Robust Ultrasound-Based Room-Level Localization System Using COTS Components

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***Abstract*—Location-based services have become very popular in recent years. Although many previous works targeted the problem of indoor localization, several reasons still prevent the widespread adoption of most systems' implementations. Some of these reasons are their insufficient availability, and the need for extensive node deployment and maintenance. In this work, we present a highly accurate room-level indoor localization system that is based on ultrasound technology. Our system is robust to noise, scalable, has a low complexity on the receiver, and does not require synchronization between transmitter and receiver. Moreover, it uses commercial off-the-shelf (COTS) components and does not require special hardware or additional infrastructure to be deployed. The system relies solely on ultrasound, and does not use any RF signals. To deal with the problem of signal interference, we explain how signal collisions can be detected, and we propose a method for collision avoidance. The system was implemented and tested in scenarios with realistic conditions. The results prove that the proposed system is accurate and robust to ambient noise. This work was conducted in the frame of the European project 'SmartHeat', which aims to improve heating conditions of elderly people, and reduce energy consumption. It employs rooms' occupancy information with other inputs, to adapt the heating according to users' habits.**

I. Introduction and Related Work

In recent years, location-based services have become very popular, due to the fast increase in the number of mobile devices. As people spend most of their time indoors, a reliable indoor localization system would have a great impact on the location-based applications that they use. Global Navigation Satellite Systems (GNSS), like the Global Positioning System (GPS), are the prevalent technology for positioning outdoors. However, it is not possible to use them for indoor localization, as their signals are obstructed.

For indoor localization, several technologies have been investigated [1], [2], [3], many systems were tested, and numerous methods were suggested to improve their performance. These systems rely on different technologies like WiFi [4], [5],Bluetooth [6], [7], ultra-wideband [8], ultrasound [9], or hybrid technologies [10], [11]. However, there is currently no standard for an indoor localization system, like it is the case for GPS. Some of the main reasons are the insufficient availability, and the need for extensive node deployment and maintenance, which prevent the widescale adoption of most systems' implementations [12]. Thus, a robust, reliable, and widely available indoor localization system would pave the way for a wide range of applications.

The required accuracy level varies according to the corresponding application. While exact positioning is needed for some applications, room-level accuracy would be sufficient for some others. As exact positioning usually requires more hardware to be deployed, applications that only require a room-level accuracy, aim for a localization system that uses the least possible equipment, and that is easy to deploy. Moreover, an ideal room-level localization system should be easily scalable.

Room-level localization has been the subject of many research works. Some of the works suggest the use of RF-based technologies, using the received signal strength (RSS) to infer the position of the receiver. RSS values are compared against known propagation models to determine the receiver's position. One option is to use Bluetooth Low Energy (BLE), by placing one BLE beacon per room, like in [13], [14]. However, as electromagnetic signals are not confined to the room limits in general, the accuracy may deteriorate due signal leakage leading to confusion of RSS values, especially when the rooms have different dimensions. Therefore, a dense deployment of beacons is required to get a satisfactory accuracy, which may become expensive and impractical in large deployments. The accuracy of RF-based systems can be enhanced by using fingerprinting techniques. In this context, previous works suggested the use of cellular networks signals [15], WiFi signals [16], [17] or Bluetooth [18]. Collecting fingerprint maps of the RSS values requires an off-line training phase, in order to compare them to the measurements obtained in real time, and map these measurements to the correct room. However, these systems in general do not achieve perfect room accuracy, as in some scenarios we might end up with different points having very similar RSS fingerprints. Additionally, the need for an off-line phase is time consuming and can add a significant overhead when deploying on a large scale.

Some other studies proposed the use of sound waves. SoundLoc [19] uses sound signals to infer unique signatures

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for different rooms. A limitation of this sytem is that it requires a training phase, as well as relying on audible sounds which might be disturbing for people. Shahid *et al.* [20] used dedicated ultrasound beacons for room-level localization. However, their system requires special ultrasonic transducers that operate at a frequency of 40kHz. Borriello *et al.* [21] used a combination of ultrasound and WiFi packets, generated by PCs to achieve room level accuracy. Nonetheless, the system requires having PCs in all the rooms, which may not be available on all environments.

The contribution of our work is a room-level localization system that uses ultrasound signals solely, without any RF signals. Moreover, our system uses commercial off-the-shelf (COTS) components, like mobile phones, commercial loudspeakers, and does not need special hardware or an additional infrastructure to be deployed. The proposed system is accurate and robust to ambient noise and signal interference. It was implemented and experimentally tested in order to characterize its performance.

The rest of this paper is organized as follows. Section II provides a general background about ultrasound technology. Then, Section III details the design aspects of our system, Section IV presents the packet collision detection and avoidance methods, and in Section V the system's characteristic features are discussed. The experimental setup and the testing results are shown in Section VI. Finally, future work directions along with conclusions drawn are presented in Section VII.

II. Background

Ultrasound signals are sound waves above the human hearing range, and share the same physical properties with audible acoustic waves. The human hearing capability is limited to a certain frequency range, considered to be between 20Hz and 20kHz [22]. Sound waves above 20kHz are non-audible and are called ultrasound. Figure 1 shows the frequency ranges of sound waves, which can be categorized into infrasound, audible sound, and ultrasound.

Fig. 1. Frequency ranges of acoustic signals

The use of ultrasound technology for indoor localization is interesting. Because of their nature, ultrasonic waves are inherently limited by walls and doors, which makes them an excellent choice to achieve room-level granularity, as compared to other RF-based technologies (WiFi, Bluetooth, etc). Another interesting fact is that most commercial devices support a certain frequency range of ultrasound, namely that of 20-22kHz. The common sampling rate used in sound cards is 44.1kHz, while some are even higher. This rate determines the Nyquist frequency, which is the maximum frequency that speakers and microphones can support, and is equal to half of the sampling rate, or 22.05kHz.

Filonenko *et al.* [23] demonstrated the ability of mobile phones to support ultrasound at the frequency range of 20-22kHz. In our work, we have run additional tests to prove that it is also the case for other devices including commercial loudspeakers and microphones, in addition to mobile phones. The devices that we tested are the following: Samsung Galaxy S4 and S5, HTC One M7, Nexus 5X, Logitech and Creative loudspeakers, Logitech and Blue microphones. Although we have tested a limited number of devices, other ones should also enjoy the same capabilities, given that they use a sampling rate of 44.1kHz or above.

III. System Design

A. Architecture

Our localization system is composed of one transmitter per room and a single receiver. The transmitter is a commercial loudspeaker. However, custom made ultrasound beacons can also be used instead. Each room needs to have one transmitter, which periodically emits an ultrasonic signal. The broadcasted signal contains information thar relates it to the room. On the other side, the receiver is a mobile device that captures the ultrasonic signals and identifies the corresponding room. The receiver needs to have a microphone, it can be a smartphone, a tablet, a smartwatch, or even a robot equipped with a microphone.

B. Ultrasound Signal Design

The design of the transmitted ultrasonic signal used for localization is critical. It should be supported by commercial loudspeakers and microphones, and also be non-audible at the same time. Moreover, the signal should be detected and decoded robustly in noisy environments, and has to accommodate for multiple rooms. The previous requirements translate into the following points:

1) The signal frequency bandwidth should be picked from the frequency band 20-22kHz
2) The signal form should ensure a good autocorrelation
3) The signal modulation is to be carefully chosen so that it accommodates for any number of rooms

Taking these constraints into consideration, we decided to use the chirp signal, and design the ultrasound signal as a packet containing two parts, as shown in Figure 2: the first part is the *pilot signal*, common to all rooms, and the second part is the *identifier* represented by a binary sequence. Having the transmitted signal composed of two parts, instead of one, reduces the computational complexity at the receiver side, and makes the decoding process simpler, as will be discussed later in Section V.

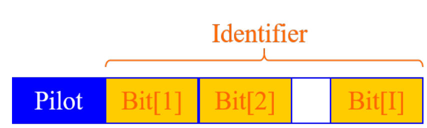

Fig. 2. Design of the transmitted ultrasound packet

1) Pilot Signal: The pilot signal is composed of one chirp pulse. Peng *et al.* [24] proposed the use of the linear chirp signal in ultrasound systems, as it has a good autocorrelation function. A linear chirp is a signal whose frequency increases linearly with time. During experimental tests, when the amplitude of the chirp signal was not properly scaled, we noticed that the loudspeaker generates an unpleasant tick sound, due to the abrupt change in the amplitude of the audio signal. Therefore, to guarantee a smooth performance, we decided to scale the chirp pulse by a triangular function, so that its amplitude increases gradually at the start, and decreases similarly at the end. The continuous time domain representation of the chirp scaled by a triangular function is given by the following formula:

$$x(t) = \begin{cases} \frac{2t}{T_{chirp}} \sin(2\pi f_0 t + \frac{q}{2}t^2) & \text{for } 0 \leq t \leq \frac{T_{chirp}}{2} \\ (2 - \frac{2t}{T_{chirp}}) \sin(2\pi f_0 t + \frac{q}{2}t^2) & \text{for } \frac{T_{chirp}}{2} < t \leq T_{chirp} \end{cases}$$

where T_{chirp} is the chirp duration, f_0 and f_1 are the lower and upper frequency limits of the chirp respectively, and $q = {(f_1 - f_0)}/{2}$.

In our system, we manipulate and process the ultrasonic signal in discrete-time domain. The discrete-time representation of the chirp then becomes:

$$x[n] = \begin{cases} \frac{2n}{N} \sin(2\pi(\frac{f_0}{f_s})n + \frac{q}{2}(\frac{n}{f_s})^2) & \text{for } 0 \leq n \leq \lfloor \frac{N}{2} \rfloor \\ (2 - \frac{2n}{N}) \sin(2\pi(\frac{f_0}{f_s})n + \frac{q}{2}(\frac{n}{f_s})^2) & \text{for } \lfloor \frac{N}{2} \rfloor < n \leq N \end{cases}$$

where f_s is the sampling frequency, and $N = f_s \times T_{chirp}$.

As a design choice, we select the lower and upper frequency limit of the chirp to be 20kHz and 20.5kHz respectively. The length of the chirp pulse is an important factor for accurate detection. The pulse needs to be long enough to be resistant to noise, and short enough to reduce computational complexity and power consumption on the receiver side. As a trade-off, we empirically chose the pulse duration to be 10ms. Figure 3 shows the time plot of the pilot signal, composed of a single chirp pulse.

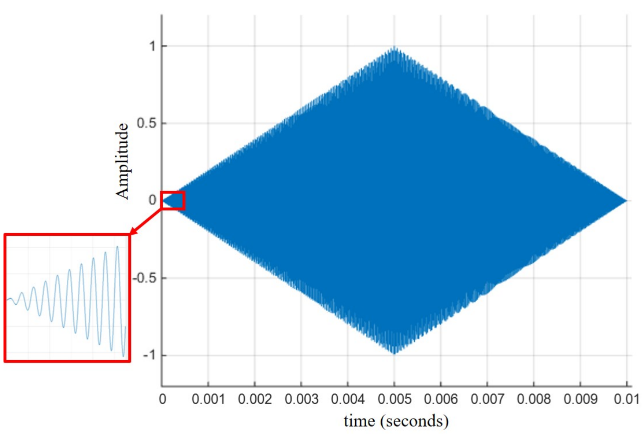

Fig. 3. Time plot of the scaled pilot chirp signal

2) Identifier: Our system is intended to rely only on ultrasound, without the need for RF signals like Bluetooth or WiFi. Therefore, the source's unique identifier should be embedded in the ultrasonic signal itself. To achieve this, we use frequency multiplexing as a modulation scheme, and we append additional chirp signals to the pilot. This way of signal modulation ensures flexibility and scalability of the system. The identifier is a unique binary sequence, represented by a train of chirp pulses. Bits 0 and 1 are assigned to two chirp signals with different frequencies. We choose to represent the bit 0 by a chirp whose frequency band is 20.5-21kHz, and the bit 1 by another chirp of 21-21.5kHz. Figure 4 shows the frequency allocation of the signals.

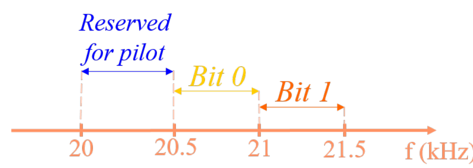

Fig. 4. Frequency allocation of chirp signals

The number of rooms determines the length I of the identifier. As a rule, $I = \lceil \log_2 N \rceil$ bits are needed to represent N rooms. To give an example of the transmitted ultrasonic signal, and without loss of generality, we consider a scenario where we have 8 rooms, so that the identifier is composed of 3 bits. With 3 bits, the binary sequence identifiers are: 000_2,001_2,...,111_2. Each one of these unique identifiers is assigned to a room. Figure 5 shows four of the eight signals assigned to the rooms, while the remaining four are similar and go from 100_2 to 111_2. The period of emission T defines the update rate of the receiver, which should also be equal to the recording time.

C. Ultrasound Signal Decoding

The receiver is responsible for identifying the room it is inside. It continuously listens to the environment and records the received sound. To identify the correct room, the receiver processes the recorded signal to decode the ultrasonic component. The detection process is divided in three steps, in order to ensure its robustness while keeping computations as low as possible. Decoding starts by filtering the recorded signal, then a coarse detection step locates the pilot signal, and finally a fine decoding step decodes the information embedded in the ultrasonic signal, and retrieves the identifier bit sequence.

1) High-Pass Filter: The signal recorded by the microphone contains different frequencies ranging from low audible frequencies, up to high non audible ones. In order to filter out low frequencies and make the system immune to noise, we filter the recorded signal by a discrete-time high-pass filter to keep only the ultrasonic components at 20-22kHz, before proceeding in the decoding process.

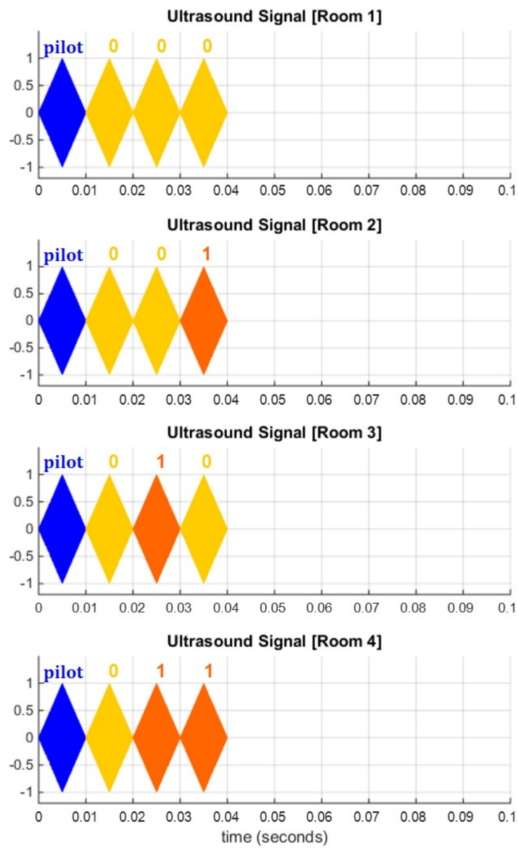

Fig. 5. Transmitted ultrasonic signals for different rooms

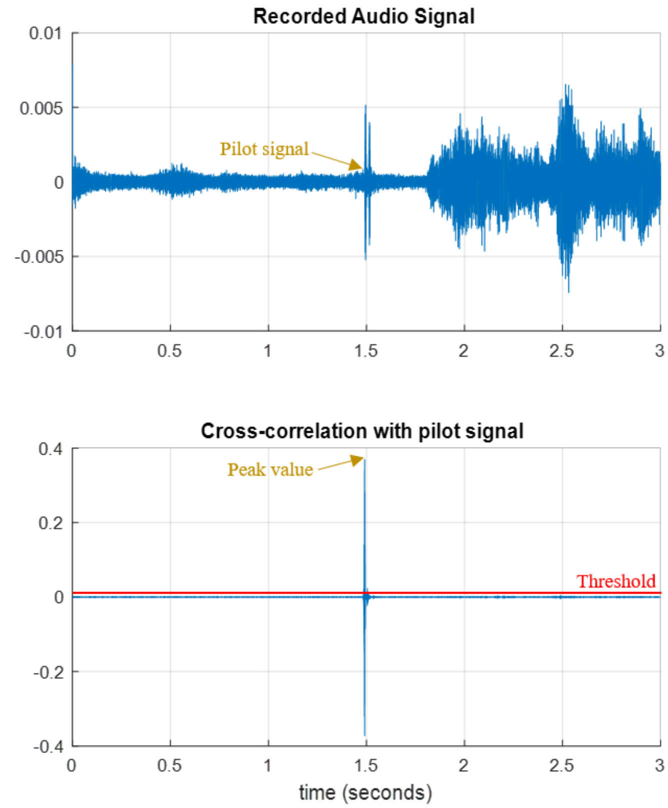

Fig. 6. The first plot shows the recorded audio signal. The second plot shows the result of its cross-correlation with the known pilot signal

2) Coarse Detection: In this step, the receiver checks whether the ultrasonic signal was actually received, indicating that the device is in range of the localization system. The algorithm looks for the pilot signal in the whole recorded signal, and, if found, locates its position inside this signal. If the pilot signal is not found, the receiver is assumed to be out of range, and is not in any of the designated rooms. To detect the pilot signal, a matched filter is used by correlating the received signal with the known pilot signal. The matched filter was chosen as it is the one that maximizes the signal-to-noise ratio. The peak correlation result is compared against a certain threshold, which is empirically calculated and set. If the peak correlation value exceeds the threshold, the ultrasonic signal is considered to be received successfully, the mobile device is then assumed to be in one of the designated rooms, and the fine decoding step takes place. Otherwise, the mobile device is assumed to be out of range. The position of the peak correlation indicates the starting point of the pilot signal, as shown in Figure 6. The position of the pilot in the recorded signal is used to decode the subsequent bits.

Let the transmitted pilot signal be $X = [x_1, x_2, ..., x_N]$ and the recorded signal be $Y = [y_1, y_2, ..., y_L]$ where $L \gg N$. The peak correlation value is given by Equation 1:

$$peak\ correlation = \max_k \sum_{n=1}^{N} x_n y_{(n+k)} \quad \text{for } 0 \leq k \leq L - N \tag{1}$$

The starting point of the pilot signal corresponds to the index of the peak correlation:

$$K^* = \arg\max_k \sum_{n=1}^{N} x_n y_{(n+k)} \quad \text{for } 0 \leq k \leq L - N \tag{2}$$

3) Fine Decoding: Once the pilot signal is located, the receiver proceeds to decode the identifier binary sequence, bit by bit. To decode one bit, the receiver correlates the corresponding signal with the two chirps that are used to represent the bits 0 and 1. Assuming the two chirps that modulate the bits 0 and 1 are respectively $A = [a_1, a_2, ..., a_N]$ and $B = [b_1, b_2, ..., b_N]$, the receiver calculates the following two quantities to decode the first bit that follows the pilot signal:

$$bit\,zero\,correlation = \sum_{n=1}^{N} a_n y_{(n+N+K^*)} \tag{3}$$

$$bit\,one\,correlation = \sum_{n=1}^{N} b_n y_{(n+N+K^*)} \tag{4}$$

where K^* is the index found in Equation 2. If the signal is successfully received, one of the two quantities resulting from Equations 3 and 4 will be positive and above the threshold. This quantity corresponds to the actual received bit, while the other one will be close to zero, as a result of correlating with the wrong bit. If the result of Equation 3 is the one that is positive, then the signal is decoded as 0, and if it is the second one who is positive, the signal is decoded as 1. However, if both quantities of Equations 3 and 4 are positive and above the threshold, this indicates that two different signals were superposed and that a collision took place between the ultrasonic packets of adjacent rooms. In Section IV, we will explain how the occurrence of such collisions is minimized.

Decoding the subsequent bits goes similarly. The receiver should know the length of the identifier beforehand. Once all bits are decoded and no collision is detected, the identifier binary sequence can be mapped to the correct room number, and the room is successfully identified.

D. Confidence Score

When looking for the pilot signal in the recorded sound, the receiver selects the highest peak of the correlation result. In case multiple packets from different rooms are received, this will yield the strongest signal among them, which will be used then to identify the corresponding room. However, this does not indicate how reliable the localization result is. Therefore, we introduce the *confidence score*, as a measure of the reliability of the result. Instead of considering just the highest peak value of the correlation, the receiver also locates all other peaks that are above the threshold, which indicate the signals that are received from the adjacent rooms. If M peaks are detected in total, we refer to the i^{th} peak as P_i, and to the maximum peak as P_{max}. Then, the following formula is used to compute the confidence level as a percentage:

$$\textit{confidence score} = 100 \times \frac{P_{max}}{\sum_{i=1}^{M} P_i} \tag{5}$$

The previous formula can be interpreted as the following: if only one signal is detected, the confidence score of the result of room localization is 100%. Otherwise if multiple signals are received, although the strongest among them is used to identify the room, the confidence score in this case is penalized by an amount that is equivalent to the relative intensities of other received signals. Figure 7 shows an example where three different packets were received. The highest peak in this case (P_2) is used to identify the room, while the other two are considered to be received from the adjacent rooms, and are used to calculate the confidence score, which in this example is equal to around 60%.

As a summary, the flow chart of Figure 8 depicts the complete localization process.

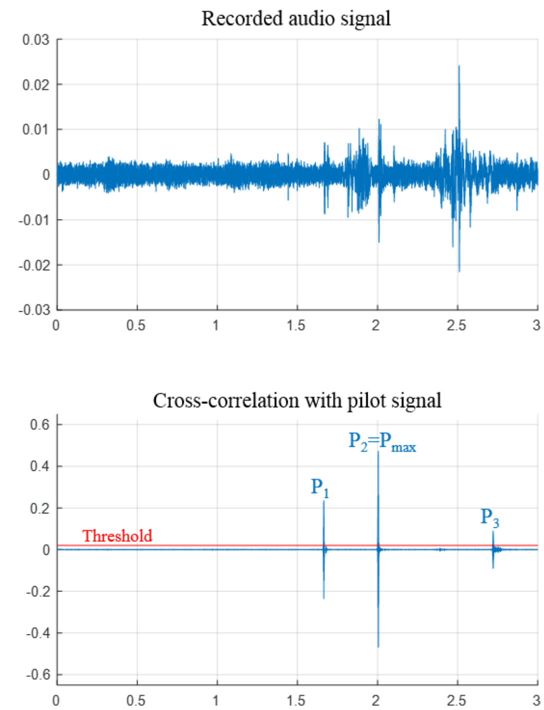

Fig. 7. Three different signals received with different intensities

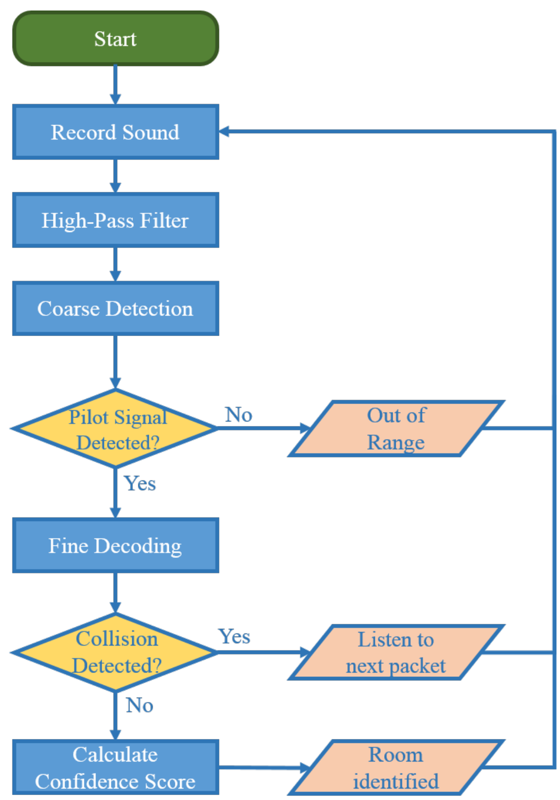

Fig. 8. Flow chart of the localization process

IV. Packet Collision

Transmitted signals from adjacent rooms may interfere, especially when the user is at a boundary point between rooms. Collided ultrasonic packets may lead to erroneous detection by the receiver. This section explains how such collisions could be detected, and also suggest a method to avoid collisions.

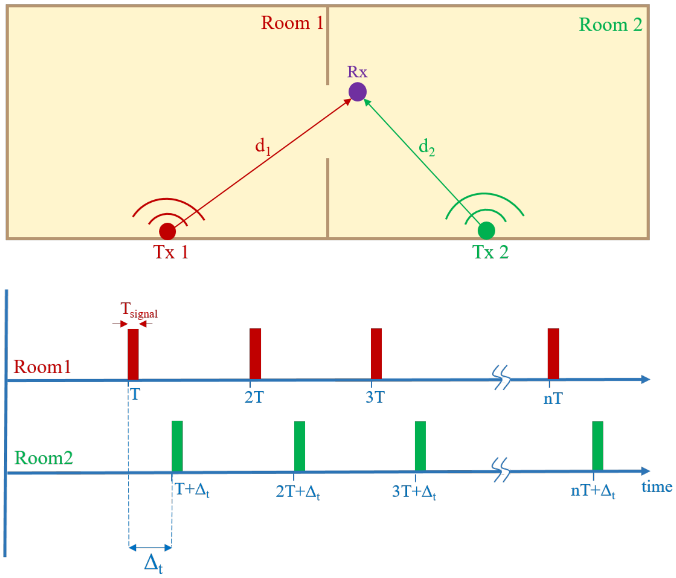

Fig. 9. A scenario showing two transmitters of adjacent rooms, and the receiver in the boundary regions between them

A. Collision Detection

A collision is assumed to take place at the receiver when the latter is not able to decode the received signal correctly. Failing to decode one or more bits in the identifier sequence will indicate a collision of two or more signals. As mentioned earlier, if the results of Equations 3 and 4 both give positive values above the threshold, then this indicates that two different signals modulating bits 0 and 1 have interfered, and a collision of packets has occurred. In this case, the receiver cannot identify the correct room, and reports an error due to collision. Then, it listens to the next transmitted packet in order to identify the corresponding room.

B. Collisions Elimination

Collisions are desired to be fully eliminated. In our system design, we start from the assumption that the transmitters are not synchronized, aiming for a system that has a low complexity and which does not require the deployment of extensive infrastructure. Hence, we assume that we do not have control over the emission time instants of different transmitters. Under this assumption, we show that packet collisions cannot be completely eliminated.

We consider the scenario depicted in Figure 9, where two transmitters are placed in two adjacent rooms. Each transmitter emits an ultrasonic packet periodically every T seconds. The two transmitters are not synchronized, we denote by Δ_t the time difference between their emission time instants:

$$-T < \Delta_t < T$$

The receiver Rx that needs to be located is somewhere in the boundary region between the two rooms, and can hear both emissions. Assume that the ultrasonic packet emitted by the first transmitter reaches the receiver at time t_1, and the one emitted by the second transmitter at time t_2. Taking into account the propagation time of the ultrasonic signal, t_1 and t_2 can be written as:

$$t_1 = nT + \frac{d_1}{c_{air}}$$

$$t_2 = nT + \Delta_t + \frac{d_2}{c_{air}}$$

where c_{air} is the speed of sound in air.

Assuming that the signal duration is T_{signal}, the condition on t_1 and t_2 so that no packet collision occurs is such that:

$$|t_2 - t_1| > T_{signal}$$

which yields:

$$|\Delta_t + \frac{d_2 - d_1}{c_{air}}| > T_{signal} \quad (6)$$

This means that in order to guarantee no packet collision, Δ_t and the distance difference $(d_2 - d_1)$ should satisfy the condition in Equation 6. But since Δ_t can take any value in the interval $(-T, T)$, the aforementioned condition is not guaranteed to hold. An example that violates the condition is when Δ_t is very small (close to 0), and the values of d_1 and d_2 are very close to each other, making the result of $|\Delta_t + {}^{(d_2-d_1)}/_{c_{air}}|$ less than T_{signal}.

Moreover, if a collision happens at some point P, it will lead to infinite collisions at that point, because the values of T, T_{signal}, and Δ_t are constants.

C. Collision Avoidance

As collisions cannot be fully eliminated, we aim to reduce the probability of their occurrence. In other words, if a collision occurs at a certain time, we try to maximize the time that will pass before another collision would occur again. We found that this is not possible if different transmitters have the same period of emission T. To reduce the probability of collisions between signals of adjacent rooms, we propose to assign different periods of emissions to the corresponding transmitters. We found that the best strategy to reduce the probability of collisions is to assign periods of emissions which differ exactly by T_{signal}. Figure 10 shows the emission time instants of transmitters of adjacent rooms.

With this technique, the chance of successive collisions is eliminated. Moreover, if a collision occurs at a certain time at some point P between signals of adjacent rooms 1 and 2, the next collision at point P will occur at $t_{collision}$, which in this case is:

$$t_{collision} = nT_1 = mT_2$$

where m and n are the number of emissions of transmitter 1 and 2 respectively, before the next collision occurs (as shown in Figure 10). Knowing that the first collision occurs when $m = n - 1$, and replacing T_2 by $T_1 + T_{signal}$, we get:

$$t_{collision} = nT_1 = (n-1)(T_1 + T_{signal})$$

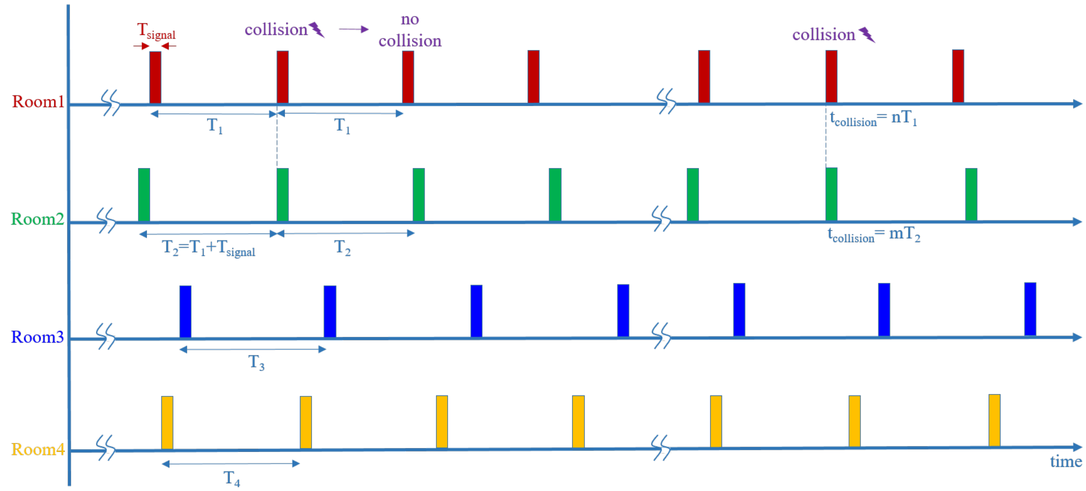

Fig. 10. Adjacent rooms have slightly different periods of emissions: no successive collisions occur, and the time between two collisions is maximized

which yields:

$$n = 1 + \frac{T_1}{T_{signal}} \tag{7}$$

This means that one collision will happen every n transmissions, so the probability of collision is:

$$collision\ probability = \frac{1}{n} = \frac{T_{signal}}{T_1 + T_{signal}} \tag{8}$$

V. System Characteristic Features

The proposed system enjoys the following characteristics:

- Availability: as it is sufficient to have loudspeakers for our system to work, it is suitable to use in many environments, such as museums, hospitals, offices, and shopping malls, without the need to deploy additional infrastructure. As ultrasounds do not alter audible sounds, the same speakers can still be used to play music or to broadcast voice messages.
- Robustness: the methods that are used for signal modulation and processing, like chirp signals, frequency multiplexing, and matched filters, make the system robust against ambient noise. Moreover, assigning distinct periods of emission guarantee low collision rates.
- Scalability: the system is easily scalable to accommodate any number of rooms.
- Ease of deployment: the system can be easily deployed and ready to use without the need for an offline training phase.
- Low complexity: by dividing the ultrasound signal in two parts, the decoding process becomes of low complexity in terms of number of operations, which guarantees a fast response time on the receiver side. Having the pilot signal as a common part for all rooms, requires the receiver to correlate the recorded signal with the pilot signal only, before proceeding to identify the corresponding room. If we did not have a common signal part, the receiver would have to match the recorded signal with all possible signals from different rooms, in order to identify the correct room. In that case, signal decoding becomes computationally expensive, especially when the system is scaled to accommodate a large number of rooms.

VI. Experimental Evaluation

A. Experimental Setup

In order to test the system's functionality, we have implemented it in our lab, at the Battelle building of the University of Geneva. We used one fixed loudspeaker per room, which periodically transmits a unique ultrasonic packet. The chosen periods of emission are around 5sec. We focused the tests on two adjacent rooms with different dimensions, along with the corridor, as shown in Figure11. The rooms were assigned distinct periods of emissions as described in Section IV. On the receiver side, an Android application was developed for room localization. This application receives the broadcasted ultrasonic signals, and implements the decoding process described in Section III. It was installed on a Samsung Galaxy S5 smartphone.

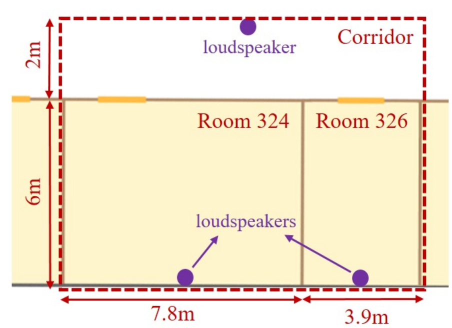

Fig. 11. A map showing the rooms subject to testing

B. Tests and Results

We chose 20 different points to cover the selected area, as shown in Figure 12. At each of these points, 100 measurements were recorded consecutively, using the Android localization application, as Figure 13 shows, and under ambient noise conditions. The experiments were repeated twice: the first time with closed doors, and the second with open doors.

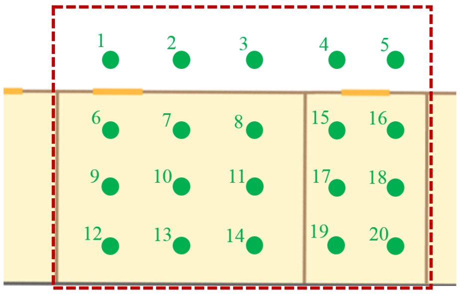

Fig. 12. Points at which the tests were performed

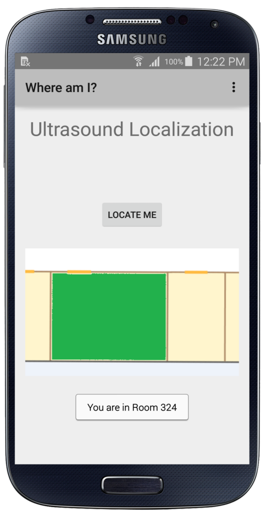

Fig. 13. A snapshot of the Android localization application

Tables I and II show the results for the case with closed doors, and that with open doors respectively. The tables show the percentage of the results that match the correct room in which the user is, and the average of the confidence scores of these results.

TABLE I. Room Localization Results - Closed Doors

Point Number	Correct Room Results	Average Confidence Score
1	100%	94.8%
2	100%	95.2%
3	100%	96.7%
4	100%	95.1%
5	100%	94.5%
6	100%	94.6%
7	100%	95.1%
8	100%	94.5%
9	100%	95.3%
10	100%	96.2%
11	100%	95.1%
12	100%	95.6%
13	100%	97.7%
14	100%	96.5%
15	100%	95.1%
16	100%	94.8%
17	100%	96.0%
18	100%	95.9%
19	100%	98.2%
20	100%	97.7%

TABLE II. Room Localization Results - Open Doors

Point Number	Correct Room Results	Average Confidence Score
1	99%	68.3%
2	99%	77.1%
3	100%	82.8%
4	99%	76.5%
5	99%	70.8%
6	99%	73.2%
7	99%	77.7%
8	100%	84.0%
9	99%	80.9%
10	99%	81.5%
11	100%	86.2%
12	100%	89.4%
13	100%	93.3%
14	100%	90.7%
15	99%	75.1%
16	99%	68.0%
17	100%	83.5%
18	99%	76.2%
19	100%	90.4%
20	100%	91.9%

Interpretation of Results

In the case of closed doors, the ultrasonic signals are confined to the room in which they are emitted, and the signals leaking from adjacent rooms are very weak. This leads to perfect room localization results, with high confidence scores, and also causes the collisions to vanish. On the other hand, when the doors are open, the signals from adjacent rooms can interfere, leading to packet collisions. However, the probability of such collision is very low, thanks to our suggested method. This explains why we obtain very low false detection results, which correspond to collided packets.

The confidence score is affected by the strength of the signals received from adjacent rooms. Nonetheless, it is up to the application layer to use this score, in order to judge the reliability of the localization result, when multiple signals are received. It is also notable that the confidence score is high when the receiver is close to the transmitter, and it decreases as we move away from it.

VII. Conclusion and Future Work

In this work, we have proposed an ultrasound based room-level localization system, that can be built out of COTS components. The designed system is robust, scalable, and has a low computational complexity and collision rate. It was shown to have a very good performance in ambient noise environments. The system was designed for localization inside houses in the context of smart heating, however its characteristic features make it a suitable solution to use for other applications and in different environments, such as hospitals, museums, offices, shopping malls, etc. A future plan is to use an error-correcting code in the transmitted ultrasonic packets, and, potentially, make some modifications to the signal, so that it works also in more challenging environments. Moreover, the effect of chosen ultrasound signals on pets may be also of interest to investigate in a future work.

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