An indoor Bluetooth-based positioning system: concept, Implementation and experimental evaluation

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Abstract
This paper presents the experimental evaluation of a Bluetooth-based positioning system. The method has been implemented in a Bluetooth-capable handheld device. Empirical tests of the developed considered positioning system have been realized in different indoor scenarios.

The range estimation of the positioning system is based on an approximation of the relation between the RSSI (Radio Signal Strength Indicator) and the associated distance between sender and receiver. The actual location estimation is carried out by using the triangulation method. The implementation of the positioning system in a PDA (Personal Digital Assistant) has been realized by using the Software “Microsoft eMbedded Visual C++ Version 3.0”.

Keywords:
position estimation, indoor positioning, Bluetooth

1 INTRODUCTION

In recent years, position based services becomes more important. Several application in the area of m-commerce are depending on a well estimated position of customers in wireless networks. For example, an advertisement in large stores or a guidance in museums with handheld devices is only feasible if a precise position estimation of the mobile terminal. Furthermore, automatic handover procedures based on the user location are necessary to provide quality of service in wireless networks especially in cases of traffic overloads.

The Bluetooth specification developed by the SIG (Special Interest Group) presents a technology which is well suitable for future application in the indoor area [1]. Therefore, this paper deals with issues related to the location estimation and presents the development and evaluation of a Bluetooth-based indoor positioning system. The position estimation occurs in the mobile terminal without the need of changes in the already fixed installed network topology. The developed system is based on the known and already published triangulation methods using the received signal power strength of the surrounding Bluetooth access points.

For a precise position estimation, the dependence between the distance and the received signal strength has to be determined. Especially in the indoor area, boundary conditions like reflections and wall damping make the use of the equation for the free-field propagation impossible. Therefore, the required calculations of the distances are estimated by an approximation of the *Received signal Strength Indicator* (RSSI) [1]. Since the Bluetooth device do not provide any interface to extract the real received signal strength, our developed positioning system is using the RSSI value provided as defined in the standard in order to derive a range estimation between an access point and a mobile terminal.

The paper is organized as follows. In the next two sections we introduce the mathematical methods on which the positioning system is based. We starts with the position estimation based on signal strengths using LSE (least squares estimation), followed by a section about the convertion of RSSI measurements to a distance. Afterwards, the implementation is briefly documented in section 4. Finally, the results of empirical tests are presented.

2 Position Estimation Based on Signal Strength

In the following a position estimation method based on signal strength using LSE is introduced.

Assume $N \geq 2$ is the number of base stations in a mobile communication network and the position of a base station k is defined by $\vec{p}_k = (x_k, y_k)^T, k \in 1..N$. It follows, that the distances $r_i(\vec{x}), r_j(\vec{x})$ between the base stations *i, j* and a point in the x-y-plain, given by $\vec{x} = (x, y)^T$:

$$\begin{cases} r_i(\vec{x}) = \sqrt{(x-x_i)^2 + (y-y_i)^2} \\ r_j(\vec{x}) = \sqrt{(x-x_j)^2 + (y-y_j)^2} \end{cases}, \quad (1)$$

The solution of the equation system (1) results in two possible intersections of the corresponding circles. Therefore, in order to derive a unique solution it is necessary to calculate the position of a mobile device based on the distance between the terminal and at least three different base stations. The single distances can be determined by the functional correlation to the signal strength (s. section 3).

If the distances between a number of $N>2$ base stations and a mobile terminal are already known the position estimation can be efficiently calculated by using the LSE method. In the numerical operations this method computes that point in the x-y plain which position provides the least square sum of the distance to all possible section boundaries given by equation (2).

$$\begin{cases} r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} \\ r_j = \sqrt{(x-x_j)^2 + (y-y_j)^2} \end{cases}, i, j \in 1..N \quad (2)$$

The section boundaries are derived from (3)

$$r_i^2 - r_j^2 = (x - x_i)^2 + (y - y_i)^2 - (x - x_j)^2 - (y - y_i)^2 \quad (3)$$

We assume that the position estimation is defined by $\vec{m} = (\hat{x}, \hat{y})^T$. Then $\vec{m}$ is calculated by:

$$H \cdot \vec{m} = C \quad (4)$$

with

$$H = \begin{bmatrix} h_{x(2,1)} & h_{y(2,1)} \\ \vdots & \vdots \\ h_{x(N,1)} & h_{y(N,1)} \\ \vdots & \vdots \\ h_{x(N,N-1)} & h_{y(N,N-1)} \end{bmatrix}_{\binom{N}{2} \times 2}, \quad \vec{m} = \begin{bmatrix} \hat{x} \\ \hat{y} \end{bmatrix}, \quad C = \begin{bmatrix} c_{2,1} \\ \vdots \\ c_{N,1} \\ \vdots \\ c_{N,N-1} \end{bmatrix}_{\binom{N}{2} \times 1}$$

and

$$\begin{cases} h_{x(i,j)} = 2(x_j - x_i) \\ h_{y(i,j)} = 2(y_j - y_i) \\ c_{i,j} = r_i^2 - r_j^2 + x_j^2 - x_i^2 + y_j^2 - y_i^2 \end{cases}$$

Hence, the location estimation of the terminal is determined by:

$$\vec{m}^T = (H^T H)^{-1} H^T C \quad (5)$$

3 Approximation of RSSI-Measurements

For converting the signal strength measurement to distances between a sender and receiver in free-fields, the equation

$$s(\vec{x}) = c(d(\vec{x}))^{-\alpha} \quad (6)$$

introduced in [7] is valid.

Fluctuations of the signal propagation in indoor areas caused by fading, shadowing and reflections are considered by (6). Because of no line of sight restrictions and the effects (reflection and attenuations) due to the person who holds a Bluetooth device, the equation for signal propagation in free-fields is not suited for the indoor area. Therefore we decide to approximate the correlation between the signal strength and the distance based on measurements in order to improve our estimation. The Bluetooth specification does not provide any possibility to extract the signal strength in a direct way. Therefore, we are using the value of the RSSI defined by the Bluetooth protocol to get a correlation to the distance between sender and receiver in the network [1].

The RSSI value is providing the distance between the received signal strength and an optimal receiver power rank so called *the golden receiver power rank*. The definition of the golden power receiver rang is displayed by figure 1.

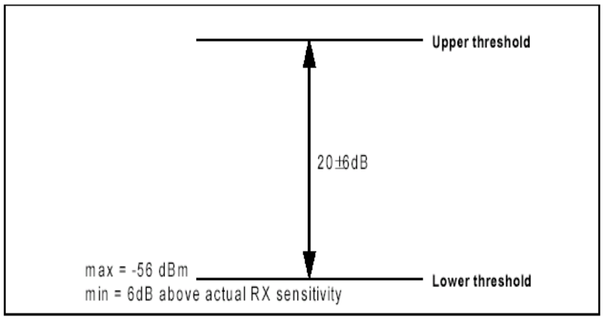

Figure 1: Golden receiver power rank of the RSSI

The golden receiver power rank is limited by two thresholds. The lower threshold is clearly defined by an offset of 6dB to the actual sensitivity of the receiver. The maximum of this value is predefined by -56dBm. The upper threshold is 20dB over the lower one. The accuracy of the upper threshold is about ±6dB.

Assume S assign the received signal strength, the value of S is determined by:

$$S = RSSI + T_0, \text{ for } RSSI > 0$$
$$S = RSSI - T_u, \text{ for } RSSI < 0$$
$$T_0 = T_u + 20dB \qquad (7)$$

where T_0: upper threshold,
T_u: lower threshold.

The definition of the golden receiver rank limits the convertion of the RSSI to a distance. If the value of the RSSI is in the golden receiver range defined by zero no unique function can be approximated. Therefore only measurements which results in a positive range of the RSSI can be considered by a functional approximation.

We are deriving the approximation by choosing the best fitted function given by determining the parameters of one of the following functions

$$y = c \ln x + b,$$
$$y = c_0 + c_1 x + c_2 x^2$$
$$y = c_0 + c_1 x + c_2 x^2 + c_3 x^3 \qquad (8)$$

minimizing the least square sum of the deviations to the RSSI measurements.

4 Implementation of the Bluetooth-Based Positioning System

The prototype implementation of the Bluetooth-based positioning system provides a user interface which is subdivided in three sequences. First, in a preparatory phase the considered indoor area is covered by a defined x-y plain, in a second phase the RSSI function which is fitting the environmental conditions is approximated. In the last phase our software-solution uses the location method described by section 2 in order to determine the position estimation of a mobile terminal based on RSSI-measurements. In this context we are involving the so called triangulation method by applying the mathematical calculations (s. section 2) on the RSSI value of three access point. The flow-chart of the system illustrated by figure 2 presents an overview of the operation breakdown.

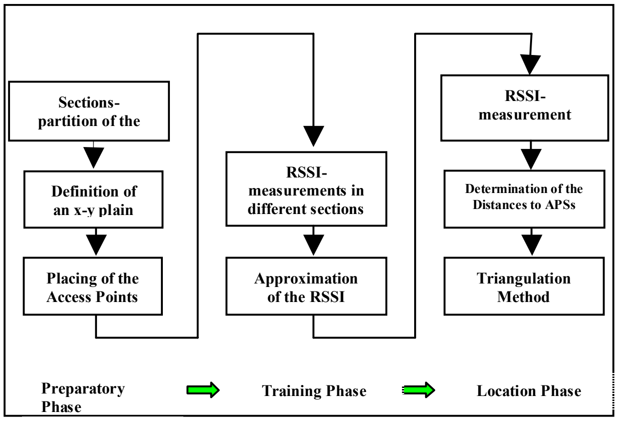

Figure 2: Flow chart of the Bluetooth-based positioning system provides

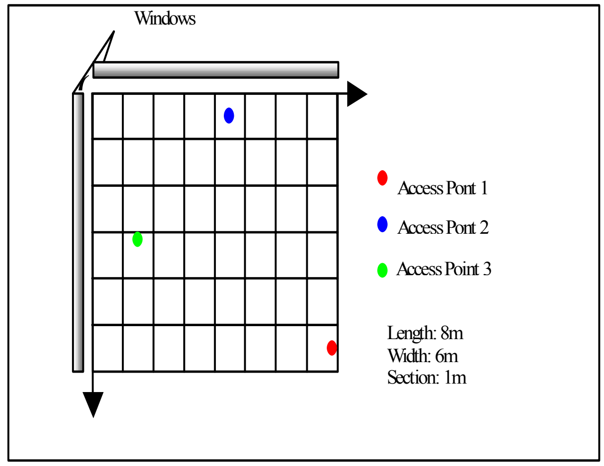

Figure 3: Example of a Bluetooth scenario

The positioning system has been implemented in a PDA of the type Compaq iPAQ Pocket PC H3970 with a Compact Flash card by using the Software "Microsoft eMbedded Visual C++ Version 3.0. The system extracts the value of the RSSI by using the HCI instructions, *HCI_Read_RSSI* of the Bluetooth specification. The accuracy of this value is not standardised and depends on the Bluetooth hardware manufacturer.

5 MEASUREMENTS

In this section we are presenting results based on empirical tests. The implemented system has been tried out in an indoor scenario consistsing of three Bluetooth access point and a PDA which provids the location system. The Bluetooth access points are realized by notebooks equipped with the Bluetooth-modules BT-DG02 of the company EpoX. The access points have been distributed in a laboratory room with a size of 46m^2. The room is portioned in 1m x 1m sections or squares. The scenario is illustrated by figure 3.

To obtain a good approximation function between the RSSI and the single access point distances in a number of randomly chosen sections several measurements have been recorded. The mean of all measurements belonging to one section and access point has formed the reference values of the RSSI in a section. In our scenario the RSSI value of all access points was best fitted by a polynomial function of the order 3 (s. figure 4).

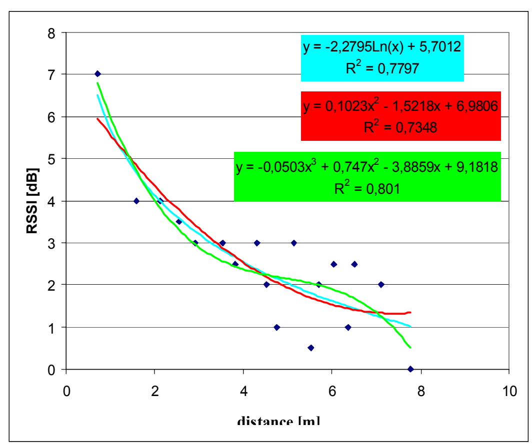

Figure 4: Example of the RSSI approximation of one AP in the tested scenario

Unfortunately, the measurements have shown that the positive value of the RSSI is limited by a distance of maximal 8 m between an access point and the mobile terminal (Note that both the access points and the handheld are of class 2). This restricts the coverage of the positioning system .

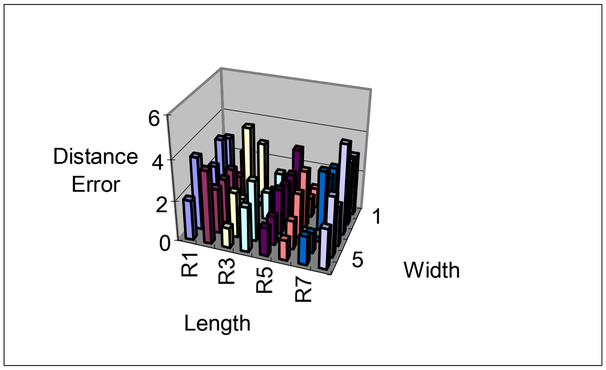

Figure 5: Distance Error over the regional position

The obtained positioning error depending on the regional position is presented in Figure 5. The average is given by a deviation of 2,06 m between the real position of the PDA and the calculated results.

6 CONCLUSIONS

In this paper, we have presented an indoor positioning system based on signal strength measurements, which were approximated by the received RSSI in a mobile device. The triangulation method combined with least square estimation is used to predict the position of the terminal. The functional dependence between the received RSSI and the distance was got by a well fitted polynomial approximation. This function is general restricted by a positive sign of the RSSI. Thus, in the tested scenarios our system has been limited by a distance of less then 8 m between the access points and the mobile device. Additionally, the empirical tests show that the positioning system realize a position estimation of a PDA with a precision (RMS) of 2,08 m. It is expected that the accuracy of the estimation could be increased by combining the method with the results of other kinds of location esitmation. For example, a combination with an inertial system and the development of adequate Kalmann Filter is the object of undergoing works at our institute.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

[1] Specification of the Bluetooth Core System 1.1, www.bluetooth.org

[2] Nathan J. Muller: "Bluetooth", 1. edition, mitp, Bonn, 2001

[3] J. B. Andersen, T.S. Rappaport, and S. Yoshida: “Propagation messurements and models for wireless communications channels“, IEEE Communications Magazine, 33(1):42-49, 1995

[4] Paramvir Bahl, Venkata N. Padmanabhan: “RADAR: An In-Building RF-based User Location and Tracking System”, Proceedings of IEEE INFOCOM 2000, Israel , March 2000

[5] Thomas Fritsch, Kurt Tutschku, Kenji Leibnitz: “Field Strength Predication by Ray-Tracing for Adaptive Base Station Positioning in Mobile Communication Networks”, 2nd ITG Conference on Mobile Communication, Sep. 1995

[6] Yongguang Chen, Hisashi Kobayashi: “Wall Map Aided Indoor Geolocation Based on Signal Strength”, Communications, 2002. ICC 2002. IEEE International Conference on, Volume: 1, 2002, Page(s): 436 –439

[7] M. Hellebrandt, R. Mathar; “Location Trackings of Mobiles in Cellular Radio Networks”, IEEE Transactions and Vehicular Technology 48, Nr. 5, Sept.: 1558-1562