Estimation of Position and Orientation of Mobile Systems in a Wireless LAN

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Abstract-In this paper, a method to estimate position and orientation of a mobile system in an indoor scenario is described. The proposed method for localizing the mobile system is based on the use of signal strength values of WLAN access points in range. A radio map based method and Euclidean distance in combination with Delaunay triangulation and interpolation is proposed. The radio map method is divided in two phases. In the initial calibration phase, the radio map is built by moving around and storing signal strength values of an omnidirectional antenna and a beam antenna at various predefined points of the indoor environment. In the localization phase the mobile system moves in the same environment and the localization engine estimates position and orientation of the system. The main disadvantage of radio map based methods is the high manual effort to build the map in the calibration phase. The use of Delaunay triangulation and interpolation allows a radio map with a low density of calibration points and reduces the time for manual generation of the map. The paper presents the experimental results of measurements in an office building.

I. INTRODUCTION

Navigation is a key ability of mobile systems. The task of navigation can be divided into localization and path planning. Aim of localization is to estimate position and orientation of a mobile system with respect to its environment. The problem is called global localization, if there is no priori estimate of position and orientation.

Nowadays mobile systems often are equipped with IEEE 802.11 WLAN adapters, in order to communicate with computers or other mobile devices. Furthermore, many buildings are already equipped with an IEEE 802.11 WLAN infrastructure, as a popular and inexpensive technology. Most WLAN adapters are able to measure the signal strengths of received packets, as part of their standard operation. The signal strengths of received packets vary noticeably by changing the position. Thus, the signal strength can be used to estimate the position of a mobile device by cheap technology.

Several methods for localization in WLAN environments have been developed. In [1] a radio map and a Bayesian algorithm is used to estimate the position of a mobile system. Other Approaches uses Kalman filters [2], Monte-Carlo algorithms [3], statistical learning [4] or Fuzzy [5], [6] to improve the accuracy of the estimation. All of these methods estimate only the position, but not the orientation of the mobile system. In this paper, the problem of global localization is solved using the WLAN infrastructure in an indoor scenario. It extends the existing WLAN localization techniques in two ways. First, it describes a technique for estimating the orientation of a mobile system. A measured set of signal strength values of an omnidirectional antenna and a beam antenna is compared with a radio map in order to estimate position and orientation of a mobile system. Second, Delaunay triangulation and interpolation is proposed in order to reduce the density of the calibration points in the radio map and thus minimizing the manual effort to build the map.

II. POSITION ESTIMATION IN A WLAN

Different techniques exist to locate a mobile device in a wireless network. The general techniques can be described as follows [7]:

- *Cell-of-Origin*: This technique is easy to realize and determines the access point (AP) to which the mobile device is currently connected. Due to the known position and AP range a relatively exact position can be determined. Since mobile devices know the MAC hardware address of the AP which they are connected to, this technique can be used in every wireless infrastructure.
- *Received Signal Strength (RSS)*: In this technique the position of a mobile device is estimated using the RSS values received from APs in range. The estimation is more accurate than in Cell-of-Origin. Most modern mobile devices are able to monitor the RSS values of packets received from APs in range.
- *Time-based*: This techniques is more accurate than RSS or cell-of-origin. The position is determined according to the time of a received signal. A disadvantage is the need for a precise clock in the mobile device for synchronization. This technique require a more expensive wireless network infrastructure which is usually not present in today's installations.

The proposed approach for localizing the mobile system is based on the use of RSS, because this technique can be used in most of today's WLAN installations.

III. CHARACTERISTIC OF RECEIVED SIGNAL STRENGTH

A. Measurement of Signal Strengths

Most mobile devices are able to monitor the RSS values of packets received from APs in range as part of their standard operation. There are two kinds of scanning modes: passive scanning and active scanning. In passive scanning mode, the WLAN card is put into monitoring mode and waits

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for incoming packets. In active scanning mode, the mobile device sends a probe request packet on every frequency and waits for the probe response packets of the APs in range. Active scanning is an important feature in WLAN positioning, because it obtains new RSS values of all APs in range at the time of scanning.

B. Modeling of Signal Strength

The propagation model of RSS depends on the free space loss of the signal. The free space loss F is defined as

$$F = \frac{P_{\text{Rx}}}{P_{\text{Tx}}} = \left(\frac{c}{4\pi d f}\right)^2 = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1}$$

where P_{Rx} is the power of the received signal, P_{Tx} is the power of the transmitted signal, *c* is the speed of light, *f* is the frequency of the signal, *d* is the distance to the sender and λ is the wavelength of the signal. Equation (1) can be expressed in logarithmic scale:

$$F/dB = 10 \log_{10} \left(\frac{P_{Rx}}{P_{Tx}} \right)$$
(2)
= -32.4 - 20 \log_{10}(f/MHz) - 20 \log_{10}(d/km)

where the unit of f is MHz and the unit of d is km.

In an indoor environment, where multi path effects occur, equation (2) leads to the log distance path loss model [8],

$$P_{\rm Rx}/\rm dBm = P_0/\rm dBm - 10\,\gamma\,\log_{10}\left(\frac{d}{d_0}\right) \tag{3}$$

where P_0 is the RSS at the distance d_0 and γ is the path loss exponent. Parameters P_0 , d_0 and γ have to be adapted to the geometry of every room in the building. Fig. 1 compares the



Fig. 1. Propagation model versus real measurements

log distance model with measurements in an office building. It shows, that there are several measurements with equal RSS values at points with distances of more than 10 m.

The propagation model is sensitive to disturbances as reflections, diffractions and multi-path effects. The signal propagation depends on building dimensions, obstructions, partitioning materials and surrounding moving objects. This problem makes the use of a propagation model for accurate localization in an indoor environment almost impossible.

IV. LOCALIZATION APPROACH

The proposed method for localizing the mobile robot is based on the use of RSS values of WLAN APs in range. A radio map based method and Euclidean distance in combination with interpolation is used, because of the described reasons. A measured set of RSS values of the omnidirectional antenna and the beam antenna is compared with the radio map. The radio map is built in an initial calibration phase and contains measured sets of RSS values at various predefined points (x, y, θ). In the experiments, four orientations (0°, 90°, 180°, 270°) at every position are stored. In the localization phase, RSS values of several APs are recorded and compared with the radio map. One observation in both phases consists of RSS values of both antennas and all APs. Values of APs out of range are set to a minimal value $c_{\min} = -100$ dBm.

A. Euclidean distance

The Euclidean distance is a metric to compare the observations of the localization phase with the radio map. The Euclidean distance between two points $P = (p_1, p_2, ..., p_n)$ and $Q = (q_1, q_2, ..., q_n)$, is defined as:

$$d = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \dots + (p_n - q_n)^2}$$
(4)
= $\sqrt{\sum_{i=1}^n (p_i - q_i)^2}$

In WLAN localization the calibration data are compared with the measured data:

$$d_{j} = \sqrt{\sum_{i=1}^{n} \left(c_{j}^{AP_{i}} - s^{AP_{i}} \right)^{2}}$$
(5)

where $c_j^{AP_i}$ is the RSS value of AP_i at point *j* in the radio map, s^{AP_i} is the measured RSS value of AP_i and *n* is the total number of APs. The Euclidean distance d_j is a metric for the distance between the calibration data $c_j^{AP_i}$ and the measured data s^{AP_i} . After calculating d_j for all calibration points, there will be at least one point with minimal d_j . One approach is to declare this point to be the estimated position and orientation of the mobile system. The accuracy of this method depends beside other factors on the density of the underlying grid of calibration points.

The proposed method for estimation of position and orientation uses interpolation in order to reduce the density of the calibration grid. The set of points (x_i, y_i, θ_i) in the database is arranged by the Euclidean distance. The estimated orientation $\hat{\theta}$ is interpolated with values of the beam antenna. The orientations are weighted and interpolated vectorial:

$$\hat{\theta} = \operatorname{atan2}\left(\sum_{j=1}^{J} \frac{1}{d_j} \sin \theta_j, \sum_{j=1}^{J} \frac{1}{d_j} \cos \theta_j\right)$$
(6)

where J is the number of weighted orientations (with least Euclidean distance) and d_j is the Euclidean distance between measured RSS values from the beam antenna and stored RSS values in the radio map. The function atan2 is used in order to interpolate the orientation in the range from $-\pi$ to π .

Interpolation of the estimated orientation allows a relatively low density of orientations in the calibration phase. In the experiment, only four orientations ($\Delta 90^{\circ}$) are stored in the database for every location.

B. Interpolation of the position with lines of constant signal strength (isolines)

The main problem of radio map based localization systems is the manual generation of the map [9]. In order to reduce the manual effort to build the map, the density of calibration points should be as low as possible [10]. Thus, the interpolation of the estimated position is proposed. In this case a lower density of calibration points is possible. The interpolation is based on Delaunay triangulation and lines of constant signal strength (isolines). For interpolation purposes of the position only the signals of the omnidirectional antenna are used. With Delaunay triangulation a network of triangles for a set of points (nodes) in the plane is developed, such that no point is inside the circumcircle of any triangle [11]. The nodes are represented by the calibration points. Fig. 2 shows the Delaunay triangulation of an office floor, where the experiments are performed.



Fig. 2. Delaunay triangulation of the 2nd floor of the Computer Science Department

ith least whole area of triangulation. Fig. 3 shows the isolines of AP_1 , between Fig. 4 shows the isolines of AP_2 .



Fig. 3. Lines of constant RSS (isolines) for AP1



Fig. 4. Lines of constant RSS (isolines) for AP22

Given a measured RSS value of one AP, triangles whose nodes show RSS values higher and lower than the measured value can be selected. Linear interpolation between node values within the triangle delivers a more detailed radio map consisting of a surface of interpolated RSS values over the triangle. Moreover, it is possible to calculate an interpolated line of constant RSS (isoline) within the triangle and in the Given two RSS values of different APs it is possible to select triangles whose interpolation surfaces include the according isolines. If there is an intersection of both isolines, the intersection point within the triangle can be calculated. Fig. 5 shows the merged radio map for AP_1 and AP_2 . There are two points of intersection in the radio map for this measurement.



Fig. 5. Merged radio map for AP₁ and AP₂

The estimated position (\hat{x}, \hat{y}) is calculated with weighted points of intersection:

$$\hat{x} = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i}, \qquad \hat{y} = \frac{\sum_{i=1}^{N} w_i y_i}{\sum_{i=1}^{N} w_i}, \tag{7}$$

where w_i is the weight of intersection x_i, y_i and N is the total number of intersections. Experiments have shown, that measuring positions closer to APs are more reliable than those in larger distance (see Fig. 1). Hence, the weight w_i of intersection i is calculated with the RSS values of the crossing isolines:

$$w_i = (s_{i,1} - s_{\min})^2 + (s_{i,2} - s_{\min})^2$$
 with $s_{\min} = -100 \, dBm$
(8)

where $s_{i,1}$ and $s_{i,2}$ are the RSS values of the isolines at intersection *i* and s_{\min} is the lowest possible RSS value.

The test bed is characterized by a coarse grid consisting of triangles of large sizes (Fig. 2). The existing WLANinfrastructure was used for the measurements. Triangles are set up by a Delaunay triangulation using calibration points as nodes of the triangles. Fig. 2 shows some unsuitable triangles, e.g. triangles covering an area outside the building. Thereby triangles and points of intersection had to be eliminated from the calculation of the estimated position. The elimination of points of intersection was performed using an acceptance circle. As center of this circle the balance point of a most 'suitable' triangle was assumed. For each triangle the sum of the Euclidean distance of the RSS values of the triangles three nodes are calculated. The triangle with minimal s was assumed to be the 'best' triangle. The largest edge of this triangle was taken as radius of the circle. All intersection points outside of the acceptance circle were excluded from the weighted mean calculation (Fig. 6). Filled circles represent calibration points. Lines with numbers show



Fig. 6. Radio map with isolines

isolines with according RSS values. The red circumscribed acceptance circle is shown covering the 'best' triangle. The small green circle close to the right node of the 'best' triangle represents the estimated position.

V. EXPERIMENTAL SETUP

A. Hardware

The experiments are carried out with a mobile robot Pioneer3-AT manufactured by ActivMedia (Fig. 8). The robot is equipped with an embedded computer for real time robot control and an additional PC with two WLAN cards for communication and localization. One WLAN card is connected to an omnidirectional antenna, the other card is connected to a beam antenna. The directionality of the beam antenna is used to estimate the orientation of the robot.

B. Software

A robot server is included in the operating system of the embedded computer. It manages the low-level tasks of robot control and operation, including motion and odometry. For programming purposes ActivMedia provides the toolkit ARIA (ActivMedia Robotics Interface for Application) [12]. ARIA provides an interface to control the robot's velocity, orientation, relative orientation, and provide detailed information about odometry and operating conditions from the mobile robot.

The operation system on the PC is SuSE Linux, which offers support for wireless communication by the wireless extension (WE). WE is an application programming interface



Fig. 7. User interface



Fig. 8. Pioneer3-AT

(API) allowing a user space program to configure a WLAN driver and receive statistic information.

The software is divided into three parts: a localization engine, a graphical user interface (GUI) and a database module. The GUI is used for monitoring the information to the user (Fig. 7). The communication between GUI and localization module is build with TCP/IP sockets. The database module stores the position of the system along with the APs in range and RSS values. The communication between database module and localization engine is based on TCP/IP. The database module runs on a Linux PC.

VI. EXPERIMENTAL RESULTS

Experiments are performed in an office building of the Computer Science Department. Fig. 2 shows a map of the building where measurements are conducted. With experiments, position estimations with errors in a range from 1 to 5 m are achieved. The accuracy depends directly on the position of the APs in range. At the margins of the radio map, the accuracy is mostly not as good as inside the map, where more APs are in range. In this case, a deviation between real position and estimated position of 1.5 m can be achieved in most estimations. For a good and reliable estimation, three ore more APs in a short distance are required. The placement of additional APs increases the accuracy of the estimation. Fig. 9 shows the RSS values of the beam antenna from three APs in four orientations (0°, 90°, 180°, 270°) of the mobile system. Not all RSS values differ equably with the orientation. The RSS values of the blue arrows (-70 dBm, -70 dBm, -64 dBm, -73 dBm) depend not as much on the heading as the RSS values of the green (-77 dBm, -80 dBm, -77 dBm, -66 dBm) and red



Fig. 9. RSS of 3 APs in 4 headings (calibration point 5)

arrows (-76 dBm, -67 dBm, -58 dBm, -68 dBm). The positions in the building have not all the same variation of RSS values over the orientation. This is caused by large reflections and multi-path effects at some positions. Hence, the accuracy of the estimation of the orientation depends on the position. Fig. 10 shows the RSS values of a point in the radio map,



Fig. 10. RSS of 3 APs in 4 headings (calibration point 1)

where the variation of the RSS values over the heading of the robot is small. This leads to a larger estimation error in the heading, when the robot moves near to this position.

VII. CONCLUSION AND FURTHER WORK

This paper has presented a method for estimating position and orientation of a mobile system. The method is based on a radio map and uses RSS values of WLAN APs in range. In order to reduce the density of calibration points in the radio map, Delaunay triangulation is used to interpolate the position of the mobile system. The density of calibration points is much lower compared to other methods published in the literature. This reduces the manual effort to build the map significantly. Furthermore the estimation of the orientation of a mobile system with the help of a beam antenna was presented. The orientation is estimated using Euclidean distance and interpolation. Since the accuracy of the estimation depends highly on the positions of the APs in the environment, the placement of the APs has to be optimized, in order to get a good and reliable position estimation.

In future work the accuracy of the estimation should be improved by using a Kalman filter or a Monte Carlo particle filter. Furthermore the accuracy may be improved by fusion with position information obtained from other sensor e.g. odometry, sonar or laser.

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