Indoor Positioning with Unsynchronized Sound Sources

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***Abstract* – This paper describes a work on indoor positioning system for cellular phones and IoT devices. The uniqueness of the system is its ability to provide simultaneous and accurate positioning of many users, based on merely three acoustic signals transmissions from stationary Beacons, without timing synchronization or position calibration. In the demonstrated system, cellular phones were operating with their internal, unsynchronized clock at a sampling rate of 44,100 samples per second. This sampling rate has enabled using positioning signals beyond the human hearing range, not interfering with audible signals. The system was deployed and demonstrated successfully in crowded places while providing positioning accuracy of centimeters.**

Keywords – Acoustic Positioning, Localization, Time of Arrival.

I. Introduction

In recent years, cellular phones are widely used for GPS-based navigation. There is a growing demand to provide navigation in areas where GPS signals cannot be received such as airports, hospitals, and shopping centers. Furthermore, in the IoT era it is required to provide better than GPS accuracy for locating appliances and devices, finding rental cars pickup spots or a hotel room door in a corridor.

Indoor positioning methods are based either on electromagnetic waves such as Wi-Fi and Bluetooth or on acoustic waves. An advantage of acoustic based positioning is that acoustic waves propagation speed is a million times slower than that of electromagnetic waves. Thus, for a desired positioning accuracy, the sampling rate of an acoustic wave can be considerably lower than that of an electromagnetic wave. Another advantage of acoustic based positioning is that while Wi-Fi and Bluetooth commercial components in cellular phones and IoT devices merely provide binary data and received signal strength (RSSI), sampling an acoustic wave at the signal Nyquist rate provides all the information about the received signal at any point in time, which enables applying advanced signal processing algorithms.

A common configuration of an acoustic positioning system is based on transmission of acoustic signals from Beacons, composed of audio amplifiers and loudspeakers located at known positions. In such a system, we refer to the devices to be positioned as "Mobile Devices". The Mobile Devices receive the Beacons' signals and measure the time differences between their arrivals. This method, known as "Time of Arrival" (ToA), can provide an accurate positioning of the Mobile Devices. Yet the disadvantage of such systems is that all the Beacons' transmissions must be synchronized for accurate ToA measurements by the Mobile Devices. Since timing synchronization is essential, a straightforward approach is to drive all the Beacons from the same audio source [1], resulting in considerable constraints on the system design.

If the Beacons are not synchronized, synchronization can be achieved by transmission of acoustic signals by the Mobile Devices [2]. Transmission of acoustic signals by the Mobile Devices eliminates the possibility to position multiple devices simultaneously and requires adding strong enough loudspeakers to the Mobile Devices.

In this paper, we describe an acoustic positioning system implemented and demonstrated successfully without the requirements of neither acoustic transmission by the Mobile Devices, nor timing synchronization of the Beacons. The system is self-calibrating, and thus immediate deployment and use are provided.

II. System Configuration

Fig. 1 shows the proposed system for positioning a Mobile Device with unsynchronized sound sources. The system includes three stationary Beacons, each equipped with a loudspeaker and a microphone. The Beacons are connected via a wireless link to a Server. The Mobile Device is equipped with a microphone and is connected to the Server via a wireless link.

The acoustic signals emitted by the Beacons are received by the microphone of the Mobile Device and by the microphones of the Beacons, including the emitting Beacon.

There is no common clock source in the system, and each Beacon and Mobile device operates with its own local unsynchronized clock source for sampling.

The signal sampling rate of the Beacons and the Mobile Device is 44,100 samples/second, enabling the use of acoustic signals beyond the human hearing range.

Since any cellular phone supports an audio sampling rate of 44,100 samples/second, cellular phones were used as the Mobile Devices in the demo system.

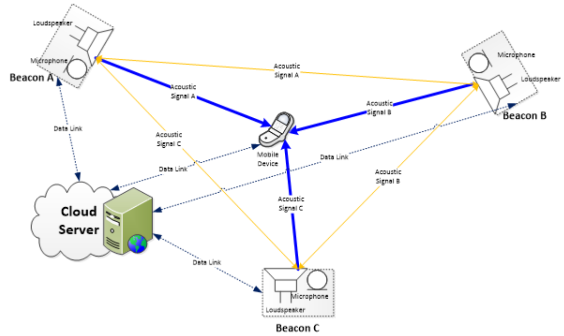

Figure 1: proposed Acoustic Positioning System Configuration

Cellular phones were used for the Beacons microphones, for server communication and for the sound source of the Beacons audio amplifiers.

In the proposed positioning system, acoustic signals are emitted only by the Beacons, while Mobile Devices only receive and do not transmit any sound. As a result, there is no limit to the amount of Mobile Devices that can be positioned simultaneously by this system. Accurate positioning of multiple Mobile Devices is achieved immediately following three acoustic signals transmission by the Beacons.

The user interface is comprised of a simple "Find" button, requesting the server to position all the devices connected to it in the same area as the user. The Mobile Devices display the Beacons and Mobile Devices positions on a map.

In the following description of the positioning algorithm, the Beacons are referred to as "Active Devices" since they emit acoustic signals. The Mobile Devices do not emit acoustic signals; hence, they are referred to as "Passive Devices"

III. Active Devices Positioning

The method in which the system operates without a common clock source is that each device (Active or Passive) measures the time delay between the acoustic signals they receive, including their own emitted signal in case of an Active device. The measurement results are uploaded to a server.

In the first stage, the server computes the Active Devices positions. As shown in Fig. 1, an Active device is equipped with a loudspeakers and a microphone.

Distance measurement between two Active devices is shown in Fig. 2. The process begins when Active Devices 1 and 2 start to record using their microphones. Then, Device 1 emits an acoustic signal that is recorded by both Device 1 and Device 2. As shown in Fig. 2, after receiving Device 1's signal, Device 2 emits an acoustic signal which is recorded by both devices.

The audio recordings are analyzed by each device in order to determine the time difference between the recorded signals. For that purpose, correlation with the known waveform of the emitted signals is applied. Signal correlation is also a matched filter applied on the received signal, eliminating any frequency components outside of the transmitted signal band and thus improving the system's immunity to noise.

For distance calculation, we denote ΔT the Round Trip Time (RTT) of the signal from Device 1 to Device 2 and back, and Δt as the time delay between receiving Device 1's signal by Device 2, and transmitting a signal by Device 2, as shown in Fig. 2.

Since both the transmitted and received signals are sampled by both Devices, ΔT can be measured internally by Device 1 without clock synchronization with Device 2. Similarly, Δt can be measured internally by Device 2 without clock synchronization with Device 1.

The distance between two devices can then be calculated by using eqn. (1), in which the response time is subtracted from the round trip time and v_{sound} is the speed of sound.

$$d = \frac{\Delta T - \Delta t}{2} \cdot v_{sound} \qquad (1)$$

The algorithm described above for measuring the distance between two Active Devices can be extended to measure the distances between all the Active Devices in the system with a single transmission per Active Device, eliminating the need to measure the distances per each pair separately. The signals recorded by the Active Devices, including of their own emitted signals, can be used in various combinations to calculate the distances between all the Active devices. Only a single transmission is required per Active device as shown in Fig. 3.

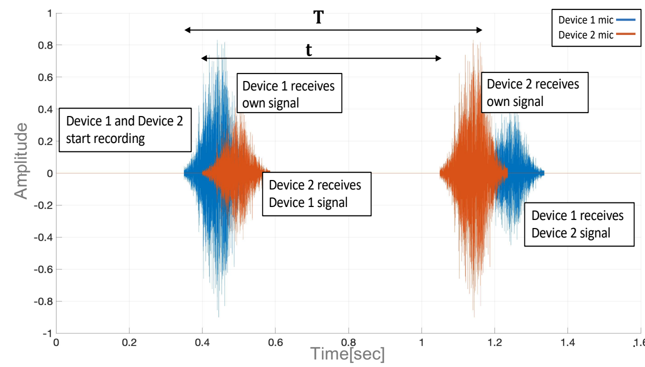

Figure 2: Active Devices Distance Measurement

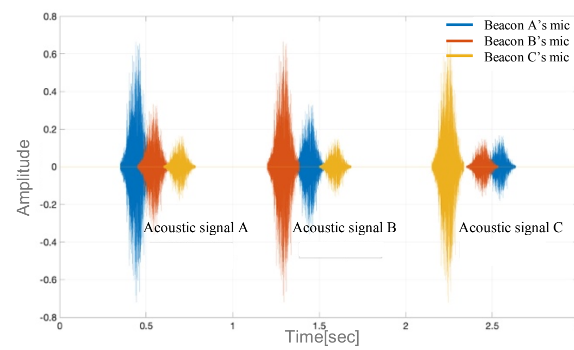

Figure 3: Multiple Active device signals recording with a single transmission per Active device

IV. Area Mapping

The second stage of the algorithm is area mapping. As shown in Fig. 4, once the distances between all the Active Devices are calculated, Active Device (Beacon) A is considered to be at the Origin of a Cartesian coordinate system and Beacon B is on the x-axis of this coordinate system with its x coordinate value equal to its measured distance from Beacon A. The coordinates of Beacon C are computed through circle intersection where the centers of the circles are Beacon A and Beacon B, and their radii are the measured distances from Beacon A to Beacon C and from Beacon B to Beacon C, accordingly.

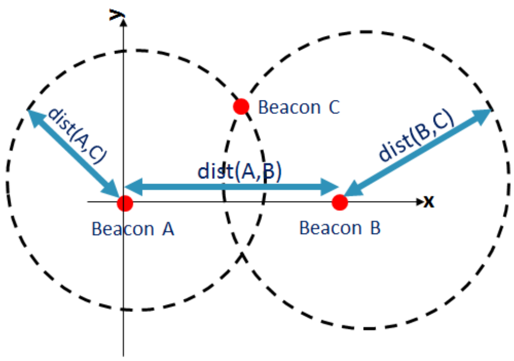

Figure 4: Beacons Positioning through distances measurements and circles intersection

V. PASSIVE DEVICES POSITIONING

At the third stage, occurring after the Active Devices are positioned on a map, the signals received by the Passive Device are analyzed to determine its position.

In Fig. 5, three Active Devices M, N and P and a Passive Device X are shown. At this stage, the distances α, β and γ between the Active devices are known, and the distances **a**, **b** and **c** between the Passive device and the Active devices shall be computed.

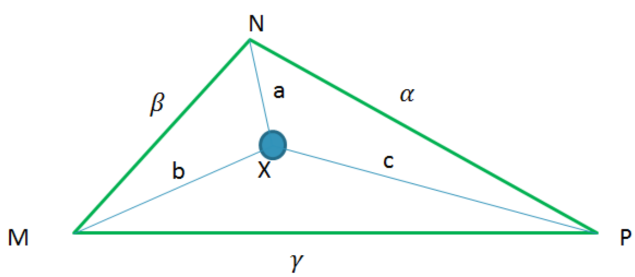

Figure 5: Three Active devices M, N, P and a Passive device X

From the measurements performed by the Passive Device, the following set of linear equations can be constructed:

$$\begin{pmatrix} \beta \\ \gamma \\ \alpha \end{pmatrix} + \begin{pmatrix} -1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} b \\ c \\ a \end{pmatrix} = \begin{pmatrix} \Delta d1 \\ \Delta d2 \\ \Delta d3 \end{pmatrix} \qquad (2)$$

$\Delta d1$ is the length difference between an indirect path from M to X through N and the direct path from M to X. This path length difference can be measured by the Passive Device based on the signals it receives and sample by its internal clock, and the known distance from M to N. In a similar manner, we compute the path length differences $\Delta d2$ and $\Delta d3$ between the direct and indirect paths from M to X through P vs. the direct path from M to P, and the path length difference from N to X through P vs. the direct path from N to P correspondingly.

The matrix in (2) is a singular matrix, and thus linear algebra will not provide a unique solution for the values of **a**, **b** and **c**. To overcome this, we applied an iterative method based on circle intersection. As depicted in Fig. 6, three circles are centered at the Beacons positions. The radii of these circles are the iterative distances estimation from each Active Device to the Passive Device. Once we set a value for **a**, the values of **b** and **c** are determined by eqn. (2).

An iterative process starts with setting a minimal value for **a** and calculating the corresponding values of **b** and **c** from (2). Using **a, b** and **c** three circles are drawn with the corresponding radii around Beacons M, N and P. Then we find the four (or less) intersection points of the three circles. The minimum Euclidian distance between the intersection points of the circles is a success criterion for the current iteration. In the next iteration, the value of **a** is incremented by a small step according to the required accuracy of the positioning estimation.

The minimum Euclidian distance between circle intersection points per iteration provides an error function, as depicted in Fig. 7. The value of **a** corresponding to the minimum of the error function provides the best estimation for the distance of the Passive Device from Active Device N. The distances **b** and **c** from Active Devices M and P are then calculated from (2).

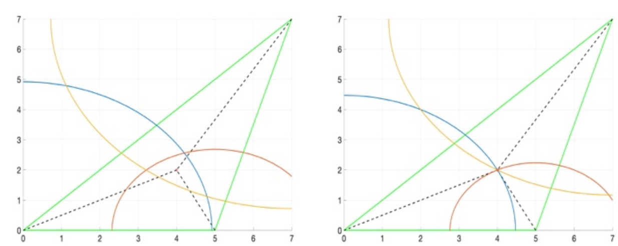

Figure 6: Iterative process for finding the Passive device position through circles intersection

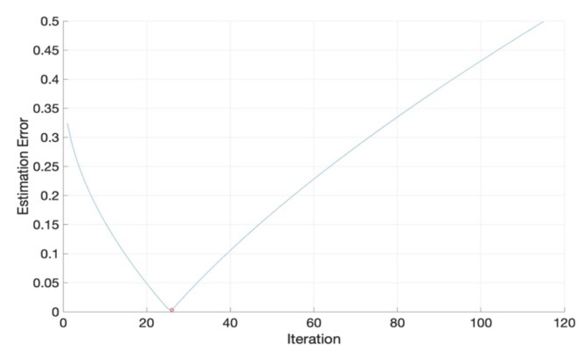

Figure 7: Example of error function Vs. Iteration number

The Cartesian coordinates of X can then be computed. First, the distances between X and each of the edges α, β, γ are calculated by applying the law of Cosines. For instance, to find the distance between X and γ, the Law of Cosines is applied in triangle ΔMXP:

$$b^2 = c^2 + \gamma^2 - 2c\gamma \cdot \cos(\measuredangle MPX) \qquad (3)$$

$$\Rightarrow \cos(\measuredangle MPX) = \frac{c^2 + \gamma^2 - b^2}{2c\gamma} \qquad (4)$$

$$\Rightarrow c \cdot \cos(\measuredangle MPX) = \frac{c^2+\gamma^2-b^2}{2\gamma} = e \qquad (5)$$

$$\Rightarrow e^2 = \frac{(c^2 + \gamma^2 - b^2)^2}{4\gamma^2} \quad (6)$$

$$\Rightarrow \sqrt{c^2 - e^2} = \sqrt{\frac{4c^2\gamma^2 - (c^2 + \gamma^2 - b^2)^2}{4\gamma^2}} \quad (7)$$

$$\Rightarrow d = \sqrt{\frac{4c^2\gamma^2 - (c^2 + \gamma^2 - b^2)^2}{4\gamma^2}} \quad (8)$$

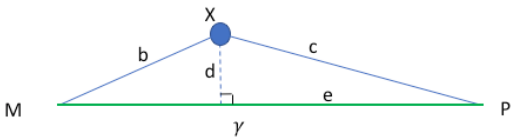

Figure 8: MXP Triangle

Applying similar calculations in triangles $\Delta MXN, \Delta NXP$ will derive X's distances from β and α, respectively. Now, the equations of the three lines parallel to the triangle edges with the calculated distances above are computed. The slopes of the lines are the same as the edges' slopes. For example, the slope of MP:

$$m_{MP} = \frac{y_P - y_M}{x_P - x_M} \quad (9)$$

To find the y-intercept of each line, the distance between two straight lines formula is applied:

$$dist = \frac{|n_2 - n_1|}{\sqrt{m^2+1}} \Rightarrow n_2 = n_1 \pm dist \cdot \sqrt{m^2 + 1} \quad (10)$$

where m is the slope and n_1, n_2 are the y-intercepts of the two lines. Since m, n_1 and $dist$ are already known, n_2 is easily derived for each of the three parallel lines. The common intersection point of the three lines is in the Cartesian coordinates of X.

VI. Performance Evaluation

Evaluation of the proposed system performance was done by setting three Beacons in a hall with different distances ranging from 0.5[m] to 5[m], and measuring the error of the Passive Devices between 1.5[m] to 2.5[m] with an equilateral triangle Beacon setups. The performance has met the design goals both for the Beacons and the Mobile Devices positioning, which is an error rate of 5% and under, as depicted in figures 9 and 10.

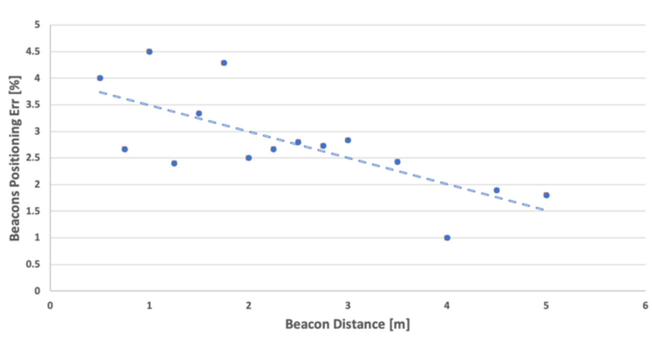

Figure 9: Beacons positioning error

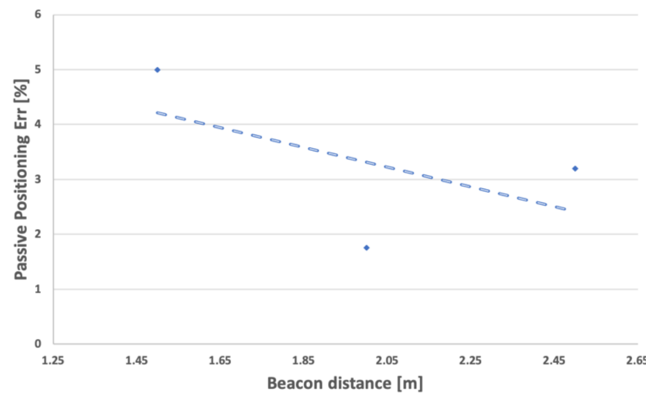

Figure 10: Passive Device positioning error with equilateral triangle Beacons setup

VII. Conclusions

The motivation for this work was to build and demonstrate an accurate indoor positioning system for cellular phones and IoT devices based on commercially available elements. A key requirement derived from using commercial elements was independence in timing synchronization. For easy and immediate deployment, the system is self-calibrating and thus no prior knowledge about the Beacons' positions is required.

We have achieved a performance suitable for high accuracy positioning applications, with successful signal detection in noisy areas and with real-time implementation on a server.

Future work shall include computation complexity reduction through analytic rather than iterative process, signals waveform optimization in both duration and frequency range, distributed computation by the Mobile Devices rather than by the server in order to increase the system's overall processing power with proportion to the number of mobile devices, and multi-room support where one cloud server shall control positioning of multiple devices in several areas.

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