused by obstacles,
- conditions are very good, if the additional attenuation in radio path caused by obstacles does not exceed 2 dB, for each station,
- conditions are good, if the additional attenuation caused by an obstacle exceed 2dB is from 0% to 25% number of stations
- conditions are bad, if the additional attenuation caused by an obstacle is greater than 2 dB is from 25% to 50% number of stations,
- conditions are very bad, if the additional signal attenuation caused by obstacles is greater than 2 dB from more than 50% of the stations.

IV. ANALYSIS OF THE REFERENCE NODES PLACEMENT

A. Assumptions

The following assumptions regarding the assessment of reference radio stations placement have been taken into account in the article.

- In every part of room, radio signals from at least three reference radio stations should reach the receiver. It is also assumed that the number of stations within range should not exceed four. The increase of the number of stations does not necessarily improves the location accuracy but significantly increases the cost of network construction.
- The power levels of the received signals should exceed some minimum threshold level.
- Reference stations should be as far separated as possible, which allows to reduce the spatial density of the stations.
- Another important aspect is to provide direct visibility of reference stations (LOS) at each point in the room. Alternatively, signal attenuation due to the obstacles should not exceed the assumed maximum level.
- In the ideal case the angles between the reference stations in relation to the terminal position should be equal.

B. Simulation software

To examine the impact of the reference stations placement on the localization accuracy, a dedicated simulation software has been developed. The software allows evaluation of reference nodes placement for an assumed two-dimensional room layout using the criteria presented in Section III. Apart from the assessment of the reference nodes placement, the software allows to optimize the initial locations of the nodes in order to maximize the values of quality of placement coefficients. We implemented an iterative algorithm based on the idea described in [9], [10]. Every placement of the reference nodes can be described with an overall system of a so-called "energy function". The energy of the system is computed as the sum of the energies assigned to test locations in the room. The test locations are randomly distributed within the area under investigation, and the energy assigned to a single location is a function of coefficients defined in Section III.

$$E = \sum_{n=1}^{N} \quad (a_1Q_1 + a_2Q_2 + a_3Q_3 + \cdots + a_1Q_1) \qquad (9)$$

where:
E - an overall system energy,
Q_k - value of quality factor,
a_k - weight quality factor,
N - number of all measurement points,
n - measuring point number,

The model of the system is based on resilience phenomenon, i.e. when the distance between the two neighboring reference nodes increases, the force repelling these nodes decreases. The goal of the algorithm is to minimize the overall system energy and to maximize coefficients describing the quality of the reference nodes placement. In every iteration, the software estimates reference nodes placement quality coefficients as well as system energy and forces repelling the neighboring nodes. Additionally, a random Brownian motion of the nodes is assumed to minimize the risk of stopping the optimization algorithm in some local minima. As a result, new positions of the reference stations are estimated.

$$V = \sum_{n=1}^{N} \quad (ad_n + b) + V_B) \qquad (10)$$

where:
N - number station in range
a, b - coefficient
d - distance between stations
V_B - Brown motion vector

The flow diagram of the reference nodes placement optimization algorithm implemented in the software is presented in Fig. 4.

In the simulations, to calculate signal attenuation and to estimate the distance between the antennas a Multi-Wall indoor radio propagation model [2], [3] was used. For distances d < 1m we assume free space signal propagation loss:

$$L(d < 1)_{dB} = 40 + 20\log(d) \qquad (11)$$

For distances d > 1m we compute the propagation loss with the use of the Multi-Wall model:

$$L_{MWM}[dB] = 40 + 10 \cdot 4\log(d) + \sum_{s=1}^{s=Sn} \quad (n_{ws} \cdot L_{ws}) \qquad (12)$$

where:
L - signal attenuation,

Fig. 4. Reference stations placement optimization algorithm.

d - distance between the antennas,
n - number of walls on the signal propagation path,
S - type of wall material is made,
Sn - number of wall types,
Lws - attenuation of a single wall,

C. Simulation results

Firstly, we try to see the relationship between placement of the reference stations and the size of the area where the terminal can receive signals from at least three of the beacon stations. For the simulations we assumed an example of 25 m x 25 m room layout and the following algorithm parameters: transmit power level is equal to 5 dBm and minimum received signal strength required at the receiver antenna equal to -85 dBm. Fig. 5 and Fig. 6 present results of the reference stations placement. Black rectangles denote obstacles and blue circles indicate reference stations. Areas where the quality requirements are not met are marked with crosses.

To assess localization conditions, we evaluate quality criteria for test points distributed in the area of the room layout. The test points are located randomly in the room and the number of points is determined by the program user. The higher the number of points, the greater the accuracy but also the longer the computation time. Fig. 7 shows sample results obtained for the scenario presented in Fig. 6, and the bars indicate percentage of the room area as a function of a number of visible reference stations.

To evaluate the performance of reference stations placement optimization algorithm, we performed a series of simulations for sample room layout and for various initial placements of

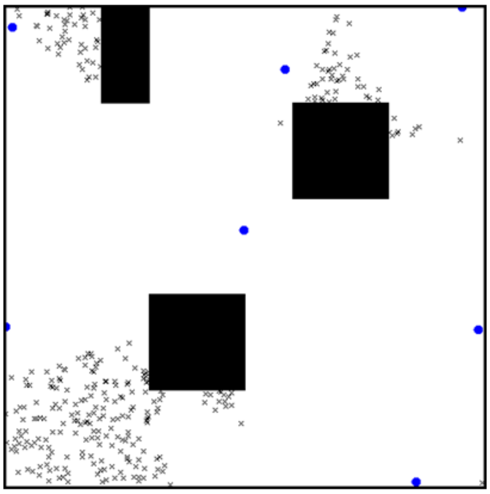

Fig. 5. Example placement of 7 reference stations in room No.1 25m x 25m.

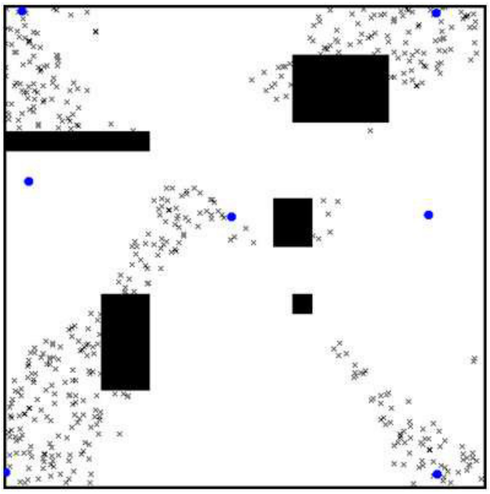

Fig. 6. Example placement of 7 reference stations in room No.2 25m x 25m.

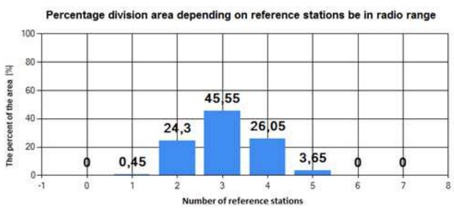

Fig. 7. Percentage division area depending on reference stations being in the radio range.

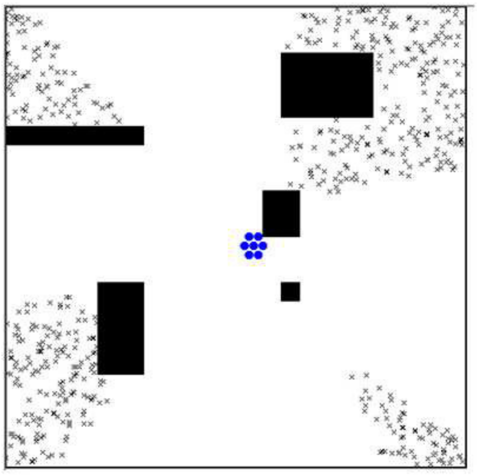

Fig. 8. Initial simulation conditions ij a room with a number of reference stations placed in its center.

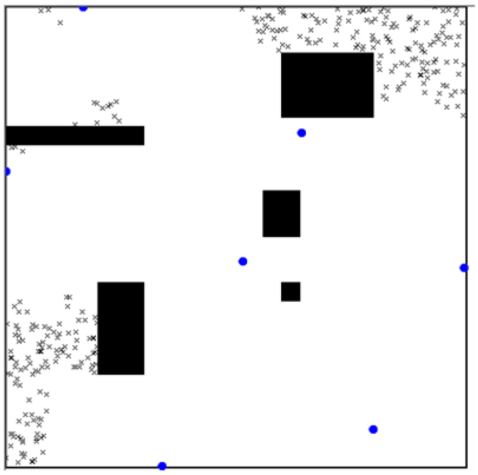

Fig. 9. The result of the reference stations placement optimization.

the stations. Fig. 8 and Fig. 9 show the initial conditions and optimization results for the same room layout as in Fig. 6.

V. Summary

In the paper, we described parameters that can be used to evaluate the quality of reference nodes placement and its influence on the network terminal positioning accuracy. We also presented a software for computer aided optimization of the reference stations of indoor positioning systems. The software implements an optimization algorithm based on resilience phenomenon and Brownian motion model. The results of simulations carried out for sample room layouts proved the suitability of the proposed approach to finding such locations of the reference stations that maximize positioning quality criteria. However, it must be noted that the resulting reference stations placement depends on the initial positions of the nodes. The goal of the further research is to evaluate results the optimization of reference stations placement for sample real life scenarios. Measurement campaigns verifying simulation results are planned in a university campus buildings. The measurement data will be also used to further adjust the proposed algorithms.

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