RF-Beep: A light ranging scheme for smart devices

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***Abstract*—In this paper, we design, implement and evaluate the *RF-Beep* system - a high accuracy, one way sensing, energy efficient and light weight relative ranging system for smart devices. The *RF-Beep* system is based on the well known Time Difference of Arrival (TDOA) scheme that utilizes the different propagation speeds of the acoustic and the radio-frequency (RF) signals. Unlike the previous works, *RF-Beep* system utilizes both the audio interface (i.e. mic, speaker and sound driver) and the RF interface (i.e. WiFi) at the kernel level of commercial-off-the-shelf smart devices. Implementing the system at lower level enables us to understand and address the challenges related to the timing uncertainties of transmission/reception process of the acoustic signals more profoundly. Moreover, RF-Beep system does not require any special hardware or infrastructure. In this paper, we describe the complete implementation of the *RF-Beep* system at the kernel space of the Linux OS. We evaluate the *RF-Beep* system under several different indoor and outdoor real scenarios. Results show that the error in estimated range is less than 40cm for more than the 95% of the time.**

***Keywords*-component; formatting; style; styling;**

I. Introduction

Ranging systems has many useful and interesting application usages such as face-to-face multiuser gaming applications [1], photo sharing [2], [3] and video viewing application [4], driver phone detection[5], advertising application [6] etc. Recently, numerous works have been proposed to enhance the accuracy of the ranging systems [7], [8], [9], [10], [1], [11]. In order to achieve high accuracy ranging (i.e., ranging error is in centimeter level), researchers have utilized acoustic based relative ranging techniques [7], [12], [13], [8], [9], [10], [1]. We observe that each of these approaches try to utilize the benefit of the relative slow propagation speed of the acoustic signal to incur the high accuracy relative ranging. In many indoor/outdoor environments, knowing the relative ranges to/between users would enable more accurate navigation directions, efficient network management, generation of safety alerts, access to merchandise and promotion information, etc.

In this paper, we design, implement and evaluate the *RF-Beep* system - a high accuracy relative ranging system for smart devices. The *RF-Beep* system is based on Time Difference of Arrival (TDOA) scheme that utilizes the different propagation speeds of the acoustic and the radio-frequency (RF) signals. Unlike the previous works, *RF-Beep* system utilizes both the audio interface (i.e. mic, speaker and sound driver) and the RF interfaces (i.e. WiFi) at the kernel level of off-the-shelf smart devices. Implementing the system at lower level enables us to understand and address the challenges related to the timing uncertainties of transmission/reception process of the acoustic signals more profoundly. We observer that the delay between when the application execute the transmission of the acoustic signal and the actually emitting acoustic signal from the speaker varies from 2 to 6 ms (figure 3). RF-Beep system reduces this variability to microseconds level by executing the transmission of acoustic signal at the kernel level.

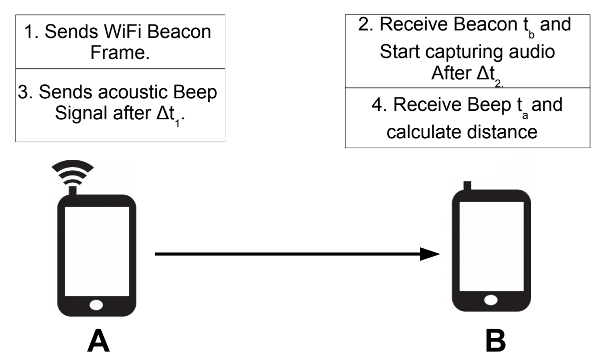

Figure 1: Basics of the RF-Beep System.

Figure 1 illustrates the basics of the *RF-Beep* system. In this illustration, device 'A' could be any smart device that is capable of generating RF and acoustic signals through RF (i.e. WiFi) and acoustic (i.e. speaker) interfaces respectively. The smart device 'A' could play different roles according to the usage scenario such as: a gateway/base node in ad hoc/sensor networks, an access point in enterprise networks, a peer node in ad hoc networks, etc. Similarly, device 'B' is a smart device that wants to estimate the relative distance to device 'A'. In RF-Beep system, device 'A' broadcasts a small RF frame that we refer to as *RF beacon* followed by an acoustic signal *Beep* after short fixed delay. The *Beep* is a sinusoidal acoustic signal with a fixed high frequency. In order to calculate the range to device 'A', device 'B' captures both the RF beacon and the *Beep* sound from device 'A'. The time difference between the reception of RF beacon and the *Beep* sound is used to calculate the relative range between the two device. As shown in Figure 1, only device 'A' transmits both the signals while device 'B' (and other neighbor devices) need only to sense the transmitted signals. Therefore, we classify the *RF-Beep* system as a one way sensing scheme in estimating the relative ranges. Since the device 'B' only sense the signal reception, so RF-Beep is also a less power consuming ranging system for the device 'B'. Moreover, In *RF-Beep* system, device 'B' calculates the relative range locally without any collaboration with device 'A'. Hence, *RF-Beep* system preserve the device 'B' privacy. In addition, the non-collaborative nature *RF-Beep* system eliminates any need for a server or infrastructure support in which it makes the system practically applicable in several applications such as high accuracy indoor localization system.

We summarize our contributions in this paper as follow:

- Develop a one way sensing and practically applicable relative ranging system; *RF-Beep*.
- The *RF-Beep* is the first system, according to our knowledge, that integrates both the audio and the WiFi interfaces at the kernel level. Such low level integration allows us to understand and address the timing uncertainties of transmission/reception of acoustic signals.
- Implement the *RF-Beep* system on the commercial-off-the-self (COTS) smartphones. RF-Beep utilizes in an integrated in a unique fashion the speaker, microphone and WiFi hardware component of the smartphones.
- Evaluate the implemented system under different indoor and outdoor realistic scenarios.

The rest of this paper is organized as follows: in Section II, we list the related work and highlight the differences between our system and these related works. We describe the details of the *RF-Beep* system and the corresponding challenges we addressed in the following section. Then, in section IV we describe the architecture of the *RF-Beep* system as well as the implementation of different components of the system. The experimental evaluation and analysis of the system is done in Section V. Finally,we conclude the paper and highlights our future work in Section VI.

II. Related Work

Most of the localization research works have been based on Radio Frequency (RF)-based techniques that leverages signal strength of RF signal from different nearby RF sources or infrastructures (e.g., WiFi Access point, Cellular Tower). Such RF based approaches with sophisticated localization algorithm can achieve reasonable accuracy with error range of 6-8m. Recent work shows that existence of the same signature or fingerprint of RF signal at different distinct location prohibits to have high accuracy in indoor localization system [14], [15], [16], [17]. Recently, researchers are combining multiple modalities such as sound with the WiFi to achieve high accuracy localization system [8], [10], [18], [19]. For example, the localization schemes [8], [10], [9], [1], utilize the acoustic based ranging [7] scheme and combine it with the RF at the application layer. In this section we highlight some of the recent and most relevant relative ranging techniques as well as location based systems that use relative ranging techniques.

A. BAT System

The BAT [18] system is an indoor localization system that utilizes the time-of-flight of ultrasound signal.The BAT system consists of multiple mobile or fixed wireless transmitter, a matrix of receiver elements and a central RF base station. The RF base station orchestrates the activity of the transmitters by broadcasting messages to them in turns. Then, the transmitter sends out ultrasound pulse which is received by the receiver elements, which also receive the broadcast message from the RF base station. The receiver determine the time interval between the RF message and ultrasound signal to infer the distance to the transmitter. BAT system requires tightly controlled and centralized architecture. Moreover, the receiver in the BAT system needs to be synchronized using the broadcast message from RF base station. However, such technique has number of uncertainties that has been discussed in Fikret et al [20]. Beside, BAT system requires their own customized hardwares to implement.

B. Cricket

Cricket [19] is a indoor localization system that utilizes the combination of RF and ultrasound to determine the distance of a targeted device. It uses concurrent transmissions of radio and ultrasound signals and their corresponding difference of arrival times to the target device to infer the distances. Although the cricket uses two different signals similar to our *RF-Beep* system, but it requires customized hardware for time stamping and to ensure concurrent transmissions of both RF and acoustic signal. The Cricket system also depends on the infrastructure to place the transmission devices. Moreover, unlike our *RF-Beep* system, the Cricket system targeted to achieve a room-level granularity of accuracy in determining the location of the target devices.

C. PinPoint

PinPoint [11] is a localization system that uses Time-Of-Arrival of radio signal. It uses mathematical approaches to compensate the clock differences between different nodes. PinPoint system does not require synchronization between nodes. However it requires two-way sensing between the nodes to estimate the relative ranging. Moreover PinPoint system uses their custom made hardware which make the system non applicable to the commercially available smart devices.

D. Beep-Beep

Beep-Beep [7] is an acoustic based high accuracy relative ranging system. In BeepBeep ranging system, each of the two smartphone generates two acoustic beep sound one after another. Then, the smartphones estimate the time difference of receiving both beep sound (from its own and the other phone) to obtain the distance between them. Beep-Beep system intelligently avoids the time synchronization requirement in determining the relative ranging. In addition, the uncertainty of sending and receiving acoustic signals has also been addressed in their work [7]. However In section III-B we have explained how Beep-Beep system overlook the uncertainty of sending and receiving acoustic signals.

The Beep-Beep is a two-way sensing ranging scheme. it requires both transmitter's and receiver's active involvement in calculating the distance. In [7], the relative distance estimating equation requires the information of the phone's dimension from both transmitter and receiver. In addition, it also requires the receiving timestamps of the two acoustic signals from both phones. Therefore, using Beep-Beep in high accuracy localization system [10], [8] requires a central controller to schedule the collaboration between the receiver and the transmitter. These requirements hinder the usages of the Beep-Beep ranging scheme in real practical localization systems.

III. RF-Beep System

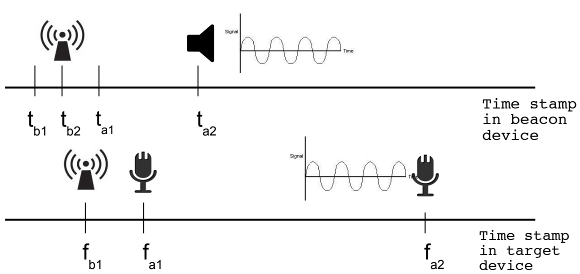

Figure 2: System overview of RF-Beep System.

In this section we describe in details the *RF-Beep* system. We start by describing the system overview, followed by the system challenges and how we address those challenges. A node in *RF-Beep* could play one of the following two roles: i) *Beacon device*: This device is responsible for the transmission of both the RF beacon and the acoustic *Beep* periodically in our system. In measuring the relative ranging distance, *beacon device* is the frame of reference. Example of a *beacon device* could be a smartphone in ad-hoc mode, a leader node among a group of sensor node in wireless sensor network, an access point in enterprise wireless networks, etc. ii) *Target device*: This device measure the range from the *beacon device*. The *target device* record the timestamps of the reception of both the RF beacon and the acoustic *Beep* signals from the *beacon device*. These timestamps help the *target device* to infer the relative distance to the *beacon device*. Example of a *target device* could be any smart device or a sensor node in wireless sensor network.

A. System overview

The *RF-Beep* is a relative ranging system based on the Time Difference of Arrival(TDOA) technique that utilizes the relative velocity of two different signals; RF and acoustic. Figure 2 gives an overview of the *RF-Beep* system and shows the time-line of the different event's timestamps for both the *beacon device* and the *target device*. These timestamps are:

- t_{b1}, Time when the *beacon device* put the RF beacon into the transmission buffer of the firmware.
- t_{b2}, Time when last bit of the RF beacon has been transmitted from the *beacon device*.
- t_{a1}, Time when audio driver started writing audio frames into the hardware buffer.
- t_{a2}, Time when speaker started to generate the *beep* sound from the *beacon device*.
- f_{b1}, Time when the *target device* receive the last bit of the RF beacon.
- f_{a1}, Time when microphone of the *target device* is turned on to capture the audio data in the audio driver buffer.
- f_{a1}, Time when the *target device* detects the starting of the *beep* sound from the captured data.

In *RF-Beep* system, the *target device* only receives the RF beacon and *Beep* signal. It does not require to share any information with the *beacon device*. Such flexibility enables the *target device* to calculate the relative ranging distance from *beacon device* locally. As we will show later, *RF-Beep* system does not require any time synchronization between the *beacon device* and the *target device*.

A typical Time-of-Arrival system uses the propagation speed of the signal to infer the distance between the transmitter and the receiver. The signal with high speed needs to have high precision in determining the travel time from sender to receiver. Since the sound has lower propagation speed compared to RF, acoustic signal has lower relative ranging error corresponding to small timing error. For example, a millisecond error of TOA estimation could result up to 30 centimeter of error in estimating the relative range of an acoustic signal. In order to limit the relative ranging error to few centimeter, it is enough to maintain the time precision in millisecond level in *RF-Beep* system. In figure 2, all event's timestamp is considered to be in millisecond precision.

Given the high propagation speed of the RF signal and the small length of the RF beacon, it takes less then a millisecond to transfer a RF beacon from a *beacon device* to a *target device*. Even though the value of t_{b2} and f_{b1} might be different in two devices, we approximate both timestamps t_{b2} and f_{b1} in representing the same event on the two different timelines. Given the speed of the sound in air is s_a and the distance between the *beacon device* and *target device* is, D then we can write the following equation from figure 2

$$\begin{aligned} D &= s_a.(t_{a2} - f_{a2}) \\ &= s_a.(t_{a2} - f_{a2} + t_{b2} - t_{b2}) \\ &= s_a.((t_{a2} - t_{b2}) - (f_{a2} - f_{b1})) \\ &= s_a.(\Delta t_{ab} - \Delta f_{ab}) \end{aligned} \tag{1}$$

In equation 1, Δt_{ab} represents the time difference between the last bit of the RF beacon transmitted and the speaker started to generate the *Beep* signal from the *beacon device*. Similarly, Δf_{ab} represents the time difference between the last bit of the RF beacon received and the start event of receiving the *Beep* signal at the *target device*. Both Δf_{ab} and Δt_{ab} values are the local time difference at the *target device* and the *beacon device* respectively. Therefore, it is worth to pint that no synchronization is required between the two device in the calculation of Δt_{ab} and Δf_{ab} values. Moreover, In *RF-Beep* system, as we will show later, we manage to eliminate the uncertainty in Δt_{ab}. Therefore, the *target device* does not require any information from the *beacon device* and the *RF-Beep* system doesn't require any collaboration between the two devices.

B. Challenges

In TDoA, accuracy of the ranging method highly depends on the precision and accuracy of measuring the arrival time of two different signals. Typically, TDOA based approach requires to track the timestamps of the different transmission and reception signals. As a consequence, such approach requires time synchronization between the receiver and the transmitter. To address this synchronization requirements, a periodic broadcast of special message is required by a centralized node [21], [22]. However, this approach introduces number of uncertainties that has been described in Fikret et al. [20]. These uncertainties reduce the chance of maintaining precise time synchronization between different devices. Recently, to overcome the requirement of time synchronization number of relative ranging scheme has been proposed [7], [8], [9], [10], [1]. Such systems utilize the time difference of two local event's timestamp rather then using a single local even's timestamp value to measure the relative range. *RF-Beep* system, as shown in equation 1, utilizes the same trick to tackle the time synchronization problem.

Authors In [7] highlighted some of the uncertainties in acoustic based high accuracy relative ranging estimation. For example, our major uncertainties, is the high variation delay between the actual emission of acoustic signal by the speaker and the signal transmission command generated by the application. Given two acoustic signals arriving from the two different phonesin Beep-Beep system, it is highly unlikely that both phone will have same uncertainty when sending both signals. It is obvious that the acoustic signal reception time at the *target device* depends on the transmission uncertainties of the *beacon device*. Figure 3 plots the CDF of the delay in generating the transmission of the acoustic signal (solid line) from 1000 samples. It is clear from Figure 3, the delay varies significantly in the range 2-6ms which lead to few meters of error in measuring the relative range.

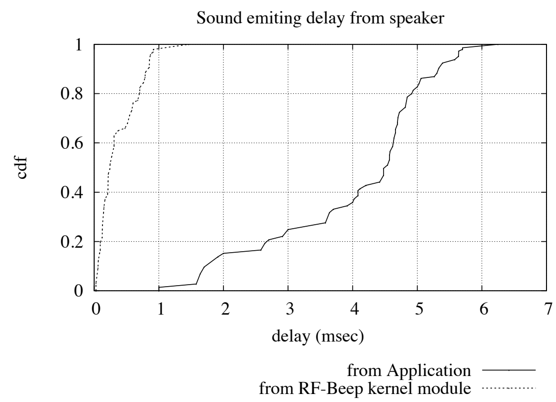

Figure 3: Sound sending delay uncertainty between normal application sending sound signal and the *RF-Beep* system sending the sound signal. We have run 1000 times get the delay values for both normal application and the *RF-Beep*. In both cases we send 4400 samples of sound data for 44100Hz sampling rate

By analyzing the sound driver action in details, we have figured out that the delay in acoustic signal transmission consists of 3 main delays that are correspond to the following three actions: i) Power up the playback stream, ii) Data transfer from application to sound driver, and iii) the DMA data transfer from sound driver to actual sound hardware. Most of the portable smart devices has a complicated DAPM (Dynamic Audio Power Management) to minimum the power consumption within the audio subsystem at all times. DAPM makes power switching decisions based upon any audio stream (capture/playback) activity and audio mixer settings within the device. DAPM also makes the power switching transparently to the user space application. In addition, powering up the playback stream, DAPM takes some initial time. Implementing the *RF-Beep* system at the sound driver level provides us the flexibility in controlling the delay of powering up the playback stream. Moreover, executing the transmission of the acoustic signal at the driver level help us to get rid off the delay of data transfer from application to sound driver. This leaves the *RF-Beep* system with only one source of uncertainty correspond to the DMA data transfer from sound driver to actual hardware.

However, the impact of this source of uncertainty is less then 1 millisecond as shown in Figure 3 (dotted line). In order to guarantee that the *target device* captures the *Beep* sound from the very beginning, we add a fixed delay before sending the Beep sound. In section IV, we will explain in details the implementation of sound transmission mechanism in the sound driver for the *RF-Beep* system.

At the receiving side, *RF-Beep* system has two uncertainties in receiving the *Beep* sound. i) Power up the capture stream, and ii) Detect the starting event of the Beep sound. Figure 4 plots the delay of powering up the capture stream of the *target device*. As shown, the delay of powering up the capture stream is between 2-2.5msec maximum. Note that, this delay measurement allows us to determine how much delay (Δt_{ab}) we should consider when sending the Beep sound from the *beacon device*. Both the power up delay and the delay of determining the starting event of sound are exclusive, so we can write the Δf_{ab} as:

$$\Delta f_{ab} = \mu + \frac{n_b}{f_s}. \tag{2}$$

where μ is the delay to power up the capture stream, n_{ab} is the starting sampling number of the captured Beep sound, and f_s is the sampling frequency of capturing event. Note that, $\frac{n_b}{f_s}$ is the delay of receiving the Beep sound. Detecting the n_{ab} in the captured sound data is a challenging task. In order to have high precision in measuring the relative ranging, it is critical to precisely detect the n_{ab} value. Number of reason can make it challenging to perform such task. For example, In non-light-of-sight situation, multipath effect could make it ambiguous to detect the start of Beep sound properly. Also, generating/receiving acoustic signal through playback/capture stream creates some pops in the sample which also make it hard to detect the starting event. Moreover, the hardware (microphone and speaker) creates some large waveform distortion while generating/receiving acoustic signal. In the implementation section we have addressed the challenge of detecting *Beep* signal in more details.

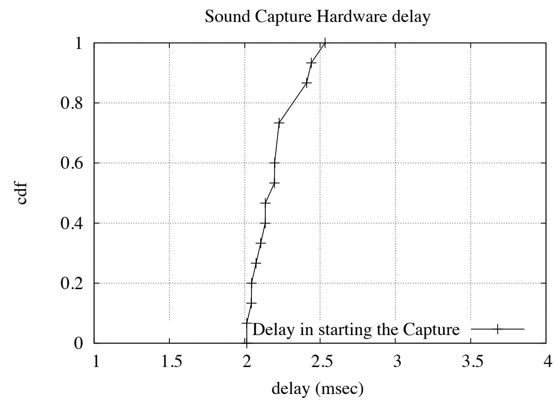

Figure 4: Audio capture starting event delay

IV. Implementation

RF-Beep system, utilizes both the acoustic interface and the RF interface at lower kernel level of the commercial available smart devices. In our implementation, we use the WiFi hardware of the smart device as our RF interface and the WiFi beacon message as an example of RF beacon. We implement the whole *RF-Beep* system at the kernel space of the linux operating system on Nokia N900. Although kernel space provide more flexibility, but It is a challenging task to combining both acoustic and WiFi interface at the kernel level in a non-real time devices. Specially, it is challenging to complete a sequence of operation within certain time constraint in a non-real time devices. In this section, we address these challenges in implementing the architecture of transmitting and capturing acoustic signals and RF beacon. Following that, we will discuss about the *Beep* signal detection technique.

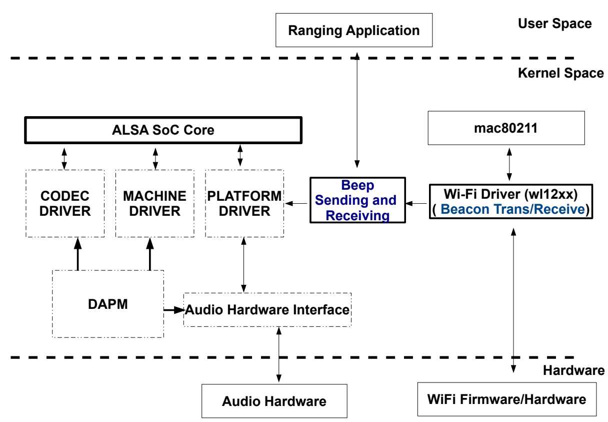

Figure 5: Architecture of RF-Beep system in linux OS.

A. *RF-Beep System Architecture*

Figure 5 shows the different components of *RF-Beep* system that is implemented at kernel space in addition with other standard components of both the sound driver ALSA SoC and the WiFi driver wl12xx. Most of the commercial off-the-self smart devices uses ALSA SoC driver that support the ALSA driver in embedded system or portable audio devices. ALSA SoC basically splits an embedded audio system into three main components i)Codec Driver, ii) Platform Driver, and iii) Machine Driver. The platform driver is responsible for the DMA data transfer between sound driver and the audio hardware. Beep Sending and Receiving (BSR), shown In Figure 5, is the main kernel module, responsible for creating the *Beep* signal and transmitting it to the platform driver for further DMA transfer to the actual hardware. In addition, this module also process the captured sound signal from the platform driver for detecting the *Beep* signal. In *beacon device*, whenever WiFi driver transmit a beacon frame, it send a notifying signal to the BSR module. The BSR module then power up the playback stream and generate the acoustic *Beep* signal. In case of *target device*, whenever WiFi receive a beacon frame, it send a signal to the beep sending and receiving module to power up the capture stream. The BSR module then start to record the audio samples in a fixed size buffer. At the end, this module detects the *Beep* signal from the captured acoustic samples and transfer all information to the *Ranging application*. The *Ranging application* finally calculate the ranging based on collected information from the BSR module.

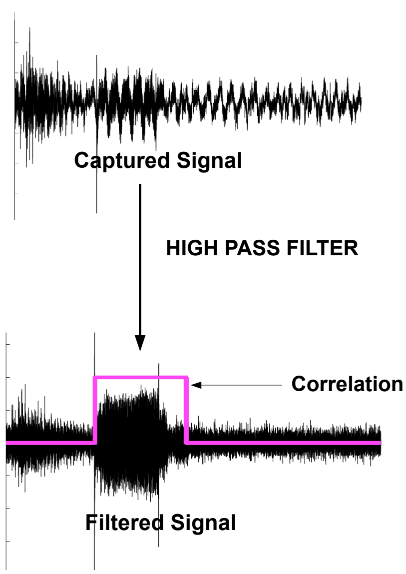

Figure 6: Beep signal detection technique.

B. Beep signal generation

IN *RF-Beep*, we track the firmware interrupt event of the WiFi driver(wl12xx) that is correspond to the transmission of the RF beacon. Such interrupt event marks the transmission of the last bit of the beacon frame. Following the interrupt event, the WiFi driver sends a command to send a *Beep* sound after a fixed period. In the implementation we chose 5 msec for this fixed period. The *Beep* signal is a sinusoidal signal with a specific frequency. In the implementation we use the frequency of 18kHz. Since, the sound frequency of 18kHz is closer to upper limit of human hearing range, so it is hard to perceive with the existing natural ambient noise. However, off-the-shelf smartphone audio hardware are sensitive enough to capture such high frequency sound. Given most of the background ambient noise is below 7-8kHz, the *Beep* sound in 18kHz will be robust to most of the background noises. The length of the *Beep* signal is also important in order to detect the signal on the receiving side. For example, large duration of *Beep* signal might creates several multi path effect which will overlaps with the original signal and make it hard to detect the original signal. On the other hand, small duration of *Beep* signals are hard to detect at the receiving side. We use number of samples In defining the duration of the *Beep* sound. In the experiment we choose a signal length of 2205 samples with sampling rate of 44100Hz. In figure 5, BSR module is responsible for generating the samples of the Beep sound and putting it to the circular buffer of ALSA SoC driver which we set the length to 2205 samples. After filling up the circular buffer with samples we initiate the DMA transfer between the platform driver and the audio hardware interface.

C. Beep Signal Detection

Precise detection of the Beep signal at the receiving side is crucial for accurate range estimation. Our detection scheme should satisfy the following two features: 1) Precise identification of the first sample of the Beep sound, and ii) light weight implementation. Figure 6 shows the steps in detecting the Beep signal. First, we apply a high pass filter over the sample data to get rid of all ambient background noise. Following the high pass filter, we apply L-2 norm cross-correlation over the filtered signal. The correlation values that passed a minimum threshold indicates the beginning of the Beep signal.

We use a lightweight filtering method in time domain to satisfy the above mentioned second feature. In defining the high-pass filter in time domain, we label the input signal as $x[i]$ and output signal as $y[i]$. In general, the first-order filter can be expressed as:

$$\begin{aligned} y[i] &= (1-k)\cdot x[i] + k\cdot y[i-1] \\ y[i] &= x[i] - y[i] \\ k &= \exp -\frac{2\cdot\pi\cdot f_c}{f_s} \end{aligned} \tag{3}$$

Based on the above equation, higher order high pass filter can be constructed. In our implementation, we use 5th order high pass filter which embed 5 samples delay in detecting the starting event of the *Beep* signal. Such delay can lead up to 4cm of error, which is negligible in our scenarios. In order to do the L-2 cross-correlation, we create a short sinusoidal signal of 25 samples with same frequency as the Beep signal. We select the length of the sinusoidal signal empirically from our previous observation. The correlation is done between the short sinusoidal signal with the filtered signal in a sliding window fashion with single sample increment. The index number of the captured sample, where the correlation value get above a threshold value indicates the beginning of the Beep sound. In the implementation, we set the threshold value to 0.8 which is enough to detect the direct path signal. In Non-Light of Sight cases, direct path signal might be weaker compare to multi path signal, but direct path signal always come earlier than the other multi-path signal. Moreover, the frequency of the multi-path signal usually get distorted from the original signal's frequency. Since we are using a fixed frequency for our original signal, so most of the multi-path signal will have different frequency from our selected fixed frequency. As a result, correlation value between the short sinusoidal signal and the multi-path signal will be less then the threshold value.

V. Experiment and Evaluation

A. Experiment Equipment

We use Nokia N900, running Maemo 5 linux based OS, for our evaluation. N900 is powered by TI OMAP3 processor which can support up to 1 GHz [23]. The system has 256MB of high performance RAM with 1GB of VM support. It has two speaker laid out at the top and the bottom surface of the Phone and the mic is located at the bottom of the front surface. The audio features of the device are provided by TI TWL4030 chip supported by ALSA SoC driver. The WiFi chipset of the N900 phone is TI WL1251 supported by wl12xx driver. Most of our implementation is done at the wl12xx and the ALSA SoC driver which are both part of linux kernel source code.

B. Test scenarios

We evaluate the *RF-Beep* system at following three environments:

- Indoor at quite environment: In this environment, we conduct the experiment at our research lab in a quite environment. Figure 7 shows the different position of the *target device* and the *beacon device*.
- Indoor at noisy environment: In this case, we conduct the experiment inside a Student Union center during lunch time. During the experiment, lot of students were moving around and chatting themselves. Such activities create a very noisy and dynamic environment for our experiment.
- Outdoor at parking lot: In the outdoor experiment, we chose an open area parking space, inside the campus of the university. During the experiment temperature was 23 °C.

For the above cases, we measure the temperature of the environment before conducting the experiment using TinkerKit thermostat sensor. During the experiment, we place both the *beacon device* and the target device in an orientation where the front surface is facing up. We measure the ranging 100 times for each location. In the experiment, we use the following model for calculating the speed of the sound, $s_{air} = 331.3 + 0.6 \cdot \theta$, where θ represents the temperature of the air in Celsius [24].

C. Experiment results

Figure 7 shows the indoor experiment setup for our RF-Beep ranging system. The red circle with 'S' indicates the position of our *beacon device* and the rest of the five red square box shows the position of our *target device*. In the figure 'A','B','C','D' and 'E' positions are respectively 460, 585, 360,930 and 700 cm away from the *beacon device*. The statistical overview of the ranging error for each position is shown in Figure 8. From figure 8, we observer that the median of the measurement error is quite stable for different position. Moreover, 75% of the ranging error are below or equal to 50cm for each position in the experiment.

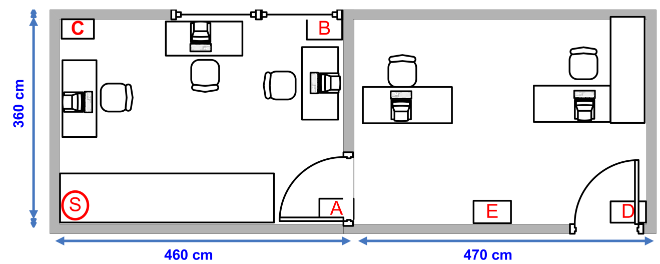

Figure 7: Room layout of the indoor environment to conduct the experiment for RF-Beep ranging scheme.

In Figure 8, we observe the max value for some positions are closer to 1m. Such occurrence of max values are very low percentage of our overall collected examples. Moreover, the size of the quartile box in Figure 8 shows consistency for different position at the indoor environment. Such results conclude, RF-Beep ranging system is quite consistent at quite indoor environment. However, we also notice the median value of the measurement error in Figure 8 is higher compare to other experimental result that we have conducted in different environment. The primary reason behind the high median of error is due to the multipath effect caused by the closer surrounding walls at our lab rooms.

In Figure 9, we see the statistical accuracy of measurement at different distance for indoor noisy environment. As we see from the figure, the lower distance shows relatively less variation of measurement error compare to high distances. In the plot, we see 75% of the error value is less then 40 cm until we reach 14 meter. Such results are better then our previous indoor experiment at quite environment. In 12 and 14 meter distance, we observer 75% of the error values are less then 70 cm. However, in that higher distance(12 and 14m) the median value is as low as 30cm. Overall this experimental result concludes that our system is robust and highly accurate in such noisy and dynamic environment.

In case of indoor noisy environment, we conducted the experiment at a large open space with many small chairs/tables inside the Student Union Center. We conducted the

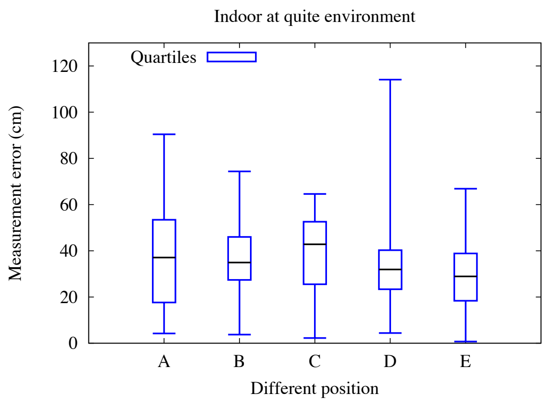

Figure 8: Error measurement of RF-Beep scheme for Indoor-quite environment. X-axis shows the different indoor position from the figure7. Y-axis represents the measurement error in cm. In the plot 25% of the samples show error value equal or less then the lower boundary value of each box. The 75% of the samples shows measurement error value equal or less then the upper boundary value of the box. The small horizontal line inside the box represents the median value of the measured error. The upper and lower limit of the vertical line shows the max and min value receptively.

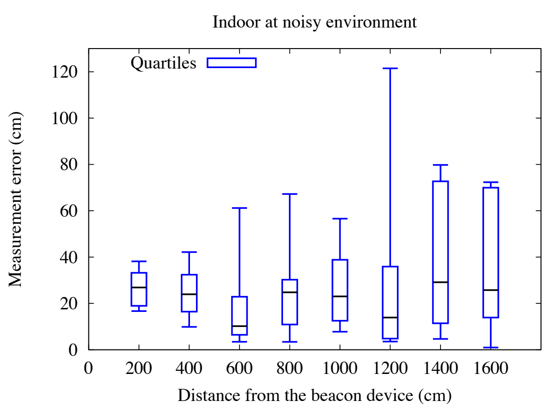

Figure 9: Error measurement of RF-Beep scheme for Indoor noisy environment at different distances from the *beacon device*. In this setting we conducted our experiment inside the Student Union center during lunch time.

experiment during lunch time so number of students were moving and chatting themselves. Despite of these dynamic environment, we still see the median of error is low in Figure 9 compare to our previous indoor quite environment setup. This result is due to the following two reasons: i) the frequency of the *Beep* v, and ii) acoustic wavelength. First, most of the human voice frequency and the background noises are below 4000Hz which is far below our *Beep* frequency. As a consequence, the chatting among students and the background noise are not effecting by the accuracy of our ranging measurement. Secondly, the acoustic wavelength is large enough to have any multipath effect due to human body and small chairs/tables. The main reason behind the multipath effect in indoor environment is due to the wall. Since the experiment was conducted in relatively open area space compare to the previous indoor experiment, plot at Figure 9 shows less median of error compare to previous plot at Figure 8.

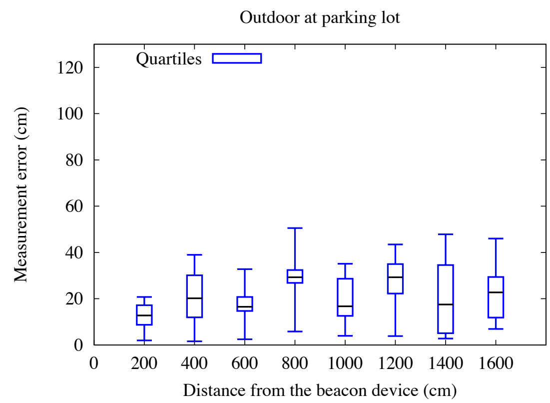

Figure 10: Error measurement of RF-Beep scheme for our door experiment at different distances from the *beacon device*. In this setting we conducted our experiment in an open area parking lot space.

The accuracy and variation of the ranging measurement error at different distance for outdoor environment is shown in Figure 10. At outdoor environment, the accuracy and variation of the measurement error is quite consistent compare to different indoor environment. We conducted our outdoor experiment in a parking area inside the university campus. In the figure the deviation as well as the median error increases as we go farther in distance. However, the variation of the measurement error is still consistent for different distances proofs the stability of our RF-Beep system at outdoor environment. At outdoor environment, we observer that 75% of the sample shows measurement error less then 35cm up to 16 meter distance. Such result indicates that RF-Beep system is highly reliable and accurate in outdoor environment. Since at outdoor environment, mutipath effects are rare compare to indoor environment, so we observer the median value of error at outdoor environment is much less then the above two different indoor environment.

VI. Conclusion and Future Work

In this paper, we have designed a light weight high accuracy relative ranging system - *RF-Beep*. *RF-Beep* is a one way sensing system that eliminates the requirement of time synchronization between the peer devices. In addition, the RF-Beep system utilizes the RF interface and the audio interface at the kernel level to address the uncertainties of transmitting/receiving acoustic signals. In this paper, we implemente the *RF-Beep* system completely at the kernel level in the off-the-shelf smart devices. Such implementation proofs the feasibility of deploying our system in any other commercially available smart devices. Moreover,RF-Bepp system doesn't require any custom made hardware to implement. Finally, we evaluate our system under different indoor/outdoor environment. Through out the experiment, we were able to achieve relative ranging error equal and less then the 40cm under different indoor/outdoor environment. In this work, we have focused on developing a light weight, one way sensing and high accuracy ranging system. Such characteristic make the *RF-Beep* system rigorously applicable for high accuracy indoor localization application. In future, we like to deploy *RF-Beep* system in large scale with multiple smart devices for indoor localization purpose.

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