# Experiments on Local Positioning with Bluetooth

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## Abstract

*This paper presents a design and an implementation of the Bluetooth local positioning application. Positioning is based on received power levels, which are converted to distance estimates according to a simple propagation model. The extended Kalman filter computes 3D position estimate on the basis of distance estimates. With the used Bluetooth hardware, the mean absolute error of positioning was measured to be 3.76 m. The accuracy can be improved if Bluetooth devices are able to measure received power levels more precisely.*

## 1. Introduction

Positioning is seen as an important function of mobile telecommunication. Location awareness enables new applications and services. Global Positioning System (GPS) is a worldwide satellite-based navigation system. However, GPS cannot be used indoors because a GPS receiver usually fails if line of sight visibility to the satellites is lost. Assisted GPS (AGPS) may extend availability indoors, but then a receiver becomes dependent on network assistance [1].

Local positioning refers to technology applied in restricted area (e.g. inside a building). In this paper the term positioning refers to local positioning.

Positioning has already been designed on the Wireless Local Area Network (WLAN) platform [2, 3]. Bluetooth [4, 5] is similar to current WLAN technologies [6] in terms of positioning. Therefore, there may be a need for positioning with Bluetooth, especially when the density of Bluetooth devices increases. According to our knowledge, only few Bluetooth positioning experiments has been reported so far [7].

The paper is organized as follows. An overview of Bluetooth characteristics related to positioning is given in Section 2. Section 3 introduces basic positioning methods and compares their applicability for Bluetooth. The most applicable method, received (RX) power level based positioning, is described more detailed in Section 4. The architecture and design of the positioning application are also illustrated. Implementation specific issues of the application are dealt in Section 5. Section 6 presents the measurements and accuracy evaluation of the application. The final section presents conclusions and future work.

## 2. Bluetooth overview

Bluetooth is a specification for short-range wireless connectivity. Bluetooth protocol stack is shown in Figure 1. Bluetooth radio operates on 2.4000-2.4835 GHz Industrial, Scientific and Medical (ISM) band, which is license-free and available almost globally. The band is divided into 79 channels. Since the transmission scheme is Frequency Hopping Spread Spectrum (FHSS), channels are used according to pre-calculated pseudo-random hop sequence [4].

Bluetooth radio is classified on the basis of output power. The maximum output power level of the class 1 is 20 dBm. In the classes 2 and 3 the maximum levels are 4 dBm and 0 dBm. Power control is obligatory in the class

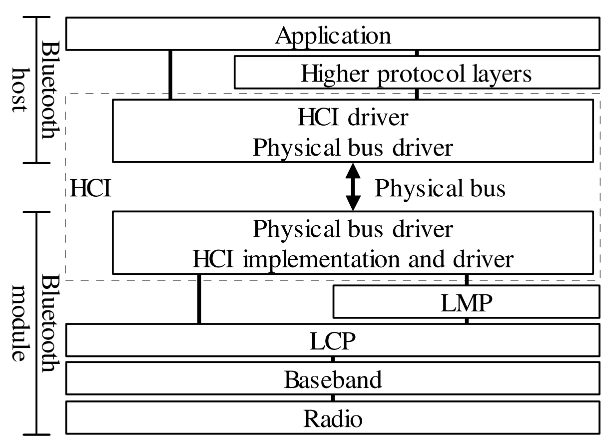


**Figure 1. Bluetooth protocol stack**

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1, but optional in the other classes.

Bluetooth baseband controls timing and performs low-level link control. A Bluetooth device can operate in two roles: a master or a slave. In some cases a slave and a master may change their roles. Slaves synchronize with their master and adapt to its FHSS sequence. A master may check the presence of a slave by sending it a POLL packet. A slave must respond with a data packet or a NULL packet [8].

Bluetooth topology is constructed by piconets. A piconet consist of a master and up to seven active slaves (and a number of slaves in power save mode). Several piconets linked together form a scatternet.

Communication between Bluetooth devices may be point-to-point or point-to-multipoint oriented. There are two link types. An Asynchronous Connection-Less (ACL) link is packet-switched with error checking and retransmissions. A Synchronous Connection Oriented (SCO) link is circuit-switched without error checking or retransmissions [8].

Link Control Protocol (LCP) controls whether a device can be found and connected with by other Bluetooth devices. LCP establishes and maintains connections. Link Manager Protocol (LMP) manages piconet operation, establishes links, and implements power management.

Host Controller Interface (HCI) consists of four sub-layers and a physical bus such as Universal Serial Bus (USB). HCI divides the protocol stack into two parts: Bluetooth module and Bluetooth host. HCI provides a standardized interface to Bluetooth module [8].

## 3. Positioning methods for Bluetooth

The following positioning methods have been considered in this research: Angle of Arrival (AOA), Cell Identity (CI), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and RX power level. From now on the term *mobile device* refers to a device to be positioned. *Stationary device* is a device, whose location is known.

AOA positioning is based on determining the direction of the arrival signal. A stationary device measures angle of arrival signal sent by a mobile device. Location can be estimated through triangulation if at least two stationary devices perform measurement [9]. Measuring angles requires a special antenna array.

In CI method, the network is divided into cells each corresponding to the radio coverage of a single stationary device. A mobile device connected to a certain stationary device is inside its equivalent cell. Thus, smaller cells improve the accuracy. In case of Bluetooth, nominal radio coverage is from 10 m (class 3) to 100 m (class 1). Therefore, pure CI positioning is quite inaccurate. Overlapping cells and using triangulation improves accuracy [7].

In TOA positioning a mobile device sends signal to a stationary device, which sends it back to the mobile device. The mobile device measures the round-trip time (RTT) of the signal. This leads to a circle, whose radius corresponds to half of RTT and centre is on the location of the stationary device. Location of the mobile device can be approximated to be at the intersection of at least three measured circles.

TOA positioning requires accurate clocks because a 1.0 μs error in timing equals to a 300 m error in distance estimate [9]. In Bluetooth the instantaneous timing of master packet transmission may deviate up to 1 μs from the average [4]. Thus, the accuracy is too low for TOA positioning.

TDOA positioning is developed to eliminate the tight synchronization requirement of TOA, but it still demands accurate clocks. Inaccuracy in measuring time differences should not exceed tens of nanoseconds [1]. TDOA positioning is applicable only if Bluetooth devices provide much more accurate clocks than the specification requires.

RX power level based positioning is quite similar to the TOA positioning. In both methods location of a mobile device can be found on intersection of three (or more) circles. In case of RX power level based positioning, radii of circles is calculated from the measured strengths of received signals. A propagation model estimates the relation between signal strength and distance.

RX power levels are typically measured in wireless networks for transmit (TX) power control and roaming. However, the results of measurement can be used for positioning as well. Bluetooth devices measure RX power level indirectly by using Received Signal Strength Indication (RSSI), which is implemented in the Bluetooth module and can be read through HCI [4]. Consequently, RX power level based positioning seems to be the most applicable for Bluetooth.

## 4. Bluetooth Local Positioning Application

A Bluetooth Local Positioning Application (BLPA) is designed and implemented in this research. BLPA implements RX power level based positioning on a Bluetooth platform. The functional architecture of BLPA is shown in Figure 2.

### 4.1. Connectivity

The lowest layer of the architecture, connectivity, contains Bluetooth specific functionality such as finding and connecting neighbor devices. A *mobile device* is Bluetooth platform and runs BLPA with User Interface (UI). A *neighbor device* represents any other Bluetooth device, which accepts connections and is situated within the radio range of a mobile device.

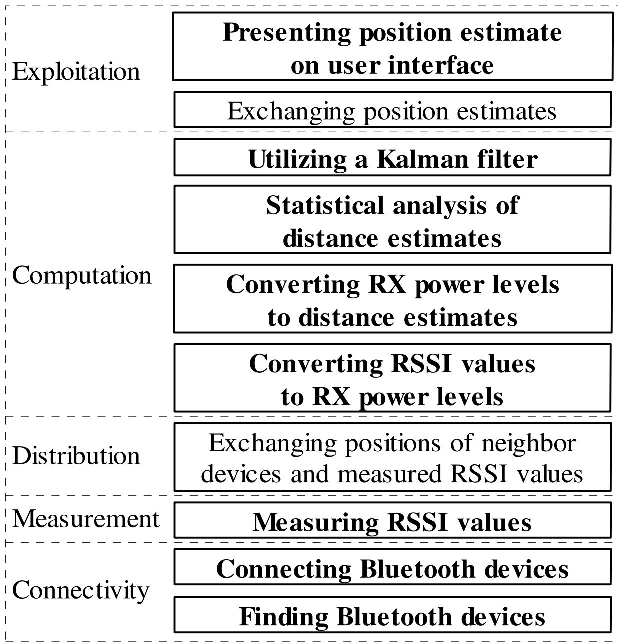


**Figure 2. BLPA architecture**

## 4.2. Measurement

The measurement layer contains operations needed in reading RSSI values. RSSI is an 8-bit signed integer. Its unit is dB in proportion to the ideal RX power range, which is called the Golden Receive Power Range (GRPR). A RSSI value greater than zero indicates that RX power level is above GRPR. A negative RSSI value means RX power level is below GRPR. If a RSSI value equals zero RX power level is inside GRPR [4]. RSSI can be discovered separately for each ACL connection by using the HCI command called *Read_RSSI*.

## 4.3. Distribution

The distribution layer enables to exchange information needed in positioning over Bluetooth links. If the positions of neighbor devices are unknown, a relative position can still be estimated. Ad-hoc networks may benefit from that information.

## 4.4. Computation

The first task in the computation layer is to convert RSSI values to absolute RX power levels. Definition of the GRPR is essential because RSSI is closely related to it. GRPR is defined in Bluetooth specification as illustrated in Figure 3.

GRPR is limited by an upper threshold and lower threshold. The lower threshold is between the minimum and maximum lower threshold levels. The minimum lower threshold is defined to be 6 dB above the actual receiver

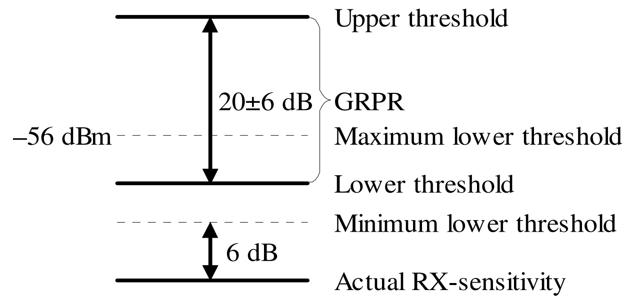


**Figure 3. Definition of GRPR**

sensitivity level. The maximum lower threshold is −56 dBm. The dynamic range of GRPR is 20±6 dB [4].

A RSSI value can be converted to an RX power level only if upper and lower threshold levels are known. Since GRPR is defined quite loosely, threshold levels must be determined separately for every Bluetooth device model.

The RX power level is converted to distance estimate by using a radio wave propagation model. A simple log-distance model [10], shown in Equation 1, was chosen.

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} + 20\log(\lambda) - 20\log(4\pi) - 10n\log(d) - X_{\alpha} \quad (1)$$

In Equation 1, $P_{RX}$ (dBm) and $P_{TX}$ (dBm) are power levels of receiver and transmitter. $G_{TX}$ (dBi) and $G_{RX}$ (dBi) are antenna gains respectively to transmitter and receiver. Wavelength is $\lambda$ (m) and distance between transmitter and receiver is $d$ (m). The exponent $n$ denotes influence of walls and other obstacles. Error is also included in the equation since $X_{\alpha}$ is a normal random variable, whose standard deviation equals to $\alpha$. Distance $d$ can be solved from Equation 1 as shown in Equation 2.

If a neighbor device is able to control TX power, the mobile device must be informed about that. TX power level can be inquired locally by using a HCI command called *Read_Transmit_Power_Level*. A neighbor device reads its TX power level and sends the result to the mobile device, which updates the value of $P_{TX}$ in Equation 2.

$$d = 10\hat{}\left(\left(\begin{matrix} P_{TX} - P_{RX} + G_{TX} + G_{RX} - X_{\alpha} + \\ 20\log(\lambda) - 20\log(4\pi) \end{matrix}\right) \Big/ (10n)\right) \quad (2)$$

The measurements are corrupted by noise. A larger number of measurement samples is preferred to decrease the effect of single measurement errors and to evaluate the uncertainty of distance measurement by computing the variance of the sample set.

Extended Kalman filter (EKF) was used to compute the positions from the distance measurements. The Kalman filter (KF) approach was selected because it can be used to fuse optimally the current position estimate with the new measurement information. Using the knowledge about the uncertainties of the current position estimate and the new measurements, KF blends the information optimally minimizing the variance of the estimation error.


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The EKF was selected because the measurement equations of this application are non-linear.

The coordinates of the 3D position of the mobile device, $\mathbf{x}$, were selected as the state variables of the filter. The state dynamics was modeled by the equation

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{u}_k \quad (3)$$

where the variance of the driving noise $\mathbf{u}_k$ is $E[\mathbf{u}_k^T\mathbf{u}_k]=\mathbf{Q}_k$. In the current study, only stationary positions of the mobile device were considered. Thus, the appropriate choice for the variance $\mathbf{Q}_k$ was $\mathbf{O}_{3\times3}$ (zero matrix). The equation that relates the measurements to the state variables is

$$\mathbf{z}_k = \mathbf{h}(\mathbf{x}_k) + \mathbf{v}_k \quad (4)$$

where $\mathbf{v}_k$ is random measurement noise with variance $E[\mathbf{v}_k^T\mathbf{v}_k]=\mathbf{R}_k$. In Bluetooth positioning, the elements of the vector $\mathbf{h}(\mathbf{x})$ are the distances between the mobile device and the neighbor devices, which can be written as function of the device positions:

$$h_i(\mathbf{x}) = \sqrt{\sum_{j=1}^{3}\left(x_{i,j} - x_j\right)^2} \quad (5)$$

Here $i$ is the index of the neighbor device, $h_i$ is the distance between the mobile device and the $i$th neighbor device, $x_{i,j}$ and $x_j$ are the $j$th position coordinates of the $i$th neighbor device and the mobile device, respectively.

In order to be used in KF, the measurement equation (4) must be linearised. In EKF, current state estimate is selected as the reference trajectory about which the equations are linearised. It is assumed that $\Delta\mathbf{x}_k$ is a small difference between the true position $\mathbf{x}_k$ and the current estimate, i.e.

$$\mathbf{x}_k = \hat{\mathbf{x}}_k + \Delta\mathbf{x}_k \,. \quad (6)$$

Then $\mathbf{h}(\mathbf{x}_k)$ can be approximated using Taylor's series expansion with first-order terms

$$\mathbf{h}(\mathbf{x}_k) \approx \mathbf{h}(\hat{\mathbf{x}}_k) + \mathbf{H}_k\Delta\mathbf{x}_k \quad (7)$$

$$\mathbf{H}_k = \left[\frac{\partial\mathbf{h}}{\partial\mathbf{x}}\right]_{\mathbf{x}=\hat{\mathbf{x}}_k} \quad (8)$$

For the measurement equations given in (5), the rows of the linearised $\mathbf{H}_\mathrm{k}$ matrix can be written as

$$\mathbf{h}_i^T = -\hat{\mathbf{x}}_k^T / h_i(\hat{\mathbf{x}}_k) \quad (9)$$

The EKF filter equations, suitable for keeping track of total estimates rather than incremental ones, were derived using the theory presented in [11].

Because we assumed that the state is constant, the prediction step simplifies to

$$\hat{\mathbf{x}}_{k+1}^- = \hat{\mathbf{x}}_k \text{ and } \mathbf{P}_{k+1}^- = \mathbf{P}_k \,.$$

Thus, the values obtained from the previous measurement update can be used in the next measurement update without prediction step. The Kalman gain for measurement update is computed using the linearised $\mathbf{H}_\mathrm{k}$ matrix and the measurement updates of the state and the covariance become

$$\mathbf{K}_{k+1} = \mathbf{P}_k\mathbf{H}_k^T\left(\mathbf{H}_k\mathbf{P}_k\mathbf{H}_k^T + \mathbf{R}_{k+1}\right)^{-1} \quad (10)$$

$$\hat{\mathbf{x}}_{k+1} = \hat{\mathbf{x}}_k + \mathbf{K}_{k+1}\left(\mathbf{z}_{k+1} - \hat{\mathbf{z}}_{k+1}\right) \quad (11)$$

$$\mathbf{P}_{k+1} = \left(\mathbf{I} - \mathbf{K}_{k+1}\mathbf{H}_k\right)\mathbf{P}_k\left(\mathbf{I} - \mathbf{K}_{k+1}\mathbf{H}_k\right)^T + \mathbf{K}_{k+1}\mathbf{R}_{k+1}\mathbf{K}_{k+1}^T \quad (12)$$

where the predicted measurement is $\hat{\mathbf{z}}_{k+1} = \mathbf{h}(\hat{\mathbf{x}}_k)$, $\mathbf{z}_{k+1}$ is the new sample mean of the distance measurements, and $\mathbf{R}_{k+1}$ is the corresponding sample variance. $\mathbf{I}$ is identity matrix of size 3×3. If all samples are equal, elements of $\mathbf{R}_{k+1}$ become zero. If this continues for several measurement updates, the innovation term $\mathbf{H}_k\mathbf{P}_k\mathbf{H}_k^T+\mathbf{R}_{k+1}$ in (9) approaches zero and the matrix inversion cannot be computed. To prevent this problem, a small positive value $var_{\min}$ was added to the variances.

The filter was initialized by setting $\hat{\mathbf{x}}_0$ and $\mathbf{P}_0$ to constant values. The first measurement update was evaluated iteratively, i.e. repeating the evaluation of equations 8-12 with the same measurement information until the predetermined convergence criterion was met.

### 4.5. Exploitation

At the exploitation layer a position estimate already exists. The estimate can simply be shown on UI or it can be used for other applications, which requires position information. Alternatively, devices may exchange position estimates and form topology of the network that way.

## 5. Implementation of BLPA

BLPA is implemented on the HCI layer. A Bluetooth module is responsible of connectivity and measurement whereas a Bluetooth host implements the rest of BLPA and controls the Bluetooth module. Ericsson Bluetooth Starter Kit (EBSK) has been used as a Bluetooth module. EBSK is connected via USB cable to a Windows 2000 PC that is a Bluetooth host.

The current version of BLPA implements the bolded blocks of Figure 2. The other blocks will be implemented later. Currently, neighbor devices must be stationary and their positions have to be configured manually. The version of Bluetooth modules attached to EBSKs is ROK 101007/21 R1A [12], which supports point-to-multipoint connections.

Neighbor devices are simply configured to accept all connections without requiring role change. The mobile device finds neighbor devices and establishes ACL links with them. This procedure creates a piconet, which contains a master (mobile device) and one or more slaves (neighbor devices).

Due to a large gain variation of the build-in antenna of the EBSK [13], external dipole antennas (AND-C-107) manufactured by M/A-COM were used instead.

The actual receiver sensitivity level of EBSK is

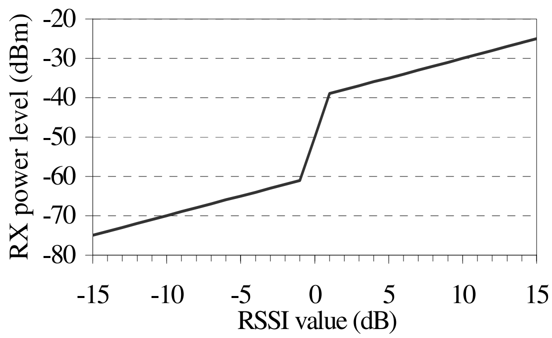


**Figure 4. Converting RSSI to RX power levels**

reported to be typically −76 dBm [14]. According to the Bluetooth specification and the data sheet of EBSK the lower threshold level is less than −56 dBm and likely more than −70 dBm. Consequently, the lower threshold level was approximated to be −60 dBm. The upper threshold level was not documented, but an approximated value −40 dBm was used.

Figure 4 shows how RSSI values read by EBSK are converted to RX power levels. TX power level is fixed to 0 dBm because EBSK does not support TX power control.

BLPA has been developed with Microsoft Visual C++ 6.0 and it uses Bluetooth PC Reference Stack (version R2B) provided by Ericsson. The stack communicates with Bluetooth module via serial cable or USB and provides Application Program Interface (API) to Bluetooth protocols. Thus, starting BLPA launches two processes: the application itself and the stack process. A C++ class called Matrix TCL Lite (version 1.13) needed for EKF

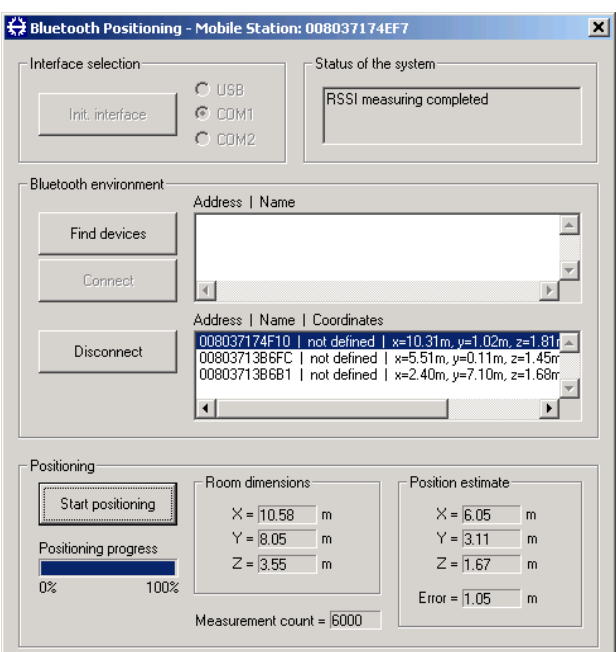


**Figure 5. Main dialog of BLPA**

was provided by Techsoft.

UI of BLPA is shown in Figure 5. The main dialog contains Bluetooth specific controls, which enables to find and connect neighbor devices. A user must insert maximum dimensions of the room. These dimensions are shown at the bottom of the main dialog. The dimensions do not limit position estimates, thus it is possible that under some circumstances the position estimate is outside the defined room. The positioning information is placed at the bottom of the main dialog.

Positioning can be started as soon as three neighbor devices are connected and the user has inserted their coordinates. For evaluating the accuracy, it is possible to insert the correct position of the mobile device before starting positioning. Current position estimate and absolute error of it are updated to the bottom-right corner of the main dialog.

## 6. Measurements

The measurements were done indoors, in typical office premises. Furnishings were moved so that there were (unless other stated) a line of sight between a transmitter and receiver. Nearby WLAN devices were turned off during the measurements because WLANs and Bluetooth share the same frequency band [15]. This interference could have lead to unreliable results. BLPA was modified to write RSSI values to disk.

### 6.1. Tuning variables of the propagation model

The relation between distance and RX power level was evaluated by measurements in order to determine the values of the unknown variables in Equation 2.

Two EBSKs were placed on the height of 0.75 m. The distance between the devices was increased step by step from 0.20 m to 13.00 m. The size of the step was 0.20 m. For each 65 distances a RSSI value was measured 1000 times at the other end of the link. Afterwards, the RSSI values were converted to RX power levels. The mean of the RX power levels was calculated and it was inserted into $P_{RX}$ variable in Equation 2.

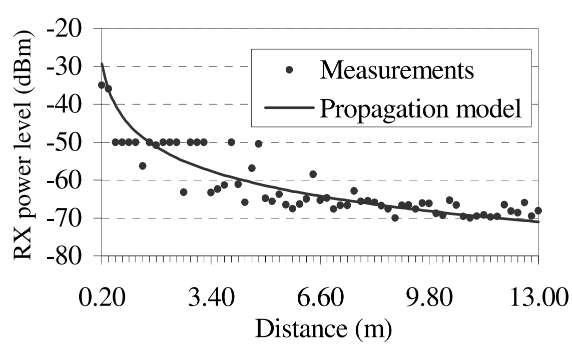


**Figure 6. Relation of distance and RX power level**

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The antenna gains $G_{TX}$ and $G_{RX}$ are equal (similar antennas at the both end) and less than 1.9 dBi [16]. The exponent $n$ equals 2.0 in free space [10] but it may vary indoors. $P_{TX}$ equals 0 dBm. $X_\alpha$ was ignored because it represents random error, whose magnitude is unknown. Since 2.4410 GHz is the middle frequency of Bluetooth channels, 0.12 m is a realistic estimate of wavelength $\lambda$.

Equation 2 was used with variable values stated above. Distance estimate $d$ was compared to the true distance and the absolute error was calculated. Finally, the mean of all absolute errors was calculated. Then the unknown variables were tuned so that the mean was minimized. According to the measurements, $G_{TX}$ and $G_{RX}$ equal –2.6 dBi and $n$ equals 2.3.

Figure 6 concludes the measurements. Every dot in the figure corresponds to the mean of measured RX power levels. The curve represents the propagation model, whose variables are tuned. There are significant differences between the measured values and the model. The mean absolute error is 1.41 m. This results from the nature of RSSI, which is defined quite loosely in the Bluetooth specification. The wide dynamic range of GRPR increases uncertainty of measurements especially on short distances. If the mean of RSSI values equal zero (−50 dBm in Figure 6) the true distance may vary from 0.60 m to 4.00 m.

### 6.2. Evaluating the accuracy of BLPA

The purpose of the following measurements was to tune parameters of EKF and evaluate the accuracy of BLPA. Altogether, 50 measurements were done in a room, whose dimensions are shown in Figure 7 and Figure 8.

In the first 25 measurements the neighbor devices were stationary in the positions marked with crosses in Figure 7. The exact XYZ-coordinates in meters were (0.50, 0.50, 0.75), (6.10, 6.40, 0.75), and (11.70, 0.50, 0.75). The mobile device was at the 0.75 m height but its position in XY-plane varied.

A grid divides the XY-plane into 24 squares, whose length of the side is 2.0 m. The mobile device was placed in the junctions of the grid. 10 junctions out of 35 had to be abandoned because there were constructional elements in those positions. In each 25 positions (marked with unfilled circles in Figure 7) the mobile device measured RSSI value 5000 times per a neighbor device.

The RSSI values were processed as described earlier and fed as an input to EKF. Three neighbor devices and 5000 RSSI values from each of them correspond to 250 EKF iterations. All measured RSSI values were saved to disk.

In the last 25 measurements coordinates of the neighbor devices were (0.50, 0.50, 1.49), (6.10, 6.40, 1.49), and (11.70, 0.50, 1.49). Positions of the neighbor devices are marked with crosses in Figure 8. The mobile device was on the floor but its position in XY-plane varied (unfilled circles in Figure 8).

After measurements the parameters of EKF were tuned. All 50 measurements were reconstructed by using saved RSSI values. Computation was redone with new parameter values of EKF. The distance between true position and the last position estimate of each measurement was calculated and saved. Finally, mean absolute error was calculated. The parameters were tuned in such a way that the mean absolute error was minimized. Table 1 presents the tuned parameter values.

Figure 9 illustrates how the mean error diminishes as tuned EKF performs new iterations. At first, the mean error decreases rapidly but finally new measurement information does not improve the accuracy of position estimates.

Filled circles in Figure 7 represent position estimates of the measurements 1-25 after 250 iterations. Each line

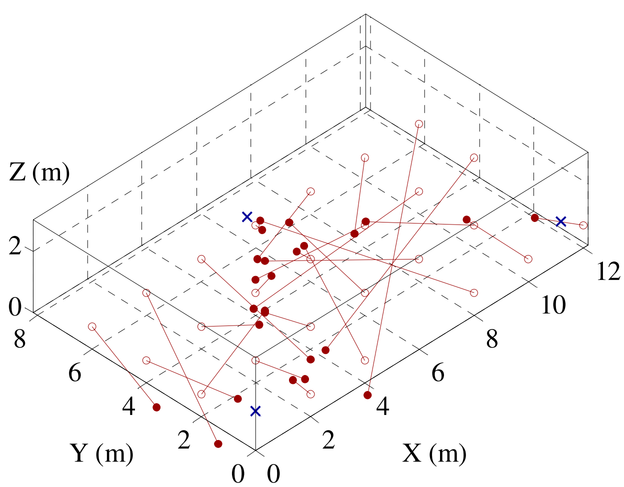


**Figure 7. True and estimated positions (measurements 1-25)**

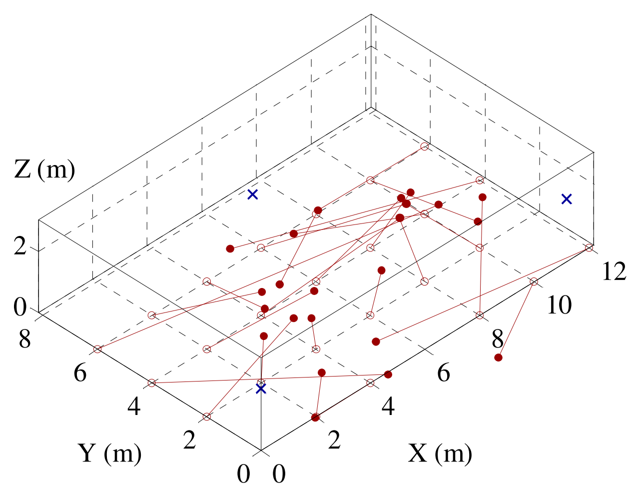


**Figure 8. True and estimated positions (measurements 26-50)**


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Table 1. Optimized parameters of EKF

| Description | Value | Unit |
|---|---|---|
| $\hat{\mathbf{x}}_0$ | $[0.0 \quad 0.0 \quad 0.0]^T$ | m |
| $\mathbf{P}_0$ | $\begin{bmatrix} 25.0 & 0.0 & 0.0 \\ 0.0 & 25.0 & 0.0 \\ 0.0 & 0.0 & 25.0 \end{bmatrix}$ | m |
| $var_{min}$ | 0.001 | |

connects a true position and a corresponding estimate, so the length of a line corresponds to the magnitude of error. The mean error would be smaller if the dimensions of the room limited estimates. Figure 8 illustrates positions estimates of the measurements 26-50 similarly.

The main reason of inaccurate position estimates is the unreliability of RSSI values. Therefore, distance estimates become unreliable as well. To demonstrate performance of EKF without RSSI errors, all measurements were also simulated in such a way that the distance estimates input to EKF were precisely correct. The mean error of position estimates after 250 EKF iterations decreased drastically being only 0.0193 m (3D error) and 0.0014 m (2D error in XY-plane). This negligible error is supposed to be caused by numerical inaccuracy and unfavorable geometry of mobile and neighbor devices.

## 7. Conclusions and future work

This paper presented design, architecture, and implementation of the Bluetooth Local Positioning Application (BLPA). Accuracy of BLPA was evaluated with measurements. It turned out that the accuracy needs to be improved for practical applications.

The main source of errors is unreliability of RSSI, which is defined too loosely for positioning purposes. Currently RSSI indicates the proportion of absolute RX power level to the Golden Receive Power Range (GRPR), which is the ideal RX power range defined by the Bluetooth specification. In order to measure absolute RX power level more precisely dynamic range of GRPR should be decreased or Bluetooth devices should be able to measure absolute RX power level directly.

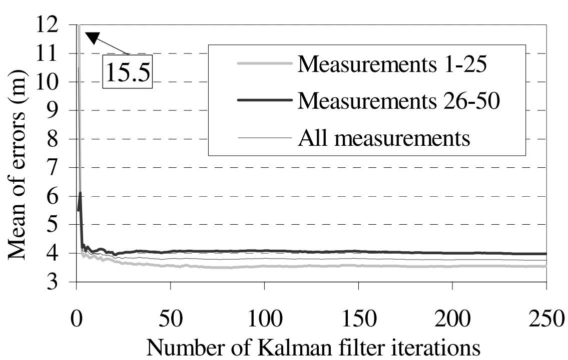


Figure 9. Mean of distance error

In future further measurements will be done to research whether adding more neighbor devices improves the accuracy. Parameters of the propagation model and EKF will be tuned. It may be worth testing other propagation models as well. However, these modifications may not improve the accuracy drastically because RSSI is still imperfect. In that sense it would be an interesting task to port BLPA onto another Bluetooth compatible platform, such as a mobile phone, to see whether some devices implement RSSI more accurate than the Bluetooth specification requires.

## 8. References


[1] J. Syrjärinne, "Studies of Modern Techniques for Personal Positioning" PhD Thesis, Tampere, Finland, 2001.

[2] J. Latvala, et. al., "Evaluation of RSSI-based Human Tracking", European Signal Processing Conference (EUSIPCO 2000), Tampere, Finland, 5-8 September 2000.

[3] P. Bahl, V. N. Padmanabhan, "RADAR: An In-Building RF-based User Location and Tracking System", IEEE Conference on Computer Communications (INFOCOM 2000), Tel Aviv, Israel, 26-30 March 2000.

[4] "Specification of the Bluetooth System: Core", version 1.1, 22 February 2001, http://www.bluetooth.com.

[5] "Specification of the Bluetooth System: Profiles", version 1.1, 22 February 2001, http://www.bluetooth.com.

[6] ISO/IEC 8802-11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, 1999.

[7] J. Hallberg, M. Nilsson, K. Synnes, "Bluetooth Positioning", The Third Annual Symposium on Computer Science and Electrical Engineering (CSEE 2002), Luleå, Sweden, 27-28 May 2002.

[8] J. Bray, C. F. Sturman, "Bluetooth: Connect without Cables", 1. ed., Prentice Hall PTR, 2001.

[9] I. Jami, M. Ali, R. F. Ormondroyd, "Comparison of Methods of Locating and Tracking Cellular Mobiles", IEE Colloquium on Novel Methods of Location and Tracking of Cellular Mobiles and Their System Applications (Ref. No. 1999/046), 1999, pp. 1/1-1/6.

[10] R. Küng, "Radio Channel: Living with Real-world Propagation Effects", Elektrobit AG, 2000.

[11] R. G. Brown, P. Y. C. Hwang, "Introduction to Random Signals and Applied Kalman Filtering", 3. ed., John Wiley & Sons, 1997, p. 484.

[12] Ericsson Microelectronics AB, "BSK Technical Documentation", tech. document BSK/S10311/1.2, 2001.

[13] Ericsson Microelectronics AB, "Introduction to Designing Antennae", tech. document BSK/S1031/2.0, 1999.

[14] Ericsson Microelectronics AB, "1522-PBA 313 01/2", data sheet, December 2000.

[15] M. Hännikäinen, et. al., "Coexistence of Bluetooth and Wireless LANs", International Conference on Telecommunications (ICT 2001), Bucharest, Romania, 4-7 June 2001.

[16] M/A-COM Division of AMP Inc., "Dipole Antenna for ISM Band", data sheet 1307028.



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