

# A 3-D Indoor Positioning Method using a Single Compact Base Station

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## Abstract

*Context awareness will become increasingly important in future domestic consumer electronics. In many domestic context aware applications, there is a need for location and orientation information about persons, devices or objects in the home. This information can be provided by a dedicated indoor location system. A consumer location system should be robust, safe, easy to set up, low cost, and should have a minimal infrastructure. In this paper, a step towards consumer location systems is taken by proposing an ultrasonic positioning method that needs just a single compact base station to measure 3D positions of mobile devices in a room. The method employs ultrasound time-of-flight trilateration to estimate device positions, using a base station containing an array of three ultrasound transducers. Five potential problems of the proposed method are identified; the main problem being line-of-sight path occlusion. The method has been prototyped, and initial results show an accuracy of 1.41 m or better for 95% of the position estimates, in case of a good line-of-sight path. It is concluded that the method is promising for providing 3D position information at around 1 m accuracy for context aware applications, but that the problem of line-of-sight occlusion requires further investigation.*

## 1. Introduction

For many applications in pervasive and context aware computing, it has been found that location is an important part of the context. Location information may include locations of persons, devices and objects, and may include their orientation as well. Indoor location systems are therefore an active topic of research [9] in pervasive computing. Until now they have mostly been designed for professional indoor environments. We expect that in the future, context aware-

ness will play an increasingly important role in the domestic consumer electronics domain. This creates the need for 'consumer grade' indoor location systems. Such a system would likely be connected to an in-home network, to share location information between multiple devices and applications.

What position accuracy (defined here as the expected distance between an estimated position and the True position) and what type of location information should a consumer location system provide? Initial requirements for both were found by analyzing in-home application scenarios where location plays a role. Such scenarios were produced in the PHENOM [1] project and in related projects at Philips Research. Applications often need some location, orientation or proximity (range) information, but the type of information and required accuracy varies a lot over scenarios. The location/range accuracy requirements could be grouped into three typical cases: low accuracy at room-scale ('in which room is the person or device?'), medium accuracy around 1 m ('in which part of the room?'), and high centimeter-scale accuracy ('at what coordinate in 3D space?').

Ultrasound time-of-flight measurements together with *trilateration* or *multilateration* algorithms are often used in indoor location systems to obtain high accuracy. Existing high accuracy ultrasonic systems are the Bat [2], Constellation and others from InterSense [6], Cricket [16], and the system by Randell and Muller [17]. Although such systems can meet most accuracy requirements, the large infrastructure required in a room and the associated installation effort are disadvantages. All current systems require several units of infrastructure in a room, e.g. fixed to the ceiling. A minimum of three such base station (BS) units is required to calculate 3D positions of mobile devices (MDs) within a room. Usually more than three BS units are advised or required [2, 6, 16, 17] to improve accuracy and reduce susceptibility to random measurement errors. Moreover, the positions of BS units need to be measured accurately and en-

tered into the system at installation time.

The required infrastructure and installation effort make these systems unsuitable for deployment in the home. Important requirements in this domain are that a location system is robust, safe, easy to install, minimal in its infrastructure, and low cost. These requirements led to our current research direction of a *single base station 3D positioning system*. (A positioning system is defined here as a location system specifically aimed at measuring absolute 3D coordinates of MDs.) A single unit is the minimum of infrastructure (apart from no infrastructure at all), is easier to install than multiple units, and may lead to a low-cost system if the BSs are mass-produced. Currently, we use ultrasound time-of-flight technology because of its proven track record in low cost accurate indoor positioning. Because ultrasound can not penetrate walls, a single-BS system will only work in one room of a house.

However, using just a single BS comes at a cost: we can't expect to get centimeter-accurate position information in an easy way. Instead, we aim for a system that provides medium accuracy for one room. Although this excludes high accuracy applications, there are many interesting applications requiring just medium/low accuracy.

We believe that the introduction of location systems in homes is viable, if it can be done gradually. A typical gradual business model e.g. allows a user to initially buy a single BS for the living room. Later, more BS devices can be purchased for other rooms in the house. Perhaps a single-BS location system in the living room could be enhanced by adding a second BS at the other side of the room, which requires a BS to be able to cooperate with other BS units. Then, unification of different coordinate systems may become a problem [18].

In the next section, a single-BS positioning method will be introduced that uses an array of three transducers in the BS. In Section 3, five potential problems of the proposed method will be stated and solutions will be discussed. Sections 4 and 5 describe our implementation of the single-BS system and experiments performed with it. The conclusions are given in Section 6.

## 2. Single base station positioning method

In this section, the single base station array positioning method and the base station (BS) design will be introduced.

### 2.1. Ultrasound time-of-flight trilateration

*Trilateration* [9, 14] consists of measuring three distances  $d_i^m$  between a target and three reference points  $\mathbf{r}_i$ , and using these distances to calculate the unknown target 3D position  $\mathbf{x}$ . For more reference points, it is called multilateration. The fixed reference points are usually BSs. In

most ultrasonic multilateration positioning systems, the distances between devices are measured using ultrasound time-of-flight (TOF) multiplied by the speed of sound in air. To measure absolute TOF, time synchronization between the BS/MD devices is needed. This is usually achieved by a radio link [2, 16] or an infrared link [6, 21]. Some systems use TOF differences instead of absolute TOF, which avoids the need for time synchronization [8]. However, this requires an extra BS unit. Many multilateration algorithms have been designed to cope with error in the measured distances  $d_i^m$ , e.g. least squares optimization methods.

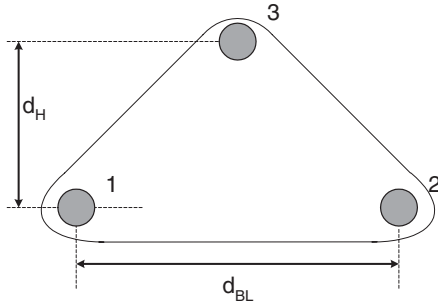
### 2.2. Base station design

A typical state-of-the-art ultrasonic multilateration system consists of three or more BSs in a room, located on the ceiling, spaced widely apart. Ceiling placement increases the probability of a clear line-of-sight (LOS) path between MD and the BSs. The wide space between BS units avoids error induced by unfavorable geometrical configurations, as will be shown later in Section 3.1. However, the large spatial extent of these setups is a disadvantage from the consumer point of view.

The configuration proposed here brings together three BSs into a single compact unit (Fig. 1). A baseline distance of  $d_{BL} = 11.5$  cm was chosen, to make it a compact device. (The influence of the parameter  $d_{BL}$  on system performance will be discussed in Section 3.1.) This BS can be placed in many ways inside a room. Good BS positions include (1) against a room wall at a high position, (2) attached to the ceiling in the middle of the room, and (3) diagonally in a ceiling corner. In this paper, position (1) is investigated for two reasons: first, it is similar to the BS position for the single-transducer BS approach in [5], so that positioning performance between the two approaches may be compared in the future. Second, position (1) is more favorable than (2) from the consumer perspective, because the BS can be more easily fixed to a wall (or simply be put upon a ledge or cupboard), and because a mains power socket for the BS is usually not available on the ceiling in the middle of a room. However, the ceiling position (2) also has interesting properties such as shortest average distance between BS and MDs.

The proposed array configuration resembles the 2D ultrasonic inter-robot localization system by Wu et al. [21], where transducers were also placed relatively close together at 5.1 cm, in a 2x2 array configuration.

For any ultrasonic location system, an important design decision is whether MDs send ultrasound as in [2], or the infrastructure sends ultrasound and the MD receives as in [8, 16]. The single-BS array method can work in both ways in principle. Other decisions about what devices send and



**Figure 1. Single-BS array with three transducers seen from the front.**

receive the RF signals for time synchronization, and where position estimates are calculated, remain open in this paper.

### 2.3. Least squares trilateration

A least squares trilateration algorithm is used in our implementation, to estimate a 3D position from three measured distances  $d_i^m$ . The algorithm iteratively updates a position estimate  $\hat{\mathbf{x}}$ , such that a cost function  $E$  is minimized. The cost function is the sum of squared errors between elements of the measured distances vector  $\mathbf{d}^m$  and estimated distances vector  $\hat{\mathbf{d}}$ :

$$E(\mathbf{d}^m, \hat{\mathbf{d}}) = \sum_{i=1}^3 (d_i^m - \hat{d}_i)^2, \quad (1)$$

where the three elements of  $\hat{\mathbf{d}}$  are given by  $\hat{d}_i = |\hat{\mathbf{x}} - \mathbf{x}_i^b|$  for  $i = 1, 2, 3$ ; and  $\mathbf{x}_i^b$  is the known position of transducer  $i$  in the BS. To solve this nonlinear optimization problem, the MATLAB [15] function *lsqnonlin* was used, which uses the Jacobian of the cost function for quick convergence. It needs an initial position estimate to start with. Equations for a good initial estimate were analytically derived, by solving an approximation of the positioning problem. The approximation holds for the assumptions that the MD is far away from the BS,  $d_i \gg d_{BL}$ , and that measured distances have zero error.

## 3. Problems of the single base station method

The design decision of integrating all infrastructure into one unit, although attractive, presents a number of specific problems. In this section five potential problems are identified and a number of solutions are proposed. The problems of unfavorable geometric configurations (Section 3.1), line-of-sight path occlusion (Section 3.2), multipath interference (Section 3.3), movement during measurements (Section 3.4), and installation (Section 3.5) are discussed.

### 3.1. Unfavorable geometric configuration

The error in a 3D position estimate depends not just on errors in the distance measurements, but also on the geometrical configuration of MD and BS positions, in a non-linear manner [14]. The position error due to small random measured-distance errors can be modeled by the *Geometric Dilution of Precision* concept [10, 14] (GDOP, or DOP for short). The DOP can be seen as a distance error amplification factor: for an expected standard deviation (SD)  $\sigma_d$  of measured distances around the true value, the expected position estimate error SD for a MD is  $\sigma_p = (\text{DOP}) \cdot \sigma_d$ . The positions of BSs and the MD influence the value ‘DOP’. For fixed BS position(s), the DOP is a function of the MD position only.

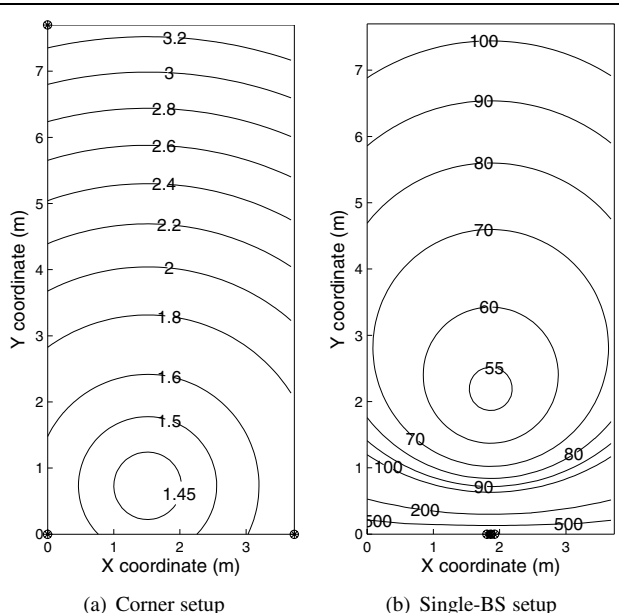
An analysis using the DOP concept will be shown now, which highlights the problem that is introduced by bringing the three BSs into one unit. Two configurations will be compared: (1) a standard three-BS setup where the BS units are placed in three ceiling corners; (2) the proposed single-BS array placed against a wall at a ceiling height of 2.97 m. For this analysis the HDOP (horizontal DOP) [10, 14] concept will be used, which only considers the position error in the horizontal plane. Although the HDOP can be calculated for a specific positioning algorithm as in [14], here the Cramer-Rao lower bound (CRB) [13] on the HDOP is calculated instead. It represents the best (=lowest) possible HDOP that any unbiased estimator of the horizontal MD position vector  $(x, y)$  can reach.

The CRB on the HDOP for both configurations is shown in Fig. 2(a) and 2(b) respectively. The bound was calculated over many MD positions  $(x, y, z)$ , where  $z$  was fixed to a typical MD height  $z = 1.20$  m.

It can be observed in the figures that the HDOP values for the single-BS array (2) are much higher than for the three-BS case (1). For the single BS, the HDOP value of 200 around  $y \approx 0.4$  means that an error SD of 1 mm (for all three measured distances) results in an error SD of 20 cm for the position estimate  $(x, y)$ . In the experiments in Section 5 it is investigated whether the high DOP causes problematically low positioning accuracy, or not.

A partial solution to the high DOP problem comes from the fact that error due to DOP can be estimated. This means that the error bounds for the MD position estimate, which are reported back by the positioning system to applications, can be dynamically adapted depending on the estimated current DOP value.

*Influence of the BS baseline distance.* The baseline distance  $d_{BL}$  (see Fig. 1) has a direct effect on the HDOP. By increasing  $d_{BL}$ , HDOP can be decreased, so a trade-off exists between BS compactness and positioning error. Note that the HDOP for positions near  $y = 0$  will remain relatively large for any  $d_{BL}$ , due to the inability of the single-



**Figure 2. Isograms of constant HDOP (lower bound) within a room, for two distinct setups. The MD height is  $Z = 1.2$  m. BS transducer positions are marked by  $\otimes$ .**

BS array to estimate y-coordinates accurately near  $y = 0$ . (This can be verified by geometry: a small position change of  $\Delta y$ , for any MD position near  $y = 0$ , induces a change of  $(\partial d_i^m / \partial y) \cdot \Delta y \approx 0$  in the measured distances  $d_i^m$ .)

### 3.2. Line-of-sight occlusion

The line-of-sight (LOS) path between the single BS and a MD can be easily obstructed by persons or furniture objects. A typical obstruction occurs when a person carrying a MD is facing away from the BS, so the person's body is obstructing the LOS path. Another typical case is a MD not pointing straight towards the BS, so that the MD casing blocks the LOS path. For all such obstruction cases the term *LOS occlusion* will be used.

Two possible cases can be distinguished: in *partial occlusion*, LOS signals can still be measured, as the acoustic waves *diffract* [4] i.e. 'bend' around the obstacle and do reach the receiver. The amplitude of a diffracted signal is much lower than that of a signal in clear LOS conditions, and the length of the diffracted wave's propagation path will be slightly longer than the LOS distance. Both the low amplitude and the increased propagation path-length can cause errors in position estimates. In the case of *full occlusion*, the LOS path is obstructed such that the amplitude of the diffracted LOS signal is too low to be measurable at the re-

ceiver. Then, it is possible that a reflected wave that arrives later is mistakenly seen as the LOS signal, which can result in large positioning errors.

A first step towards solving this problem is to detect when occlusion happens. If occlusion is detected, we can reject the measurement or assign a low confidence level to the corresponding position estimate, which will hopefully avoid large errors. One method for occlusion detection will be introduced now. The method is based on the assumption that LOS peaks in an ultrasound signal are more likely to be valid if their relative amplitude  $a_{rel}$  is higher. (The *LOS peak* is the characteristic first peak in a measured ultrasound signal, that is caused by the arrival of the acoustic wave over the shortest (line-of-sight) path. Note that if the LOS peak's amplitude is low, it may be undetectable amidst noise.) The relative amplitude of LOS peaks can be defined in a number of ways, for example as the ratio of the LOS peak amplitude  $a_1^m$  to the RMS amplitude of all other peaks:

$$a_{rel} = \frac{a_1^m}{\text{RMS}(\mathbf{a}^m)}, \quad (2)$$

where the vector  $\mathbf{a}^m$  includes all remaining detected peaks  $a_i^m$  ( $i \geq 2$ ) due to acoustical noise, cross-correlation noise, and acoustic reflections (i.e. multipath components). Given the above assumption, the value  $a_{rel}$  can be used as a confidence value for the measurement. Using a threshold  $T_{rel}$  that dictates a minimum value of  $a_{rel}$  for a measurement to be accepted, a simple occlusion classifier can be implemented. This classifier performance will be tested in Section 5.

### 3.3. Multipath interference

Even when an unobstructed LOS path exists between a BS and a MD, one source of error can disturb the measured LOS distances. This error is caused by the *multipath interference* effect, which means that reflections of ultrasonic waves (so-called multipath components or multipath signals) arrive at a receiver while it is still 'busy' receiving the LOS signal. These reflections can be caused by persons, objects or walls. The multipath components may disturb the LOS signal by alteration of its phase or shape, or by constructive or destructive interference, leading to errors in position estimates. For GPS receivers, multipath is extensively studied [20] as it is the largest source of error. For indoor ultrasonic systems, multipath error is usually not an issue because it is in the order of magnitude of a few cm or less. However, for the single-BS method even an error this small is undesirable as it may lead to large positioning errors (as was shown in Section 3.1).

Next, three solutions to the multipath problem will be given, that will not remove multipath error completely, but will reduce it. A straightforward first solution is to increase

the bandwidth of ultrasound transducers. Roughly speaking, transmissions of larger bandwidth can be made shorter in time duration, which lowers the probability that a LOS signal will overlap with multipath components that arrive slightly later at the receiver. For the theoretical limit of infinitely narrow impulse signals, multipath error would be non-existent. It is shown by Hazas and Ward [7, 8] that broadband transducers can work well in an indoor positioning system.

Secondly, solutions exist that use signal processing in the receiver to compensate for a low bandwidth channel, as shown by the body of work on GPS receivers [20] and on sonar applications (e.g. [3]).

A third solution is proposed here for ultrasonic systems that use low bandwidth piezo ultrasound transducers. This method was implemented in the experimental setup (of Section 4). It uses signal processing at the transmitter side to increase the bandwidth of piezo transducers. By increasing the bandwidth, multipath error should decrease. A software FFT filter with a specially shaped frequency spectrum is connected before the transmitter. The filter shape was chosen to widen the typical narrow band-pass peak in the frequency spectrum of a piezo transducer. This way the 3-dB-bandwidth of the combined transmitter-receiver pair could be enlarged from 0.8 kHz to a value in the 1-10 kHz range, where the value is controllable in real-time by a filter parameter. Note that the bandwidth can not be increased indefinitely, since extra bandwidth is gained at the cost of transducer efficiency.

### 3.4. Moving mobile devices

While a MD is performing distance measurements, it may be moving. This can lead to errors in position estimates if the three measurements between BS and MD are taken sequentially in a TDMA scheme. In the time between measurements (e.g. 50 ms) the MD may have moved up to several centimeters, which causes the measured distances  $d_i^m$  to be mutually inconsistent. As the single-BS trilateration method effectively relies on small differences between these distances to compute the position of the MD, movement may cause incorrect position estimates.

Three solutions are considered here to avoid errors due to moving MDs. A first one is to reverse the direction of ultrasound transmissions, and let each MD in the room sequentially transmit an ultrasound signal and let the BS transducers simultaneously 'listen', which avoids the time delays between subsequent measurements that caused the problem. A second solution is to measure distances twice and deduct from these values if a MD is stationary or not. If not, the measurement can be rejected. A third solution is to let all BS transducers transmit at the same time, using three *orthogonal signals* that do not interfere with each other when trans-

mitted over the same ultrasound channel. The well-known Code Division Multiple Access (CDMA) [19] scheme uses orthogonal signals. This approach has been used before in ultrasonic positioning [7, 8] and echolocation systems [12] to obtain multiple-access capability, so details are omitted here. A CDMA scheme is used in our implementation.

### 3.5. Installation issues

One more issue concerns the installation of the BS. The installation of a single BS by a non-expert user should be as simple as possible, perhaps even 'plug and play'. Ideally, a system should allow users to choose a convenient location for the BS unit. But how can a BS know its own position? If a user has to enter coordinates into the system, the installation becomes cumbersome. So a user-friendly method of entering or measuring the BS coordinates is needed. In the scope of this paper no solutions are presented, but it is simply assumed that the BS position is known and fixed.

Note that an interesting side effect of a single BS is that entering coordinates may not be needed in some cases. The single BS can define its own ad-hoc coordinate system in which the BS always resides at the origin. This is useful only for applications that use relative positions instead of real-world *room coordinates*, for example applications that only require a movement trajectory of a MD, and applications that need to know MD positions relative to each other.

## 4. Implementation

A measurement setup has been built to test the single-BS array method. It consists of a flexible hardware setup of up to eight ultrasound transmitters and eight receivers connected to a PC, with all signal processing and position estimation done in software.

### 4.1. Measurement hardware setup

The measurement setup is shown in Fig. 3. Three transmitters for the BS and one receiver for the MD are connected to a measurement PC. Output waveforms of arbitrary shape can be generated by the three output DACs. The outputs drive Quantelec SQ-40T 40 kHz ultrasound transmitters at  $\pm 3$  V peak. The acoustic waves propagate inside the room, and are recorded by a single Quantelec SQ-40R receiver. The received electrical signal is amplified, and filtered by a 30-100 kHz bandpass filter to remove electrical noise. The ADC samples the data  $y(k)$  and sends it to MATLAB. All equipment is connected by coaxial cables. Time synchronization between BS and MD is simulated by a shared time trigger between the ADC and DAC boards.

One MD was simulated using a 10 x 6.5 x 2.5 cm empty plastic box with the receiver transducer inside (Fig. 4(a)).

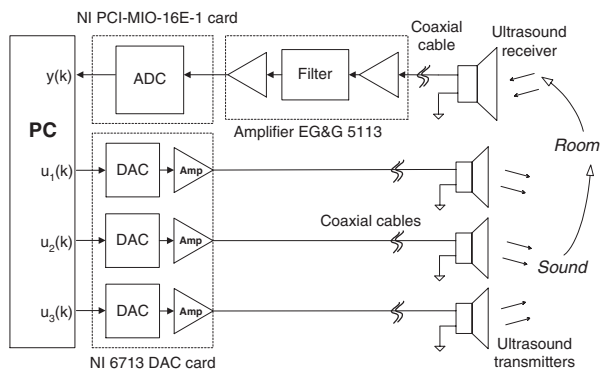


Figure 3. Measurement setup diagram.

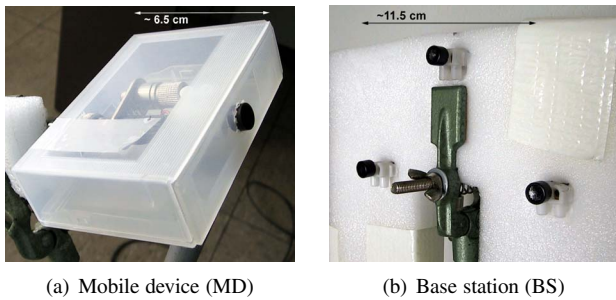


Figure 4. The MD and BS used in the experiments.

The transducer orientation was chosen to point 10 degrees up when the MD is held in a horizontal position. This orientation ensures a reasonably good orientation of the transducer towards the BS, for the typical way the MD is held in a hand. The BS (Fig. 4(b)) consists of three transmitters fixed to a piece of foam at precisely determined positions (1 mm accuracy).

## 4.2. Signal processing framework

Figure 5 shows the operations performed on the measured receiver signal  $y(k)$ , which is recorded for 105 ms starting at each transmission start time  $t_0$ . (Although this enables an update rate of almost 10 Hz, the current setup estimates positions at just 0.3 Hz, as it is not optimized for speed.) The signal  $y$  contains the combined contributions of three orthogonal coded signals in a CDMA scheme (Section 3.4) from the three BS transmitters. The goal of the processing steps is to obtain the three LOS path distances.

The first processing step of cross-correlation separates  $y$  into three signals  $x_j$  using template signals  $t_1, t_2$  and  $t_3$  respectively, where template  $t_j$  is the expected coded signal

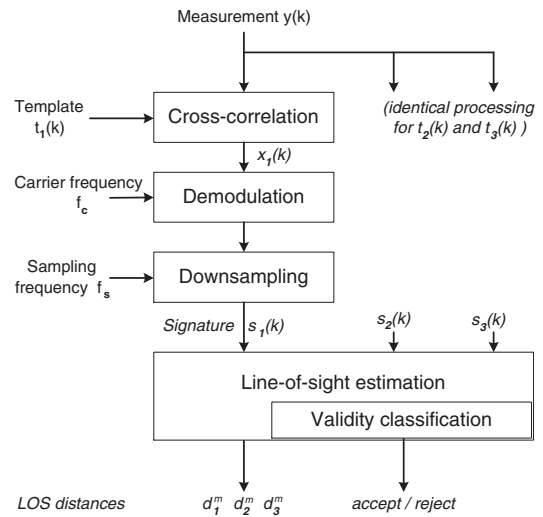


Figure 5. Signal processing operations to obtain three LOS distance estimates.

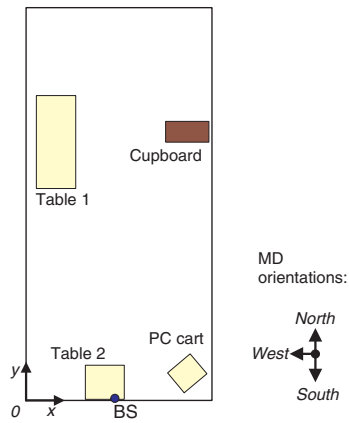
as sent by transducer  $j$  from the BS array. Three orthogonal codes for transmission were selected from a set of 127-bit  $m$ -sequences [11] optimized for good cross-correlation properties according to the MSQCC/CO criterion. The binary codes were not transmitted directly, but were used to phase-modulate a sequence of 127 sinusoidal burst signals, of 38 ms total sequence duration.

The second step demodulates an amplitude envelope from the ultrasound signal's  $f_c = 40$  kHz carrier frequency. Since the bandwidth of the envelope is less than 10 kHz, it can be downsampled in the third step by a factor ten to a sampling frequency  $f_s = 25$  kHz. We use the term *signatures* [5] for the envelopes  $s_j$ , because they retain all information from  $x_j$  about the LOS signal's TOF and subsequent multipath components.

The fourth step of LOS estimation analyzes the three signatures  $s_j$  together, and produces an estimate of the three LOS distances  $d_i^m$ . The validity classifier, integrated in this step, decides whether the measurement is good enough to be used for position estimation, by either accepting or rejecting it. The amplitude-threshold classifier described in Section 3.2 was used for this task, with a default threshold of  $T_{rel} = 4$ . Finally a position estimate is obtained by feeding the LOS distance estimates into the least squares algorithm outlined in Section 2.3.

## 5. Experiments

The single-BS array method has been tested in an experimental setting, but not yet in any applications. In this section, the experiment and results are presented.



**Figure 6. Test room layout, with base station (BS) and furniture positions.**

### 5.1. Experimental procedure

A standard office room of 3.73 by 7.70 m and 2.97 m high was used as a test room. Several furniture items like a cupboard, two tables of 0.75 m high, a chair and measurement PC cart were present that could potentially cause the problems of LOS occlusion and multipath interference. The room layout with furniture and BS positions is shown in Fig. 6. The MD was mounted on a pole to ensure a fixed height over a set of measurements. The pole was placed at about 80 locations within the room, with the MD at a height of 1.28 m for most measurements. For some positions the pole was placed on one of the tables, lifting the MD to 2.03 m high. Placement accuracy of the MD was 5 cm or better.

During measurements the MD was held by the experimenter, to simulate the carrying around of the MD by a user. Three different orientations of the ‘user’ (holding the MD) were measured for each position: North, South, and West, shown in Fig. 6. (The East orientation was not measured because it is geometrically similar to the West orientation.) For each position/orientation combination, ten repeated measurements were taken in an approximately 5 s period.

The North orientation is unfavorable, since the user’s body easily occludes the LOS path between BS and MD. Certain positions behind the cupboard suffered from LOS occlusion as well.

### 5.2. Results

First, some selected results will be shown that give an impression of the positioning performance as a function of MD location. After this, the performance over all measure-

ments will be discussed. Selected results for the South orientation are shown in Fig. 7(a). It shows a top view of the room, with 81 true measurement positions shown as circles or crosses. From each true position circle, an error vector points towards the estimated position. This gives an impression of the quality of horizontal position estimates. Note that per position only the error vector of the first measurement repeat is shown. True positions marked with a cross are rejected measurements (Section 4.2). We observe that for many points in the middle of the room, position can be found quite accurately, with errors below 50 cm. The error tends to get worse further away from the BS. Twenty-one measurements were rejected by the validity classifier because the relative amplitude of the LOS peaks was too low. For the six accepted measurements closest to the East wall, the LOS distance measurements are likely degraded by the multipath interference effect, caused by strong acoustic reflections from the East wall, which have a path length just 12 cm longer than the LOS path. However, the resulting position error is acceptable.

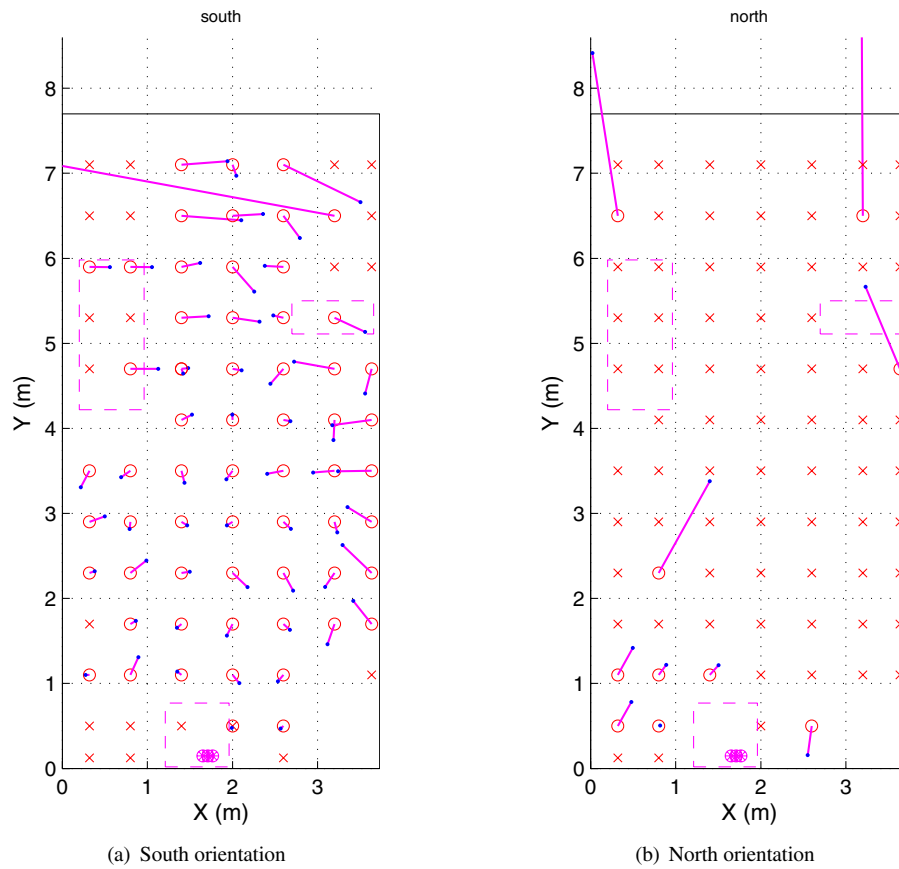
Figure 7(b) shows the error vectors for the North orientation. As expected, valid LOS distances can not be found for most positions, due to LOS occlusion by the user’s body. Still, ten position estimates are found. Four of the north-most estimates have a large error vector pointing North. This happens when acoustic reflection signals are detected instead of the true LOS signal. These reflections were caused by the northern wall, the cupboard, and the ceiling, respectively for the top two, middle and bottom positions of the four.

The total results for all 2410 measurements (now including all ten repeated measurements) are shown in Table 1. For each orientation, the second column lists the percentage of accepted measurements. The third column gives the median value of 3D position errors, over all accepted measurements. The last column gives the 95% bound on the 3D error. It can be seen that for the North orientation, the worst-case position errors are much higher, and most measurements are rejected.

The same 2410 measurements are shown in three graphs in Fig. 8, one graph for each orientation tried. Each graph shows the estimated CDF of three error distributions respectively: total 3D position error, horizontal error and vertical error. The best results are clearly for the South and West orientations, where 95% of 3D position errors are below 1.41 m.

### 5.3. Influence of the validity classifier threshold

For all results above, the measurement validity classifier proposed in Section 3.2 was used with a fixed threshold  $T_{rel} = 4$ . This threshold can be increased to get higher accuracy (with a lower acceptance rate) or decreased to get lower



**Figure 7. Results of 2D position estimation. Vectors point from true positions (o) towards estimated position. Crosses (x) mark rejected measurements. The BS position is marked by ⊗, and dashed lines show the outlines of the furniture items present in the room.**

MD Orientation	Measurement acceptance rate	Median 3D position error (m)	95% Bound on 3D position error (m)
South	74%	0.33	1.14
North	10%	0.65	3.20
West	42%	0.28	1.41

**Table 1. Summary of 3D position estimation results for South, North and West orientations.**

accuracy (but a higher acceptance rate). It should be verified whether the assumption underlying the classifier, that higher relative LOS peak amplitude implies higher probability of validity, is correct.

The assumption was tested by classifying all 2410 measurements as either accepted or rejected a number of times, using each time a different threshold value  $T_{rel}$  ranging from 0.5 to 10. Each time, the median and 95% bound on the 3D position error were calculated for the accepted measurements. Figure 9(a) shows both median error and 95%

error bound as a function of the threshold. It can be seen that error decreases for higher thresholds. However, the acceptance rate also decreases for higher thresholds as shown in Fig. 9(b). For threshold values of 9.4 and higher, all measurements are rejected.

It can be concluded from the graphs that the assumption underlying the classifier is indeed correct, and that the threshold classifier is successful at rejecting high-error measurements. From Fig. 9, the trade-off between accuracy and acceptance rate can be observed.



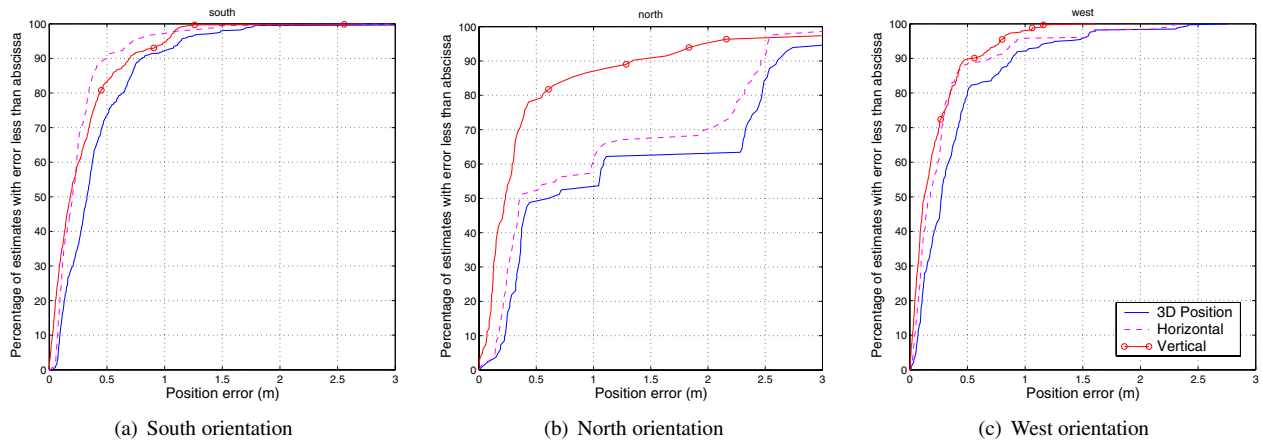
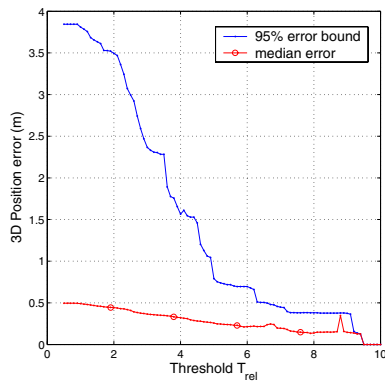
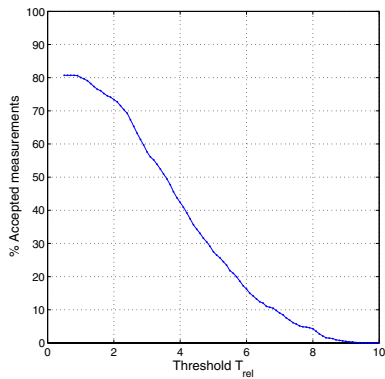


Figure 8. Accuracy distributions of all position estimates, for the three MD orientations respectively.



(a) Median error, and 95% error bound



(b) Acceptance rate

Figure 9. 3D positioning error and acceptance rate as a function of the classifier threshold  $T_{rel}$ , for all three orientation cases combined.

## 5.4. Discussion

From the high rejection rate of the North-orientation position estimates, it can be concluded that LOS occlusion is a major problem for unfavorable orientations of the MD. Also for the obstructed positions behind the cupboard, position estimates were not found because LOS peak detection failed. From the South orientation results in Fig. 7(a) the effect of the unfavorable geometrical configuration, as modeled by the HDOP in Fig. 2(b), can be distinguished. The predicted effects of higher position errors far away from the BS and in the corners next to the BS, are indeed present but are not a major problem as a general ‘awareness’ of 3D position in the room at medium accuracy is still obtained.

## 6. Conclusions

In this paper a positioning method intended for future context aware consumer applications is presented, that estimates 3D positions of devices within a room at medium accuracy (around 1 m). The method accurately measures ultrasound time-of-flight between mobile devices (MDs) and a single base station (BS), and uses trilateration to find the MD position. The BS contains an array of three ultrasound transmitters. A motivation has been given why a minimal infrastructure, and specifically a single BS, is attractive for a consumer location system. Five problems are identified that result directly from the single-BS design. For the problems of unfavorable geometric configuration, line-of-sight (LOS) occlusion, multipath interference, and moving mobile devices, a number of solutions are proposed and research challenges are identified. The fifth problem of BS installation is identified but no solutions are presented yet.

A measurement setup was built to test the single-BS array positioning method, and experiments were performed.

The BS array transducers simultaneously emit three orthogonal coded signals (in a CDMA scheme), which are measured by the MD. A threshold-based classifier was successfully used to classify measurements as valid/invalid. A least squares trilateration algorithm was used to estimate positions for accepted measurements. The experimental results show that an accuracy of 1.41 m or better can be obtained 95% of the time, if there is a good LOS path between the BS and the MD. For the tested situations of LOS occlusion, accuracy drops to 3.20 m or better for 95% of the estimates.

It can be concluded that the positioning performance is promising, but suffers from the LOS occlusion problem. Improvements in the method are needed to cope with LOS occlusion.

*Future work.* As a next step, the severity of the LOS occlusion problem should be studied further for different room layouts and different base station positions, and solutions will have to be found. Secondly it would be worthwhile to evaluate whether including one or more extra transducers on the BS could improve accuracy. Thirdly, the system could perform MD orientation estimation by adding one extra transducer on the MD. Fourth, the threshold validity classifier could be replaced by a probabilistic classifier, which can produce error bounds for position estimates. These can be used for example to combine several measurements into a single more confident position estimate. Fifth, the current LOS distance estimation method can be improved using methods that achieve sub-sample accuracy [3] in distance estimates. Sixth, the BS array could perform *beam-steering* [22] which can be used as an alternative method to obtain accurate measurements of the angular direction of a target MD. Finally, ultrasound reflections in the room could be used [5] to give clues about likely MD positions, for situations where a good LOS signal is not available.

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