Bluetooth Sensor Network Positioning System with Dynamic Calibration

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Abstract—Positioning systems based on sensor networks is one of the most promising fields in mobile computing. This paper considers the bluetooth standard to locate devices using the RSSI (Received Signal Strength Indicator). The major problem of working with this parameter is its fluctuation that happens very fast due to changes in the environment. These changes can be caused by humidity or temperature, presence and movement of people, opening and closing of doors, multipath effect, etc.... This paper introduces an innovative approach that uses the RSSI information between several fixed wireless beacons to improve the reliability of a Bluetooth positioning system. This information is used to calibrate the sensor responses. The results of several experiments illustrate how the real time calibration improves the precision and the stabilization of the position estimations. Moreover, we show the improvement obtained when increasing the number of beacons.

I. INTRODUCTION

Location systems is one of the most promising fields in mobile computing. Location systems allow developing a new kind of location-aware mobile applications [1], [2], [3]. The most common location systems, Global Navigation Satellite System (GNSS) [4], [5], [6] or positioning provided by mobile phone operators [7], are suitable for outdoor environments where direct line-of-sight respect to the satellites or base stations is available. However, they show poor indoor performance. To obtain good results in indoor environments it is necessary to have multiple reference stations. In particular, ad hoc networks, provide a fine-grained sensor system by using small and inexpensive stations (nodes). There exist many references of ad hoc networks to provide location, based on different technologies and techniques [8] (and references therein).

In addition to 2G and 3G mobile telephony standards, new mobile devices provide other wireless communication technologies such as Infrared [9], Bluetooth [10] or Wi-Fi [11]. Due to the popularization of handsfree devices, Bluetooth is being incorporated to most of the new mobile phones. In order to take advantage of Bluetooth technology, we can consider a bluetooth sensor network to develop the positioning system. In this case, mobile devices are detected through the Received Signal Strength Indication, RSSI. However, the effects of the propagation of signals through the communication channel will cause strong fluctuations in the received signal power with respect to the expression of Friis for free space [12]. The small scale propagation models indicate that in short distances (around the wavelength) there exist remarkable differences in the signal levels. The same signal received in near positions will vary depending on the combinations of the different paths followed by the transmitted signal.

This paper introduces a system that minimizes the impact of the channel variations and stabilizes the RSSI. As in [13], where WiFi 802.11 is used, we consider a calibration of the obtained RSSI in a bluetooth network that takes into account the environmental conditions to calculate the position of a device.

The article is structured as follows: Section II introduces the problem to solve. Section III describes the positioning system, focusing in the signal model, the algorithms and the applied techniques. Section IV shows the hardware implementation and the results of different experiments. Finally, Section V is dedicated to the conclusions.

II. PROBLEM DESCRIPTION

In indoor environments, the propagation of the RF signal is affected by diverse factors: multipath propagation, variations of temperature and humidity, opening and closing of doors, changes in the location of the furniture, and presence and movement of people in the environment. In previous studies it has been verified how the information used for the location of a static device that can vary significantly [13]. A positioning system should be able to adapt itself to the previously mentioned environmental effects.

Our Bluetooth system considers techniques of triangulation based on the information provided by the power of the received signal, RSSI. The system is made by one or more devices that will act as beacons in a fixed and known location. The system will consider the RSSI values received by the device to locate and the received RSSI values between beacons.

In Fig. 1 it is shown the RSSI evolution in 24 hours, received by a device, located in a fixed position, from a beacon of the system. It is observed how the changing conditions of the environment produce significant fluctuations in the values of RSSI. The tests were made in a laboratory where the environment conditions changed during the measuring time: people entering and leaving the room, opening and closing of doors,... In addition, during 24 hours there are changes in the averaged RSSI due to environmental conditions such as temperature, humidity, ... It can be seen that there are hours of the day with small variations, corresponding with the hours

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when there are less people in the laboratory and, therefore, the environment is more stable. However, around midday, there are great variation in those values, due to the activity in the room where the test was made. Also, the same day of the test, the atmospheric conditions varied radically. Due to this fact, it can be observed that the averaged RSSI had a remarkable change between the first and the last hours of the day.

III. LOCALIZATION SYSTEM WITH CALIBRATION

The proposed Bluetooth localization system translates the received RSSI from different beacons into distances that are used to determine the position of a device. Moreover, this translation will consider the received RSSI between beacons in order to take into account environment changes.

This section details the way in which the RSSI is translated into distance and how the final location is calculated.

A. Calibration system

In a classic triangulation system, it is necessary to use the received RSSIs from the beacons at the device (discontinuous lines in Fig. 2), which are processed to get the respective distances. With these distances, and the beacon locations, it is possible to estimate the device coordinates.

In the proposed system, besides the previously mentioned RSSIs, we need the RSSIs between beacons (depicted in Fig. 2 as continuous lines). These measurements are considered in order to let the Bluetooth system compensate the changes due to the channel propagation conditions.

The developed system performs a real time calibration that considers the environment conditions. This is done without the need of previous trainings or calibration stages, as the ones required in systems based on fingerprinting [14]. Our system uses the received RSSI between beacons to determine the mapping between these measures and distances. Since this mapping is made in real time, it considers any change in the environment.

B. Signal model

Considering the availability of \( m \) beacons, let’s define the following matrices of size \( m \times m \):

- \( D \): whose elements are the real distances between the different beacons. The element \( d_{ij} \) is the distance from the beacon \( i \) to the beacon \( j \).
- \( S \): whose elements are the RSSIs between beacons. The element \( s_{ij} \) is the received RSSI by the \( i \)-th beacon from the \( j \)-th.
- \( T \): translation or mapping matrix from RSSIs into distances. The element \( t_{ij} \) is the mapping coefficient between the beacons \( i \) and \( j \).
- \( E \): is the error matrix whose elements are the differences between the real distance and the estimation through the mapping of the RSSI. The element \( e_{ij} \) is the mentioned difference between the \( i \)-th and \( j \)-th beacons.

With all the previously defined variables, the problem consists in minimizing the expression of the error between the RSSI mappings and the real distances between the \( i \)-th and the \( j \)-th beacon as the following expression shows:

\[
    e_{ij} = (d_{ij} - t_{ij}s_{ij})^2
\]

Therefore, by considering matrix notation, the expression of the error can be expressed as

\[
    E = \|D - T S\|^2
\]

From (2), it is easy to obtain the dynamic mapping matrix \( T \) for the case in which the error is 0:

\[
    T = DS^{-1}
\]

To translate the RSSI obtained from the beacons into distance, for the instant \( n \), it will only be needed to use the matrix \( T \):

\[
    d_n = Ts_n
\]
where $s_n$ is a vector with the received RSSIs at the device to be located from the beacons and $d_n$ is a vector with the estimated distances for that instant $n$.

C. Obtaining the coordinates

Once it is achieved the translation from RSSIs into distances, we have to determine the client location. We calculate this by using the mentioned translations and with the beacons coordinates, which are known. There are several ways to obtain the location by triangulation but, in our case, we decide on using a simple descent gradient method.

The used method is based on the minimization of the following expression:

$$
\varepsilon = \frac{1}{2} \sum_{i=1}^{m} (f_d(x_{est}, x_i) - d_i)^2
$$

where $x_{est}$ is the estimated position for the client node, $x_i$ is the position for the $i$-th beacon, $d_i$ is the $i$-th element of the vector $d_n$ (i.e., the estimated distance to the $i$-th beacon), and the function $f_d$ calculates the euclidean distance between two points.

Using the derivative of (5) it can be obtained an iterative expression that updates the client position estimation in the iteration $k + 1$, using the previous one, $k$. The process is repeated until the distance from that position to the beacons is lower than a specific value (in our experiments we chose 0.1 meters or 150 iterations):

$$
x_{est,k+1} = x_{est,k} + \alpha \sum_{i=1}^{m} \left(1 - \frac{d_{est,i}}{f_d(x_{est,k}, x_i)}\right) (x_{est,k} - x_i)
$$

where $\alpha$, which has been set to 0.1 in our experiments, weighs the increment for each step. The initial values of $x_{est}$ are the coordinates of the beacon whose estimated distance is the nearest in euclidean distance. Also, we must clarify that the function $f_d(x_{est}, x_i)$ is 0 in the case in which $x_{est}$ is equal to $x_i$, so, in that case, it is needed to make equal to 0 the whole contribution of the beacon $i$ (to avoid the division by 0).

IV. EXPERIMENTAL RESULTS

The different experiments of the developed system have been made in a research laboratory, which has dimensions of 11.50 x 6.50 m. This environment presents very appropriate characteristics, because its activity and occupation are representative of the indoor communication channels. Inside the laboratory there are multiple obstacles and people who are continuously moving and working there. Therefore, all the phenomenon mentioned in this article will be present, affecting in a remarkable way the RSSI level.

In Fig. 3 it can be seen a laboratory map, where it is observed in grey color the different obstacles due to the furniture. Two experiments have been represented on this plan. Both have a client to be positioned and 4 beacons, numbered from B1 to B4. The difference between these two experiments is the situation of the client. In the first, the client is in the middle of the laboratory and, in the second, the client is near the beacon B2.

A. Hardware implementation

Four independent beacons have been built, composed of the following hardware:

- 1 Linksys Nslu2 with an adapted firmware for this application. This hardware has an ARM Intel Xscale 266MHz architecture, 32MB of RAM, 1 Ethernet port and 2 USB 2.0 ports.
- 1 USB 2.0 mini-hub with 4 downstream ports.
- 2 Bluetooth-USB adapters (Conceptronic CBTU2), which are Bluetooth 2.0 + EDR devices, Class 2, with a CSR4 (Cambridge Silicon Radio BlueCore4-External) chipset, connected to the mini-hub by means of an USB port.
- 1 Wifi 802.11 b/g adapter connected to an USB port. This adapter has a ZYDAS ZD1211B chipset.
- 1 2GB Flash pendrive for storing operations.

The Bluetooth 2.0 devices can use the Inquiry with RSSI mode. This mode of Inquiry was introduced in the version 1.2 of Bluetooth, and allows getting the RSSI level of a device by means of an Inquiry request. All the “visible” devices in the range which are in Inquiry Scan state (even Bluetooth v1.1 devices), will respond this Inquiry, and by each one of these answers a certain level of RSSI is obtained in the inquirer device. The main advantage of this method for obtaining the RSSI, is that it is not necessary to make a connection with the device to obtain the RSSI level of this connection later, as happened before the appearance of the Inquiry with RSSI mode, with the complication and latency required to make a connection (acceptance of connection, PIN request, ...).

In order to make the Inquiry with RSSI calls, it has been used a host with the GNU/Linux operating system. In particular Kubuntu Edgy 6.10, with kernel 2.6.17-11-generic i686, which incorporates BlueZ as Bluetooth protocol stack. In addition, the software packages BlueZ-Utils v3.7 and BlueZ-Hcidump v1.32 have been used to configure and to analyze/capture the HCI events of a device.

One of the Bluetooth adapters of the beacons acts as an inquirer and it has been configured in “invisible” mode (inquiry scan mode deactivated). The other adapter remains in “visible” mode (responding to inquiries). This second adapter has been configured with inquiry parameters that we have considered as the optimal ones in order to accelerate the measurements, based on the results of [15]. In particular, it has been changed the Inquiry interval from 1280 ms to 240 ms and the Inquiry window from 11.25 ms to 45 ms. With this configuration, we obtained more answers to Inquiries per time unit, and therefore, a larger number of total measurements to incorporate to our algorithms.

Finally, beacons are connected, through the WIFI adapter, to a server to collect the data.

B. Results

1) Calibration Vs. No calibration: In order to compare with the calibration system, we use an algorithm that directly calculates the position from the RSSI and from the positions of the beacons. Thus, in the non calibrated system, the position
is determined, at the moment $n$, by only using the position of the beacon $i$, $x_i$, and the received RSSI, $RSSI_i$.

$$\text{estimated position}_n = \frac{\sum_{i=1}^{m} RSSI_i x_i}{\sum_{i=1}^{m} RSSI_i}$$  \hspace{1cm} (7)

The differences between using or not the calibration can be seen in Table I, where the values are averaged during intervals of 30 or 60 seconds. From these results, it is observed the improvement of precision when using the method with calibration, obtaining in the most favorable case an improvement in the precision higher than the 50%. The same conclusion can be extracted when observing in Fig. 3 the distribution of the estimated positions with both methods. It can be seen as the estimated positions with the calibration algorithm have less dispersion and their average position is located closer to the real coordinates.

2) Influence of the number of beacons in the precision: The improvement of the precision can be appreciated when using a larger number of beacons in the calibration algorithm. Table II illustrates the differences between using 3 or 4 beacons for the estimation of the position for both experiments. The error is considerable reduced, due to the information provided by the additional beacon. The results shown for the case of 3 beacons are obtained when removing B2 from the computations.

V. CONCLUSIONS

This article introduces a positioning system based on a Bluetooth sensor network that incorporates real time calibration. Any bluetooth device, into the coverage area of the network, will be detected by an inquire Bluetooth procedure. In order to estimate its position, the system uses the received signal power arriving from beacon sensors. Since the beacons are at known and fixed positions, the signals received between them can be used to analyze the fluctuations due to environment changes. With this information it is possible to compensate in real time the variations of the signal levels produced by the environment conditions, allowing the improvement of the precision and the stability of the estimations.

The results illustrate how the error of the position estimation, when the calibration is used, is reduced around a 50% with respect to a traditional system. It is also shown the influence of increasing the number of beacons.

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