# Acoustic Indoor-Localization System for Smart Phones


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***Abstract*— In this paper we present our acoustic indoor-localization system ASSIST (Acoustic Self-calibrating System for Indoor Smart phone Tracking) running on embedded ARM CPUs. The developed system uses acoustic signals beyond the audible range to localize COTS (commercial off-the-shelf) smart phones. The sound receivers installed with the infrastructure are connected using a Wi-Fi network. Furthermore, the sound receivers synchronize the clocks and exchange the time differences of arrival of the received sound signals from the Wi-Fi network. In this way, using an iterative multilateration algorithm, the locations of smart phones are calculated. We present our developed novel receiver hardware. The integrated single-board computer based on ARM replaces the external computer units to synchronize the receivers with the network and calculates the position via a TDoA (Time Difference of Arrival) algorithm. By powering the receivers via power-over-Ethernet the installation effort is minimized. The integrated inertial sensors of the smart phone can be used to calculate the position in a non-line of sight condition. Therefore different methods are available to support the position calculation for ASSIST.**



***Keywords-component; TDoA, acoustic, smart phone, indoor localization.***


## Introduction

Smart phone localization in outdoor areas is reliable due to ubiquitous infrastructures such as GPS and GSM localization. Using the commercially available smart phones the infrastructure cost is significantly reduced. Moreover the cost of the indoor localization system is minimized , particularly for the end-users. However, the outdoor localization methods do not cover indoor areas. New methods are necessary for using smart phones for localization in indoor-areas. One possibility is to use the propagation of sound for localizing the smart phones [9]. The smart phones can generate sound from their built-in speaker or they can detect sound with the integrated microphone.

Fig. 1 shows an overview of the different technologies and the achievable accuracy of indoor localization systems based on COTS smart phones which were developed by different scientific research groups.

For ordinary indoor localization, which is needed for e.g. in supermarket scenarios, the sound signals should be outside of the human audible range. Most of the other systems are using the mobile phone as a receiver. Therefore the system can only work with low frequencies due to the limitation of the microphone (sampling rate / anti-aliasing filter). In contrast our ASSIST uses stationary receivers; the microphones of these receivers can be designed specifically for the task at hand, i.e. sensitivity for inaudible frequencies. At the same time, the microphones of the handheld devices need not to satisfy any specific requirements; in fact, the mobile devices would need no microphones at all. Another advantage of having the receivers stationary lies in the fact that for stationary receivers, the problem of ambient noises resulting from mechanical contact between the user and the device cannot occur. In contrast, for mobile receivers, especially when the device is worn inside a pocket, ambient noises can become significant.

As experiments have demonstrated in [11] that speakers of the smartphones are capable to produce sounds in the range between 18 and 21 kHz, or even 23 kHz. As a result, the present system improves the efficiency and robustness of a smartphone localization system based on sound. Only our ASSIST, which was presented in [1], and two other state-of-the-art systems operate outside of the audible range, cf. Fig. 1.

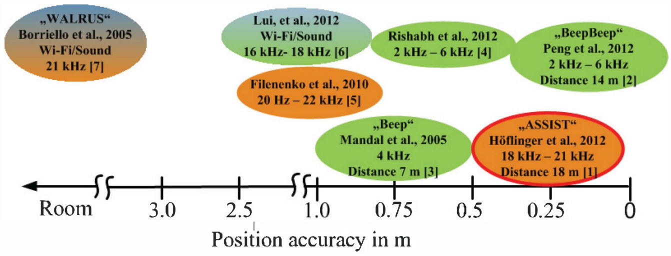


Fig. 1. Overview of the different technologies and the achievable accuracy of the indoor localization systems based on COTS smart phones developed by different scientific research groups.

## Embedded Hardware and Envelope Detection

Within this presented work the previously used external computer unit is replaced by a single-board Gumstix Overo to synchronize the receivers by network and calculate the position by Time Differences of Arrival (TDoA). Due to powering the receivers via ethernet the installation effort is minimized, as only one cable is required. Alternatively, the Gumstix could be battery powered, and Wi-Fi communication could be used [10], so no cables are required at all. Figures 2 and 3 show the block diagram of the receiver and the hardware.

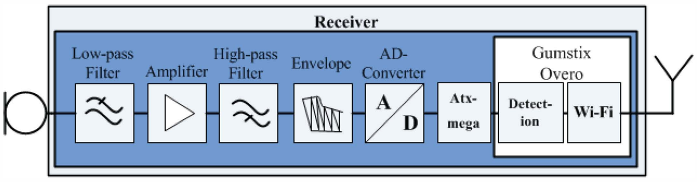


Fig. 2. Block diagram of the receiver with envelope detection.

In our first approach [1] on x86 hardware we used linear chirp signals and calculated the correlation of incoming signals. Due to the limited computing power of the embedded hardware we resort to envelope detection based on the signal amplitude, cf. Fig. 2. Here, the smart phone generates short sound impulses with 18 kHz and 300 ms period of time.

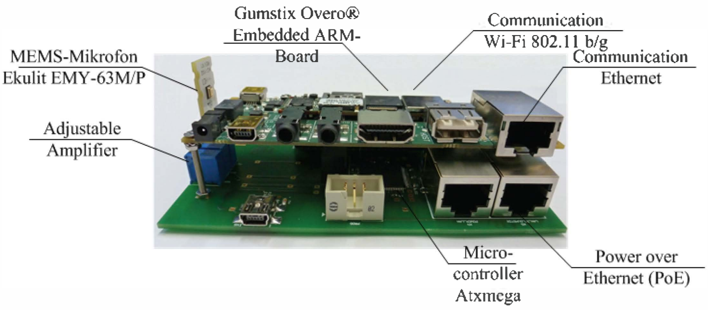


Fig. 3. Receiver-PCB with filter module, an analog to digital converter and an implemented single-board Gumstix Overo ARM board.

The approach of using envelope detection of sound signals is simple, yet the limited hardware does not allow for more sophisticated signal detection algorithms. The amplitude $A$ of sound decreases with distance $r$ according to $A \sim 1/r$. Therefore, signals become hard to distinguish at larger distances in the presence of background noise. However, using a sensitive MEMS microphone, detection ranges up to 10 m may be achieved, which is adequate for most applications.

The Gumstix Overo records the digital data and searches the sound or ultrasound stream for distinctive audio events. In this threshold-based approach, the background noise is filtered implicitly [9]. In comparison of various amplitude-based detection techniques, threshold comparison turned out to be the most robust approach with only minor drawbacks in precision. However, when signals are smooth, like the human voice, the time point of signal detection cannot be clearly determined.

## EXPERIMENTAL RESULTS

To measure the maximum transmission distance of smartphones with the envelope detection, the number of received signals was measured at different distances d. The experimental setup of the measurement is seen in Fig. 4. The height of the smartphone $h_T$ and receiver $h_R$ is 1,2 m. The experiment was taken place in an industrial hall. The signal from the smart phones reaches the receiver with several echoes and reflections from the objects in indoor areas due to multipath propagation. The reflections reach the receiver in/out of phase which generates a greater or lower amplitude (interferences). This leads to a poor identification of the time stamps from the line of sight (LOS) signals.

The percentages of received signals are depicted in Fig. 5. The figure shows the arrived signals as a function of distance. The developed receivers were able to receive more than 70% of the transmitted signals up to a distance of 10 m. Note that the variation of reception is comparatively high.

The signals reach the receiver with several echoes and reflections from the objects in indoor areas due to multipath propagation. The reflections reach the receiver in/out of phase which generates greater or lower amplitude (interferences). This leads to a poor identification of the time stamps from the line of sight (LOS) signals. In a distance of 2 – 5 m more signal losses were observed due to ground reflections.

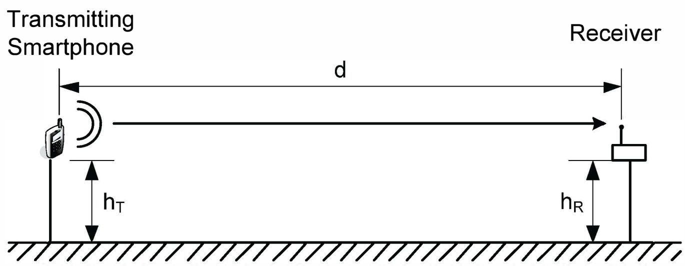


Fig. 4. Setup for determining the range of the system

In an additional static experiment with two receivers in a distance of 5 m we were able to localize the smart phone with an error of 11 cm (RMS).

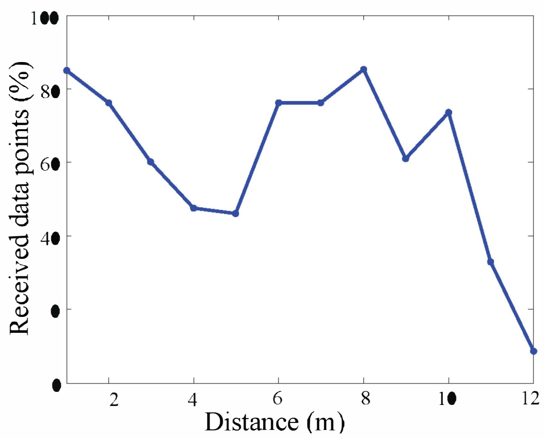


Fig. 5. Received data points of the envelope detection depending on the distance.

To evaluate the accuracy of the localization system we built a set of 10 receivers. In a real-world scenario we placed the receivers at a height of 1.2 m inside of a hall around a free space, see Fig. 6. A smartphone was carried by a user throughout of the free space on a random trajectory. The receivers obtain the sound signals and calculate synchronized time stamps through the common time base.

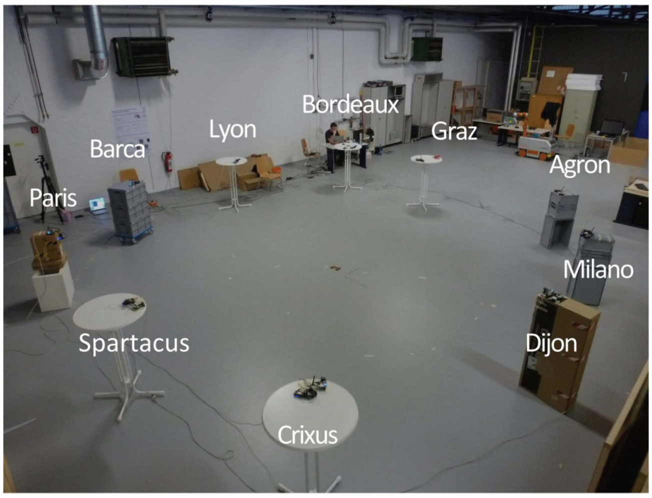


Fig. 6. Overview of the experimental setup. 10 receivers are placed around the experimental area.

A server unit obtains the recorded timestamps from the receivers via network. Knowing the propagation speed of sound and the arrival times at the receivers, the position of the smartphone is be calculated by an TDoA optimization based on spring relaxation. The algorithm was introduced in [10].

In addition to the acoustic localization system, the smartphone was tracked by a optical motion capturing system to generate a reference trajectory ("ground truth"). Fig. 7 illustrates the result of the localization. The mean square error to the reference was 0.25 m – not more than the size of a tablet. The error distribution is shown in Fig.8.

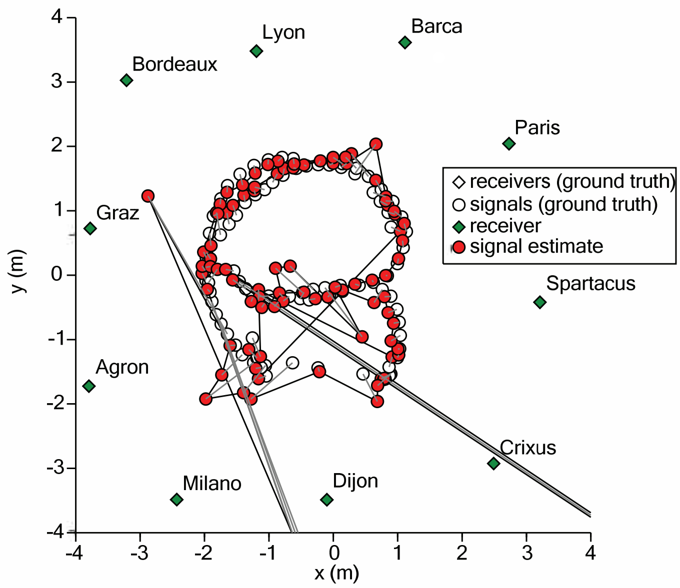


Fig. 7. Experimental localization result with iterative Cone Alignment algorithm, a spring optimization algorithm.

Measurement outliers occur due to environmental effects such as multipath propagation. The signal from the smart phones arrive at the receivers with several reflections from the objects. By using a sequential Monte-Carlo sampling method, also known as particle filter and by using a Kalman filter, the localization of the smartphone may be robustly calculated, hereby compensating for the outliers.

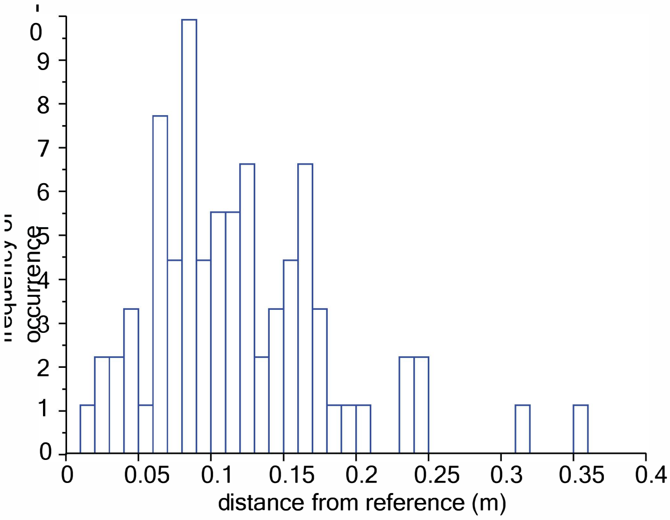


Fig. 8. Measurement errors of ASSIST with envelope detection and an TDoA optimization algorithm in a real-world enviroment

## Localization with Inertial Sensors

Besides infrastructure based indoor localization, the built-in inertial sensor in the smart phone can be used to determine position information. Similar as the conventional inertial sensor navigation application, accelerometer, gyroscope and magnetometer are able to provide long term stable orientation information using sensor data fusion. In order to determine correct velocity and position, a smart phone needs to be mounted on the foot to remove the accumulated drift error. However, attachment of a smart phone on the foot is not convenient due to its comparable large size. Besides, the smart phone is meant to be held in hand. The other solution is to analyze the acceleration data from a hand-hold smart phone to extract the step length information using either a biomechanic model or empirical method. Since the direction can be obtained using sensor data fusion, the trajectory can be successfully determined. Notice that the inertial sensor based tracking using a hand-hold smart phone is limited to two dimensions. Detail investigations focused on localization with inertial sensors can be found in [8].

## Conclusion and Outlook

In this paper, we presented new embedded receivers and an envelope detection algorithm for our smart phone indoor localization system. In real-world scenarios we could track the smartphone with an error of 25 cm. Using the envelope detection, our receiver can receive more than 70% of the transmitted signals up to a distance of 10 m from a smart phone. In future investigations we will improve the localization and port the correlation method of chirps from laptops to our single-board Gumstix Overo using a more efficient algorithmic implementation.

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