Abstract—In most cases indoor local positioning algorithms are not effective enough. RSS-based methods are very sensitive to variations in physical environment dependent on relative positions of furniture, doors, human bodies, etc. The results of ToF-based ranging in closed areas always include additional NLOS-component.

A method of combination of both RSS and ToF approaches is described. Results of conducted indoor experiments confirmed that the accuracy of position calculation significantly increased.

Index Terms—Wireless sensor networks, indoor positioning systems, receive signal strength, time-of-flight, nanoLOC$^{TM}$, IEEE 802.15.4a.

I. INTRODUCTION

Accurate indoor localization of mobile objects with low power consumption is critical for different applications, for example, in hospitals, mines, warehouse management and other services dealing with tracking transport vehicles such as pallets, carts, containers, trailers, etc. [1, 2].

Current local positioning systems based on wireless sensor networks (WSN) can be classified by the method of registration of raw data: Received Signal Strength (RSS), Angle of Arrival (AoA), Time-of-Flight (ToF) and their modifications. Due to the complexity of transceiver schematics and antenna modules stand alone AoA methods are not widely used.

Signal strength approaches are attractive because they can be used in common indoor wireless networks such as WiFi, Bluetooth, etc. The use of Time-of-Flight method needs additional localization infrastructure. Systems which use ToF estimate the range from a receiver to a sender by measuring the signal propagation delay. Although positioning systems based on ToF allow achieving better accuracy, there are situations when errors in measurements are too high.

There are certain wireless technologies which provide ranging both by RSS and ToF methods. One of them is nanoLOC$^{TM}$ standard. This article describes the possibility of combination of both mentioned methods for this technology for better localization.

II. WIRELESS NANOLOC$^{TM}$ (IEEE 802.15.4A) STANDARD

In our experiments we used radio modules with nanoLOC$^{TM}$ transceivers [3] produced by Nanotron Technologies GmbH (http://www.nanotron.com/). This technology is standardized within IEEE 802.15.4a and is positioned in a segment of wireless sensors networks. Its unique feature is automatic distance measuring which makes possible to develop location-aware wireless applications. The declared ranging accuracy is up to 1 meter. NanoLOC$^{TM}$ utilizes ISM 2.4-2.48 GHz radio band. Bit rates of up to 1 Mbit per second can be used for data transfer.

As all technologies in WSN sphere, it also provides low power consumption with several power saving modes. High robustness of radio transmission is achieved due to the special ether signal coding using chirp pulses – 1 microsecond pulses formed by sweeping (rising or falling) frequencies.

Ranging is carried out by one of the variants of Time-Of-Flight method – Symmetric Double Sided Two Way Ranging. Two radio nodes exchange radio frames and register the times of frames transmission, processing and reception. One of the nodes collects the time data and then performs the calculations of the distance between them.

It should be mentioned that high enough distance measurement accuracy is achieved by the usage of chirp pulse autocorrelation technique in a transceiver chip.

III. TYPES OF DISTANCE MEASUREMENT ERRORS

To determine the conditions in which one method is better than another it is necessary to describe the sources of ranging errors. There are several types of them [4].

1) Time dependent internal error in a chipset (as a function of temperature, consumed power, external electromagnetic field, oscillator instability, etc.) ($\Delta R_{time}$). For the nanoLOC$^{TM}$ positioning system the standard error of ToF measurements in open areas is $\approx$1 meter [3].

2) Static error determined by electrical delay in an antenna feeder tract ($\Delta R_{antenna}$). For the majority of antennas with short enough cable the value of the error is from 0 to 1 meter.
3) Environment-dependent error connected with non-line-of-sight (NLOS) signal propagation (the result of the physical arrangement of objects e.g., furniture, walls, human bodies) ($\Delta R_{NLOS}$). NLOS leads to large positive errors in the ToF estimate.

4) Environment-dependent error connected with shadowing (the attenuation of a signal due to obstructions (e.g. furniture, walls) that a signal must pass through).

The first three errors are specific for ToF methods, the third (partly) and forth – for RSS.

**IV. TOF BASED LOCALIZATION**

The combination of factors listed above leads to the large positive error in the ToF estimate. That is why distance measurement between an access point and a mobile unit is always more or equals to the true distance.

The set of ToF measurements consists of distances form static access points at predefined positions. The mobile unit location can be calculated by trilateration.

On the one hand, with the use of nanoLOC™ WSN the area of the circles intersection can be used as a location of the mobile unit, i.e. the localization algorithm reveals only an area that contains the mobile unit (grey area on figure 1, area-based approach). On the other hand it is possible to clarify the mobile unit position inside this area with the use of additional algorithms (point-based approach).

NLOS makes the main contribution in ToF measurement errors. In office environment with high density of different objects, NLOS error might be more than 10-15 meters [5]. In tracking the movement of mobile object this error can be reduced by applying different smoothing and filtering methods. One of the most popular algorithms for ToF is Kalman filtering and its modifications (biased Kalman filter, etc) [6, 7, 8] which help to mitigate NLOS error. However the effective use of Kalman filtering is possible only when ranging is frequent enough. In large systems with many mobile objects network traffic can be critically high. In order to save the radio ether measurements should be taken less frequently (every 5 seconds or more). Therefore it is difficult to filter NLOS errors for movement at velocities of 5-10 km/h and as the consequence the positioning accuracy decreases. In this case Non-linear Least Squares NLS, Weighted Non-linear Least Squares, Maximum Likelihood ML, Gaussian ML GML algorithms are frequently used [9].

The applied positioning algorithms, methods of accuracy increase, proposals for use of ToF-based ranging and description of experiments are described in more details in [10].

**V. RSS BASED LOCALIZATION**

As mentioned above the main source of errors in RSS measurements is signal shadowing. The accuracy of positioning calculations depends on the correct choice of applied algorithms. All RSS algorithms can be divided into two groups [9].

1) Lateration Based Algorithms.

The between transmitter and multiple receivers are estimated using a model of a signal-to-distance effect on RSS (the ensemble mean power at distance $d$ is typically modeled as

$$P(d) = P_0 - 10n_p \log \left( \frac{d}{d_0} \right),$$

where $P_0$ is the received power (dBm) at a short reference distance $d_0$. Knowing the distances between static reference modes and the mobile node, its position can be calculated by trilateration.

2) Classification Based Algorithms (matching algorithms). The goal of these algorithms is to match RSS observations to an existing signal map. This type of algorithms includes two phases. The first phase is called the offline phase in which the RSS from all access points is registered at a number of locations in the building, i.e. generating a “fingerprint” of all the access points at each specific location. The second phase is called the online phase, where the obtained information about signal strengths is used to calculate the location of mobile unit by comparing the registered RSS from the mobile unit with the one recorded in the offline phase [11].

Signal shadowing is critical for the algorithms of the first type. Since RSS-distance dependency in real environment with obstacles differs from the (equation 1), algorithms of this type are applied only in open areas.

The algorithms of the second type demonstrate better accuracy in the case of signal shadowing and NLOS conditions [9]. Although walls and other obstacles can severely decrease signal strength, in a particular environment objects are predominantly stationary and it is possible to use environment as a source of additional information for localization. The necessity to collect initial data during the offline phase and to recalibrate signal map in the case of environment change is the main drawback of these algorithms.

It should be mentioned that in complex environment with high NLOS errors there are situations when RSS based algorithms can demonstrate better accuracy than ToF based algorithms.
VI. THE APPLIED RSS LOCALIZATION ALGORITHM

The modification of the Area Based Probability algorithm [12] was used for the location calculation.

A. Mathematical model

The positioning system consists on \( k \) access points at known positions and a mobile unit.

Let an area consists of a finite set \( X \) of tiles. For each tile \( x \in X \) for a mobile unit inside the tile it is possible to measure the signal strength between the mobile unit and each access point.

Let \( s = (s_1, \ldots, s_k) \) is a vector of measurements for each tile, where \( s_i \) is the measurement of RSS from \( i \)-th access point. We assume that the components of vector \( s \) belongs to a discrete finite set of values. In the present model the components of vector \( s \) are jointly independent for each tile \( x \in X \).

For the given vector \( s = (s_1, \ldots, s_k) \) it is necessary to determine a tile with maximum conditional probability \( P(x \mid s) \):

\[
x^* = \arg \max_x \left[ P(x \mid s) \right],
\]

where \( P(x \mid s) \) is the probability of a mobile unit to be in a tile \( x \) under the condition that signals vector \( s \) was measured.

Using Bayes’ rule

\[
P(x \mid s) = \frac{P(s \mid x) P(x)}{P(s)}
\]

With no prior information about the exact location of the mobile unit, assume that it is equally likely to be at any tile of the set of possible tiles (i.e. \( P(x) \) are the same for all \( x \)).

Thus, for the given vector \( s \)

\[
P(x) = \frac{P(x)}{P(s)} = \text{const.}
\]

Therefore,

\[
\arg \max_x \left[ P(x \mid s) \right] = \arg \max_x \left[ P(s \mid x) \right].
\]

Since components of vector \( s \) are independent,

\[
P(s \mid x) = P(s_1, \ldots, s_k \mid x) = \prod_{i=1}^{k} P(s_i \mid x).
\]

Let \( s_i = 0 \) if there are no signals measured from \( i \) access point. In practice it is necessary to use only those indexes \( i \) for which \( s_i > 0 \):

\[
P(s \mid x) = \prod_{i, s_i > 0} P(s_i \mid x).
\]

If the situation with \( s_i = 0 \) happens because of technical failure of \( i \) access point these values must be discarded.

All these calculations are carried out during the online phase of the method.

B. Offline phase

The \( P(s_i \mid x) \) estimates can be determined by initial system training.

Let \( \Omega \) – is an entity of vectors with RSS values for all tiles measured during preliminary experiments, \( \Omega(x) \) – is an entity of vectors with RSS values for each tile \( x \in X \).

Therefore,

\[
\Omega = \bigcup_{x \in X} \Omega(x).
\]

For each \( j \in \Omega(x) \) let \( s' = (s'_{j1}, \ldots, s'_{jk}) \) – is a vector of signal strengths measured during \( j \)-th experiment for each access point.

The estimation of RSS mean is determined as an average value of measured signals strengths \( s'_{ji} \) for each access point:

\[
a_i(x) = \frac{\sum_{j \in \Omega(x)} s'_{ji}}{\left\{ \{ j \mid j \in \Omega(x) \& s'_{ji} > 0 \} \right\}}, \quad i = 1, \ldots, k, \quad x \in X.
\]

Let \( a_i(x) = 0 \) if there are no measurements for \( x \) tile from \( i \) access point.

The discrete random variable \( s_i \) for \( x \in X \) tile is approximated by normal distribution \( N(a_i(x), \sigma) \). Therefore the probability for \( s_i \) is given as:

\[
P(s_i = y \mid x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(y - a_i(x))^2}{2\sigma^2}}.
\]

The standard deviation \( \sigma \) is chosen experimentally.

C. Approximation of signal strength parameters

In real environment it is very hard to perform the offline phase for all tiles. In this case approximation of signal strength parameters for neighboring tiles can be used.

Let \( \delta(x) \) – the set of neighbors for \( x \in X \) tile, \( \delta(x) \subset X \).

If \( a_i(x) = 0 \) for the given \( x \in X \), then \( a_i(x) \) is taken as an average of positive values of \( a_i(y) \), where \( y \in \delta(x) \):

\[
a'_i(x) = \frac{\sum_{y \in \delta(x)} a_i(y)}{\left\{ \{ y \mid y \in \delta(x) \& a_i(y) > 0 \} \right\}}, \quad i = 1, \ldots, k, \quad x \in X.
\]

New \( a'_i(x) \) values can be used instead of old zero values \( a_i(x) \).

VII. RSS LOCALIZATION EXPERIMENTS

The experiments to test the proposed RSS localization algorithm indoors were carried out in the office of IT-park of Petrozavodsk State University. The size of the office is 24x14 meters. It includes two corridors (C1 and C2) and three rooms (R1, R2 and R3). Five access points (APs) were installed as shown in figure 2.

All the area was divided in 3x2 meter tiles. The size of a tile was chosen so that it would be possible to distinguish different parts of rooms. During the offline phase the mobile
unit was moved from one tile to another and signal strengths were measured between the mobile unit and each access point. It should be mentioned that signal power was high enough and all access points can register RSS values from the mobile node in any tile.

To provide reliability the experimental data for 60 RSS measurements were collected during 1 minute for each tile. RSS dynamic range consisted of 26 grades (from 63 to 38 in relative units), where 63 corresponds to maximal signal strength and 38 – to minimal signal strength. The majority of the registered values were in the range form 52 to 60.

An example of a signal strength map (average values) for access point AP1 is shown in figure 3.

After the offline phase the experiments on position accuracy estimation were carried out. Experimental traces within the office area were registered. For each trace point it was necessary to estimate the positioning error.

In order to evaluate algorithms efficiency the percentage of coincidence of the trace point with certain tile was calculated. The size of a tile was varied as shown in table 1. Three cases were studied: small tiles (2m x 3m), middle tiles (6m x 3m), and tiles matched to rooms.

The best result (84 % of correct tile determination) was obtained when the borders of a tile correspond to the rooms borders. Even in this case we failed to achieve 100% efficiency due to several reasons including insufficient RSS dynamic range for used transceivers, complexity of 3D radiation pattern of internal antennas, and other information which should be regarded during the offline phase.

In order to test the proposed approximation in the experiment described below the offline phase was carried out only for several selected tiles (grey rectangles in figure 4). The RSS values for white rectangles were calculated according to the formulas above.

The results of positioning with RSS based algorithm in this case are shown in Table 2.

These results reveal the slight decrease of percentage of correct tile determination for room sized tiles. Therefore the proposed approximation can be successfully applied in the case of insufficient training data. Moreover the duration of the offline phase can be substantially shorter.

Resuming all RSS localization experiments it should be stated that the position accuracy was not enough to apply them in navigation systems. However unreliable data can be used for clarification of position inside the area given by ToF based methods.
VIII. COMBINATION OF RSS WITH TOF BASED LOCALIZATION

A combination of both ToF and RSS methods was applied for better localization.

Consider an example with tiles of small size (2x3 meters). The typical circles corresponding to the measured distances using ToF method from access points Ap2, Ap4 and Ap5 are shown in figure 5. It is possible to use ToF measurements to choose the exact tile from several tiles with approximately the same probability. Let tile T1 has probability of 0.44, tile T2 has probability of 0.41 and tile T3 has probability of 0.35. The true location of the mobile unit is in point L (inside tile T3). If we apply only RSS based algorithm tile T1 is determined as the location of the mobile unit. With the use of ToF measurements tiles T1 and T2 are filtered because they are out of the circle from Ap1 and the mobile unit is positioned into tile T3.

Moreover, if there are several tiles with equal or similar probability within the circles limited area, one of them may be chosen as the most probable point according to another positioning algorithm.

The next example of the RSS and ToF methods combination is shown in figure 6.

ToF data can be used for clarifying a position of a mobile unit inside a tile. Let tile T3 has the highest probability from all possible tiles. With the use of distance measurements form access points Ap1, Ap2 and Ap3 it is possible to clarify a location area inside the tile T3. In figure 6 this clarified area is the intersection of the tile T3 area and the circle from access point Ap4.

IX. CONCLUSION

RSS provides additional information which can be used for positioning in TOF systems and vice versa. Such information can be especially useful in office environment, where NLOS conditions are critically harmful for TOF measurements. Due to the different obstacles (walls, furniture) signal strength changes significantly even for two adjacent spatial points. These conditions are more preferable for the offline phase of the RSS classification based algorithms.

The application of the described classification based algorithm for signal strength in the office environment allows distinguishing 3x2 meter tile with the probability of 63%. The better results of tile recognition were observed when the border of tiles corresponds to the border of rooms or corridors. The probability of 84% of correct tile recognition was achieved for such situation.

In the case of infrequent ranging it is impossible to apply filtering techniques which help to mitigate NLOS errors. In particular indoor environment when contribution of this error is of order of several meters the 95% positioning accuracy reach more than 6 meters with the use of ToF method only. The combination of RSS and ToF based approaches for room sized tiles allows achieving the localization accuracy of less than 2 meters with 95% probability in the same conditions.

The results of positioning accuracy calculation (error cumulative distribution function) with the use of ToF based, RSS based, and the combination of RSS and ToF based approaches in the office environment are shown in figure 7.

The lower bound of accuracy for RSS based algorithm relates to the size of a tile. Therefore it is impossible to define the error cumulative distribution function when error value is low enough. As we can see from the plot the use of the RSS based algorithm demonstrates low accuracy. In this case the 90% error is more than 7 meters.

ToF only algorithm gives ≈4 meters accuracy of positioning with 90% probability, but the combination of ToF with RSS localization increases the accuracy by 2.5-3 times.
Further work will be devoted to the increasing the RSS algorithms effectiveness by accounting information about antennas directivity, walls configuration, and using more complex mathematical models.

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