Master's Thesis
석사 학위논문

Asynchronous Distance Measurement for Smartphone-Based Localization Exploiting Chirp Signals

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Advisor: Professor Jae Youn Hwang

Advisor: Professor Taejoon Park

Co-Advisor: Professor Min-Soo Kim

by

Hong Jae Lee

Department of Information and Communication Engineering

DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

Dec. 28. 2015

Approved by

Professor (Advisor)	Jae Youn Hwang	(Signature)
Professor (Advisor)	Taejoon Park	(Signature)
Professor (Co-Advisor)	Min-Soo Kim	(Signature)

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Asynchronous Distance Measurement for Smartphone-Based Localization Exploiting Chirp Signals

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Accepted in partial fulfillment of the requirements for the degree of Master of Science.

Dec. 28. 2015

Head of Committee ________________(인)
Prof. Jae Youn Hwang
Committee Member ________________(인)
Prof. Taejoon Park
Committee Member ________________(인)
Prof. Min-Soo Kim

MS/IC

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ABSTRACT

In this paper, we present an new asynchronous, accurate, and real time distance measurement method using chirp signals, which is capable of accurately locating and tracking, thus forming an ad-hoc network among smartphones in an indoor (e.g., smart meeting room) environment. Also we propose a distance measurement which can overcome limitations of previous representative distance measurements of Received Signal Strength Indicator (RSSI) and Time of Arrival (TOA). It operates in spontaneous, smartphone-based ad-hoc networks (SAN), sensory-based context inference, and device-to-device context extraction systems without requiring well–organized infrastructures. We then implement our proposed method on two Samsung Galaxy S5, one of Commercial Off-The-Shelf (COTS) smartphones. Without modifying their hardware or OS kernel. Our experimental results demonstrate that it takes < 1 second to conduct network-wide distance measurements and the measurement error is <10 cm, which is treated as an allowable error, in at least 87% of the experiments.

Keywords: Sensor network, Distance measurement, Localization, Smartphone, Chirp signal, Smartphone-based Ad-hoc Networks (SAN)

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I. INTRODUCTION

As the smartphone is being rapidly distributed in all over the world, mobile application market has been achieving growth every year. Especially, as the smartphone started having various sensors internally installed and also being equipped with data processing capability as much as the computer, it is a current trend that fields of utilizing the smartphone application are being diversified. Hereupon, various research efforts were invested to effectively form an ad-hoc network of commercial off-the-shelf (COTS) smartphones.

These smartphone-based ad-hoc networks (SAN) [1, 18] aims to provide context-driven services, e.g., smart meeting systems [2], in environments that are not equipped with pre-deployed infrastructures. Previous smart meeting systems used additional devices such as Polycom CX-5000 [3] and Microsoft RingCam [4] automatically identifying the location of a human and providing beam forming microphones. Furthermore, they analyze and classify the meeting agenda conveying meaningful information to users. However, additional devices are inevitably needed in order to use such systems along with requirements to exactly identify the location of devices equipped with microphones. As for the reason for requiring fixed location, it aims to utilize the most efficient technique named Time Difference of Arrival (TDOA) [5] when measuring the location of people in the meeting room by utilizing sound signals.

TDOA finds the origin of sound by analyzing information as to how human voice arrives to two different mics in certain time intervals. Previous smart meeting systems operate in the infrastructure-based environment. Hereupon, there is no issue performing TDOA technique since the distance between mics has already been fixed. However, if converting it to a SAN, the location of smartphones differs depending on the location of users. Considering the fact that smartphones are standalone systems with high mobility, we need to satisfy a number of technical properties when forming a SAN, which include highly accurate yet cost-effective distance measurement between a pair of smartphones without having to modify their hardware or OS kernel for intensive clock synchronizations.

The BeepBeep [6] is one of the well-known methods presented in recent years, which meets the requirements with negligible distance measurement errors ($<10cm$). However, there are two technical problems when we construct a SAN using BeepBeep.

The first problem is derived from how the BeepBeep is designed to prevent overlapping chirp signals when measuring the distance. Assuming that a SAN consists of N smartphones, $N(N-1)$ 'beep' sounds must be made one-by-one to complete the network-wide distance measurements, consuming a significant amount of time.

The second problem is related to the multipath effects caused by the speaker positions of smartphones, one at the rear and the other at the front, which negatively affect the accuracy of BeepBeep. Such erroneous effects increase the distance measurement errors, which in turn leads to imprecise context extraction due to incorrect localization of smartphones in a SAN.

In this work, we present an asynchronous, accurate, and real-time distance measurement method, which can overcome existing problems. Chapter 2 explains the most representative method for distance measurement (e.g., RSSI, and TOA). Chapter 3 explains limitations of existing distance measurement method based on TOA information of acoustic or radio signals and existing asynchronous distance measurement method. Chapter 4 suggests a new distance measurement method in asynchronous environment that overcame the limitation of the BeepBeep. Chapter 5 explains system architecture including chirp signal design, chirp signal detection and device orientation for this study and experiments. Chapter 6 explains evaluation of experiments. Chapter 7 explains the conclusion made in this study and also follow-up studies to be conducted in the future.

II. RELATED WORKS

2.1 RSSI

Received Signal Strength Indicator (RSSI) [7] is the relationship between transmitted power and received power of wire-less signals and the distance among nodes. This relationship is shown in (1).

$$P_r = P_t \cdot \left(\frac{1}{d}\right)^n \tag{1}$$

P_r is the received power of wireless signal. P_t is the transmitted power of wireless signal. d is the distance between the sending nodes and receiving nodes. n is the transmission factor whose value depends on the propagation environment.

RSSI-based ranging models in wireless sensor networks is applicable to the following conditions:

1) The transmission distance is much larger than the antenna size and the carrier wavelength.
2) There are no obstacles between the transmitters and the receivers.

These occasions are called 'Free-space model' and it can be represented by the following formulas:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2}$$

$$PL(dB) = 10log\frac{P_t}{P_r} = -10log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] \quad (3)$$

In equation (2), G_t and G_r are antenna gain, and L is system loss factor which has nothing to do with the transmission. Equation (3) is the signal attenuation formula using a logarithmic expression.

2.2 TOA

Time of Arrival (TOA) [8] uses the time taken by the transmitter node's signal to reach the receiver node in a SAN. First, Time synchronization must be achieved between the receiver nodes. Second, the distance is measured by the following equation:

$$D = c \cdot \Delta t \quad (4)$$

In equation (4), c is the speed of sound and Δt is the time difference between transmission and arrival time of signal.

Three or more receiver nodes measure the TOAs of the transmission from the transmitter node, each of which make a circle, and the intersections of circles give the target location. Figure 1 shows an example of TOA measurements. In the figure, the estimated distances between the receiver nodes and transmitter node are shown by the circles. However, the circles do not intersect at a distinguishable point. So it is necessary to find a location that best fits the measurements.

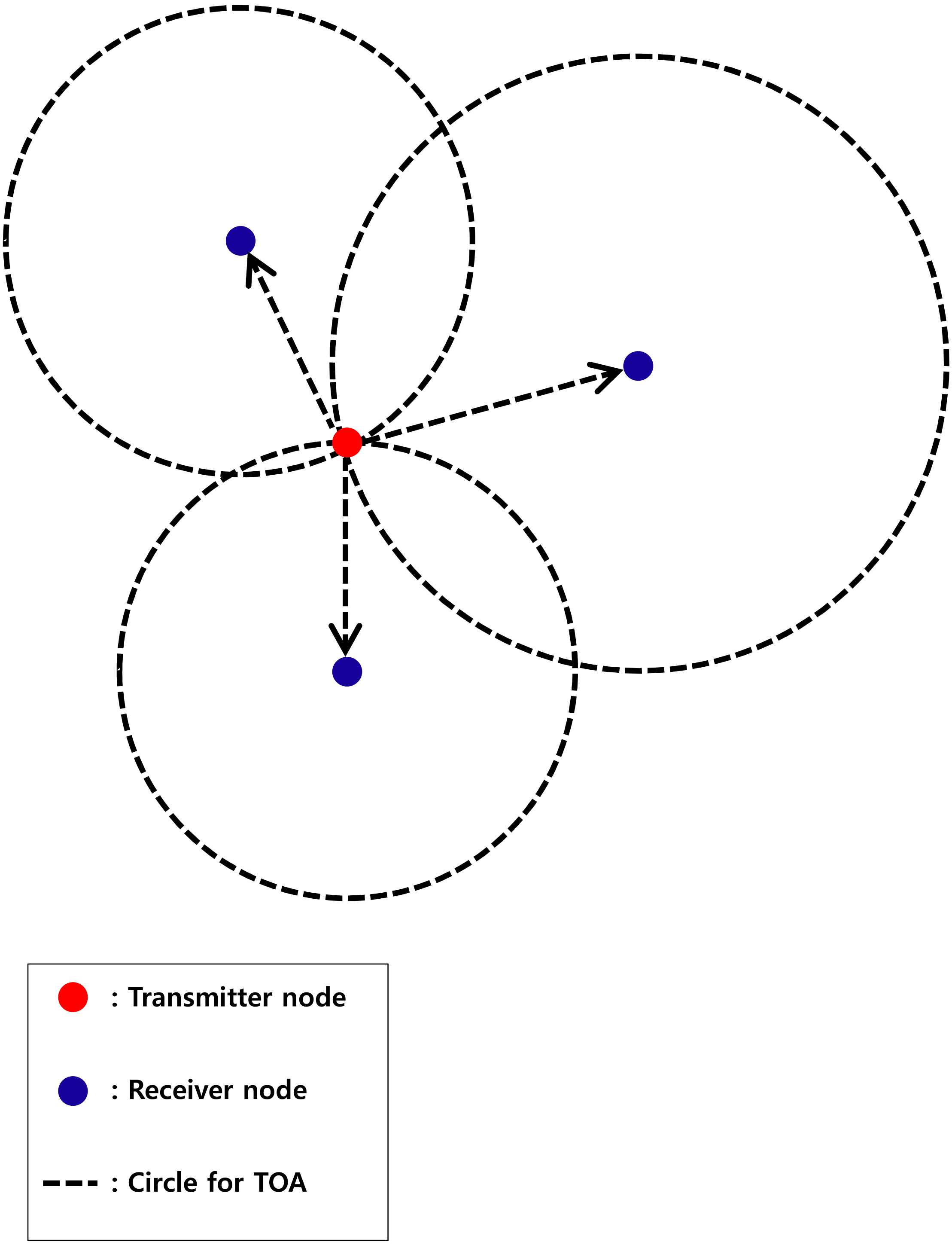


Figure 1. An example of TOA measurements.

III. CHALLENGES OF HIGH ACCURACY LOCALIZATION

3.1 Challenges of Time Synchronization

The famous approach to high accuracy localization is based on measuring TOA information of acoustic or radio signals. However, the TOA-based approach has time synchronization problems [9, 10, 11, 12, 13] as shown in Figure 2.

Typically, the TOA-based systems is done with both nodes taking a timestamp of their respective local clock at the moment the signal is transmitted and received. There are several intrinsic uncertainties in this process that will contribute to the TOA measurement errors:

1) The difference of time clock (Δi): each node in a SAN has the fine difference of time clock owing to clock skew and drifting.
2) Uncertainty of the transmission time (Δj): we cannot record the exactly signal emission time.
3) Uncertainty of the arrival time (Δk): the possible delay of a sound signal arrival being recognized because of real time control, software delay and system loads.

For these reason, we can see that we assume timestamp from the sound sampling in the recording files are actually uncertain. These uncertainties easily add up to several milliseconds and translate to several meter of distance error when TOA measurement is done in software.

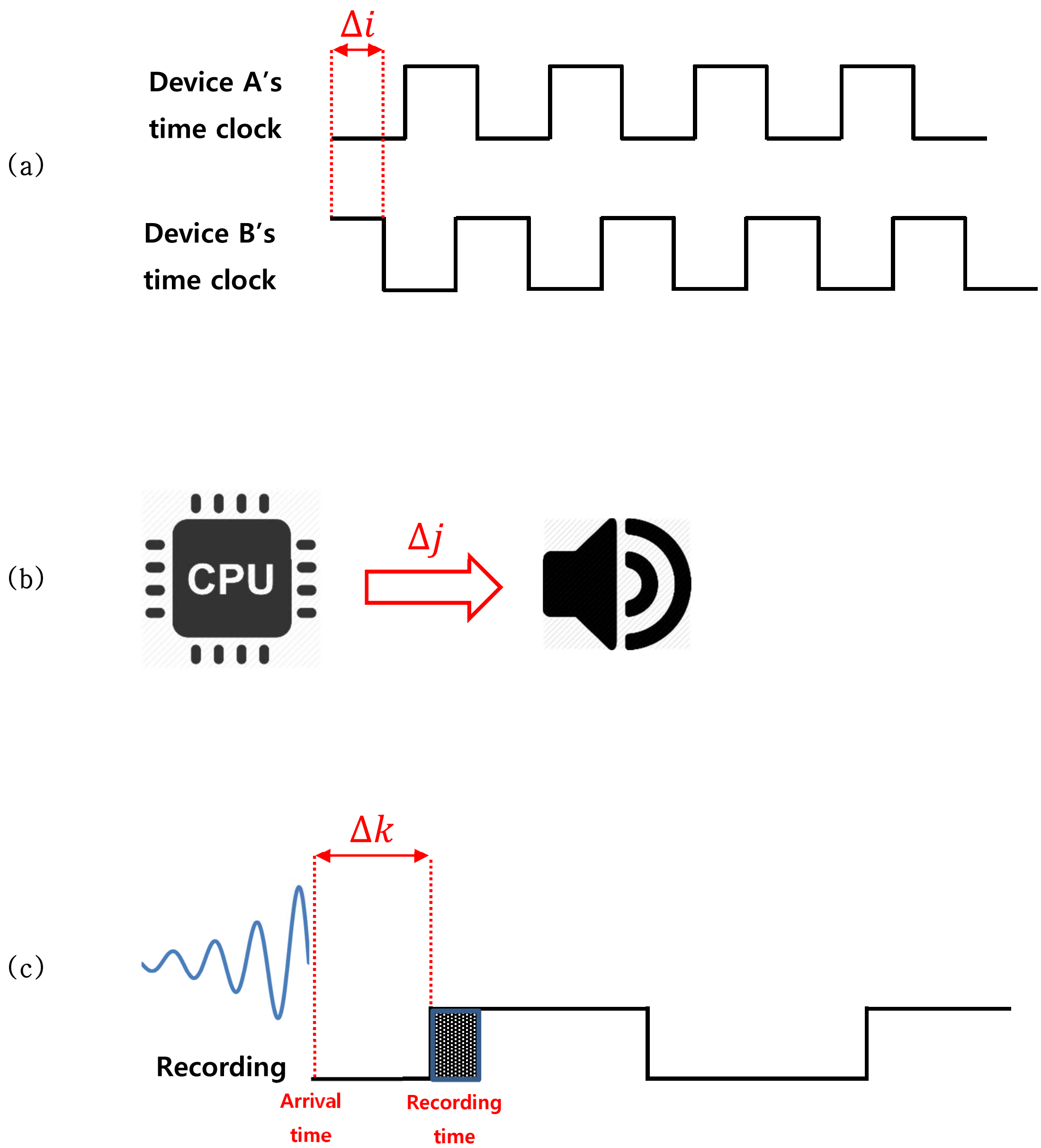


Figure 2. Time synchronization problems of TOA-based systems: (a) the difference of time clock between nodes (Δi), (b) the transmission time is uncertainty (Δj), (c) the arrival time of signal is uncertainty (Δk).

3.2 Challenges of Asynchronous Localization

Asynchronous localization is a well-studied topic [14]. Based on the work done by [14], identifying the locations of distributed asynchronous smartphones requires two major steps which include distance measurement and multi-dimensional scaling (MDS) [15]. As shown in

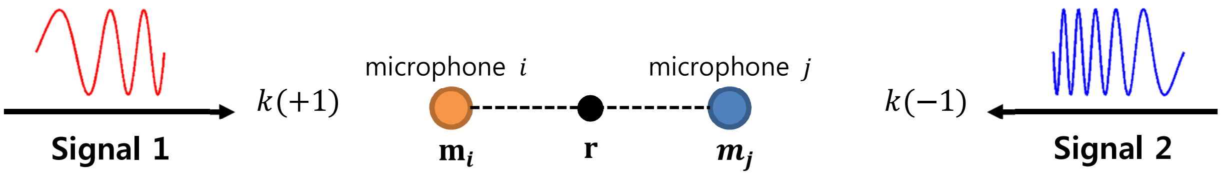


Figure 3. Two wavefronts impinge a microphone pair from directions parallel to the microphone pair's axis (marked as dotted line). The wavefronts are emitted by separate sources [14].

Figure 3, assume that two microphones m_i and m_j form a pair and that a signal 1, 2 reside in the far field where r is pair's center point $r = \frac{1}{2}(m_i + m_j)$. Therefore, the wave front time of arrival at microphone i is computed as:

$$\tau = \langle m_i - r, k \rangle + \Delta_i \tag{5}$$

where $\langle \cdot,\cdot \rangle$ is dot product, vector k is propagation direction, and Δ_i is the device time-offset. If device is synchronized precisely, then time-offset is 0, but it is very hard to synchronize smartphones in ad-hoc network with specific clocks. The Time Difference of Arrival (TDOA) is computed as:

$$\tau_{ij} = \tau_i - \tau_j = \langle m_i - m_j, k \rangle + \Delta_{ij} \tag{6}$$

where Δ_{ij} is $\Delta_i - \Delta_j$. The propagation vectors of the sound wave emitted from the sound source have a directional property that is defined by β. Combining the Equation (6) and the concept of sound propagation direction, the TDOA is redefined as:

$$\tau_{ij}(\beta) = \beta c^{-1} \| m_i - m_j \| + \Delta_{ij} \tag{7}$$

where c is the speed of sound propagation and two waves arrive from the endfire direction ($\beta \in \{-1, 1\}$). Since both TDOA values represent the physical lower and upper limits of the observation, we use terms $\tau_{ij}^{max} \triangleq \tau_{ij}(+1)$ and $\tau_{ij}^{min} \triangleq \tau_{ij}(-1)$. Therefore, the distance between microphone i and j is computed as:

$$d_{ij} = \frac{c}{2}\left(\tau_{ij}^{max} - \tau_{ij}^{min}\right) \tag{8}$$

(8) can be proved by using (7):

$$\frac{c}{2}\left(\tau_{ij}(+1) - \tau_{ij}(-1)\right)$$

$$= \frac{1}{2}\left(\| m_i - m_j \| + c\Delta_{ij} - \left(-\| m_i - m_j \| + c\Delta_{ij}\right)\right)$$

$$= \|m_i - m_j\| \triangleq d_{ij}$$

As a result, we can measure the distance among asynchronous smartphones without worrying about the time-offset Δ_{ij}.

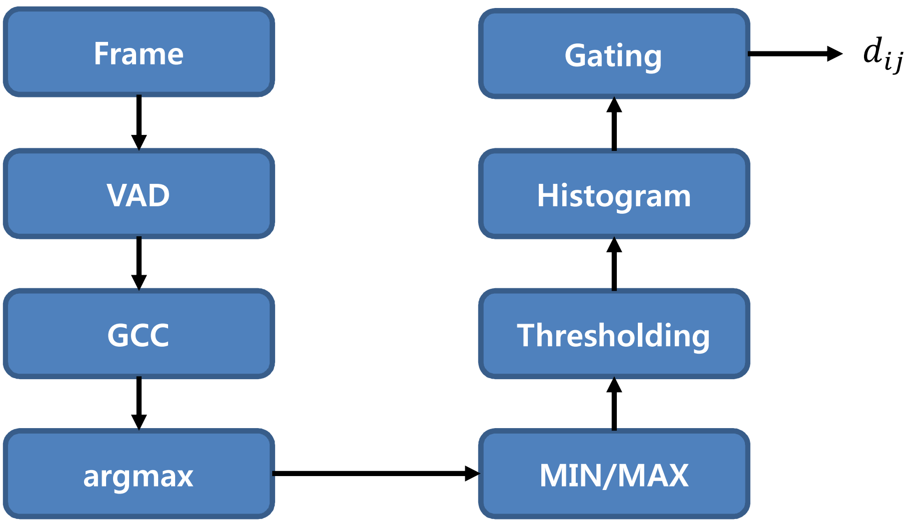


Figure 4. Block diagram of the proposed self-localization method [9].

To observe and estimate the maximum and minimum TDOA between a set of paired devices, authors of [9] proposed the following 7 steps as shown in figure 4:

1) Divide incoming signals into frames.

2) Validate whether a given frame carries significant signal strength using λ_E.

3) Compute TDOA between the sensor pair using GCC-PHAT [16] (Generalized Cross Correlation using Phase Transform).

4) Filter out noisy TDOA values using λ_G.

5) Create a histogram of accumulated TDOA values.

However, there are three major problems with the method proposed by author of [14]:

1) They require continuous speeches of peoples for self-localization.
2) Participants necessarily have to talk in turn. They don’t allow peoples to talk simultaneously.
3) To tolerate distance errors (under $10cm$) are taken after 140 seconds.

IV. ASYNCHRONOUS DISTANCE MEASUREMENT METHOD

Considering the meeting environment and general meeting room size that smart meeting system we are currently working on is to be used, the allowable distance error is within 10 cm. This is based on TOA estimation method that the time error shall be reduced within approximately 300 μs. However, it is very difficult to achieve synchronization for accurate time up to micro-second on the smartphone operating in the wireless network environment and also tends to cause extra costs [17]. In addition, as for another distance measurement technique, RSSI, heavy fluctuation on the changes are seen depending on the time flow even in the same location of wireless environment. In addition, methods developed after considering such changes tend to create error in average unit of m. Therefore, it is difficult to apply them in the indoor meeting environment.

This study suggests a new asynchronous technique without having to synchronize the time among devices by using the previous distance equation by BeepBeep System in order to overcome limitations of TOA measurement method in need of synchronization between smart phones.

Method suggested in this study measures the distance through four steps:

1) First step is to connect server PC and two smartphones with one AP forming one distinct network group.
2) Second step is that server PC makes an order of recording to smartphones. Two smartphones which receive the making sound order start recording chirp signals with different frequency in the same time frame. What is important in the second stage is a self-recording of chirp signals as shown in the Figure 5(a). In other words, it is not to

stop recording when the smartphone produces chirp signals but is required to maintain them all at the same time.

3) Third step is that each of the smartphones sends the recorded file with chirp signals of one's own and the ones of others to server PC.
4) The last and fourth stage is to analyze recorded files in the server PC calculating the distance value between devices from equation (13).

Figure 5 (b) represents the procedures proceeded with the second stage on the local time line of each of device A and B. Chirp A and chirp B represent chirp signals produced by each of device A and device B. t_{A0} and t_{B0} represent the time when chirp signals occurred by device A and B reach to their microphones. t_{A2} represents the time when chirp B arrives to device A microphone, and t_{B2} represents the time when chirp A arrives to device B.

If $d_{x,y}$ is regarded as a distance between speaker of device x and microphone of device y, the distance of each of them is defined:

$$d_{A,A} = c \cdot (t_{A1} - t_{A0}) \tag{9}$$

$$d_{A,B} = c \cdot (t_{B2} - t_{A0}) \tag{10}$$

$$d_{B,A} = c \cdot (t_{A2} - t_{B0}) \tag{11}$$

$$d_{B,B} = c \cdot (t_{B1} - t_{B0}) \tag{12}$$

c in the equation from (9) to (12) indicates the speed of sound. The equation of deriving the average distance value between microphone and speaker of device A and B is obtained as follows by using equations (9) to (12):

$$
\begin{aligned}
\mathrm{D} &= \frac{1}{2}\cdot\left(d_{A,B} + d_{B,A}\right) \\
&= \frac{c}{2}\cdot (t_{B2} - t_{A0}) + (t_{A2} - t_{B0}) \\
&= \frac{c}{2}\cdot (t_{B2} - t_{B0} + t_{B1} - t_{B1} + t_{A2} - t_{A0} + t_{A1} - t_{A1}) \\
&= \frac{c}{2}\cdot ((t_{A2} - t_{A1}) - (t_{B1} - t_{B2}) + (t_{B1} - t_{B0}) + (t_{A1} - t_{A0})) \\
&= \frac{c}{2}\cdot ((t_{A2} - t_{A1}) - (t_{B1} - t_{B2})) + d_{A,A} + d_{B,B} \\
&= \frac{c}{2}\cdot ((t_{A2} - t_{A1}) - (t_{B1} - t_{B2})) + K
\end{aligned} \tag{13}
$$

$K = d_{A,A} + d_{B,B}$ tends to have a fixed distance value from each of the devices to the microphone. Therefore, it is feasible to obtain the distance between two devices if calculating only $t_{A1}, t_{A2}, t_{B1}, t_{B2}$.

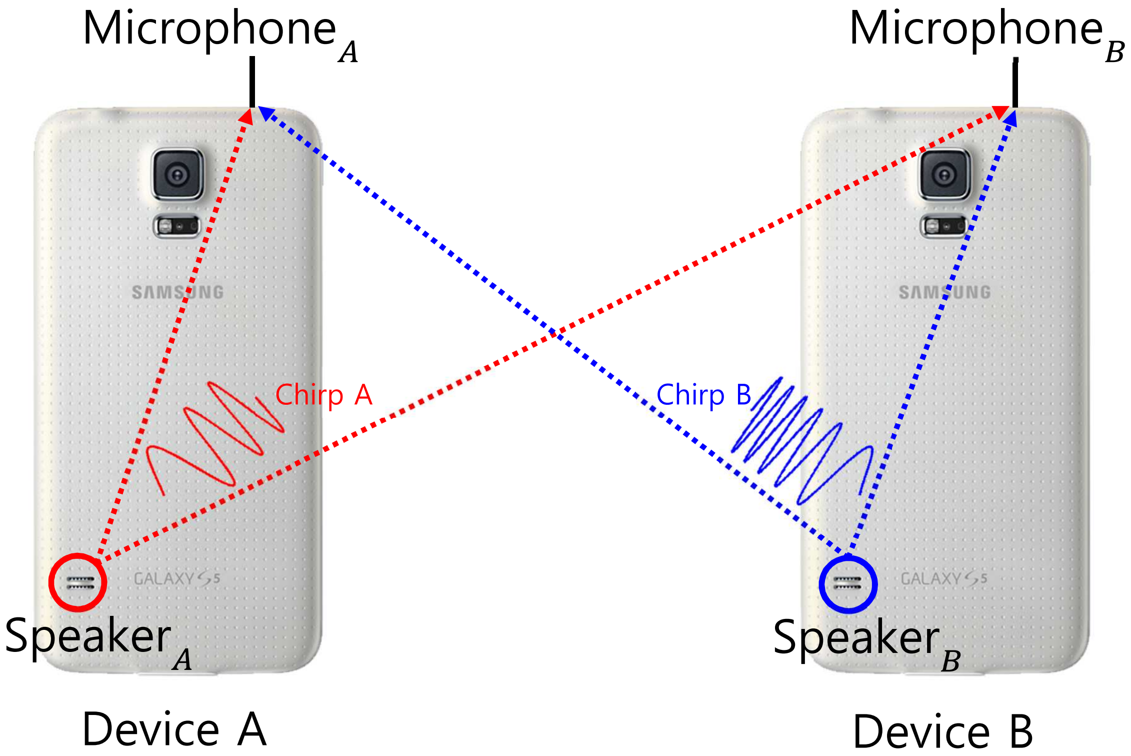


Figure 5 (a). Example of the second step (transmitting sound in different frequency when two devices start recording at the same time and record it).

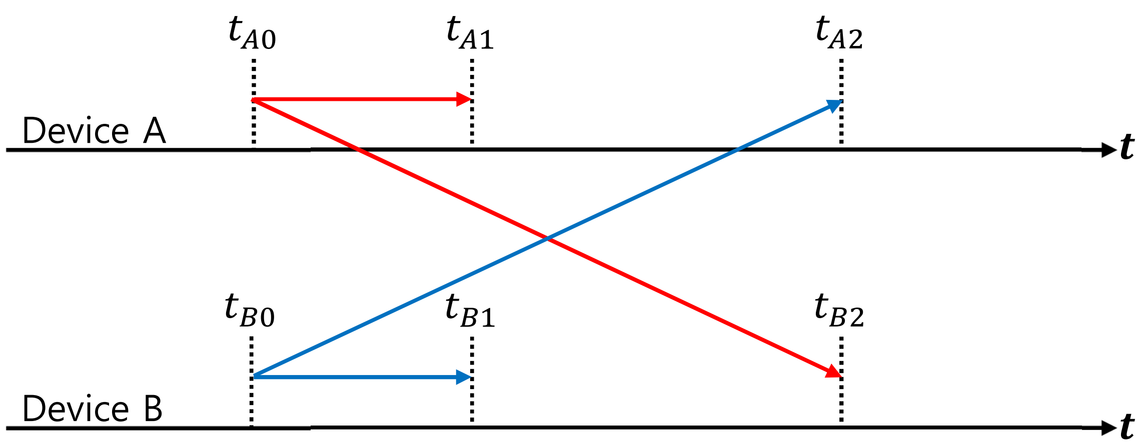


Figure 5 (b) Example of representing the second step as local time line of each of the devices.

V. IMPLEMENTATION DETAIL

We had two smartphones as a basis first and will gradually increase the number of them making it feasible to measure the distance among devices participating in the same wireless devices with each of the transit signals at the same time.

Methods suggested in this study are available to operate only with performance of application without modifying the specific hardware design of the smartphone or OS kernel. Therefore, the experiment was proceeded two devices of Samsung Galaxy S5, one of the Commercial Off-The-Shelf (COTS) devices.

5.1 Chirp Signal Design

The method suggested in this study produces different sounds while two smartphones record it. Hereupon, sound of one device as well as the one from other device is recorded at the same time. Since sound of both devise is recorded at the same time, it is needed to distinguish the sound from each device. Therefore, we have used chirp signal as a transmit sound that frequency was linearly increased in other frequency zones from each of the devices.

It was not to merely use different signals with consistent frequency but to use chirp signals that were linearly increased since it was intended to identify more accurate arrival time of sound from receiving part. We have proceeded matched-filtering [19] on original sound signals and the recorded ones to determine the arrival time. Figure 6 (a) is the result of filtering signals without changes in the frequency, and Figure 6(b) is the result of filtering chirp signals that frequency was linearly increased [20]. Peak point from the result after filtering was the highest value in correlation with original signals. Therefore, it was feasible to determine the distance based on the area receiving the signal. However, it is difficult to distinguish exact peak point in Figure 6 (a) compared to Figure 6(b). Therefore, this study has used chirp signals as a transmit sound.

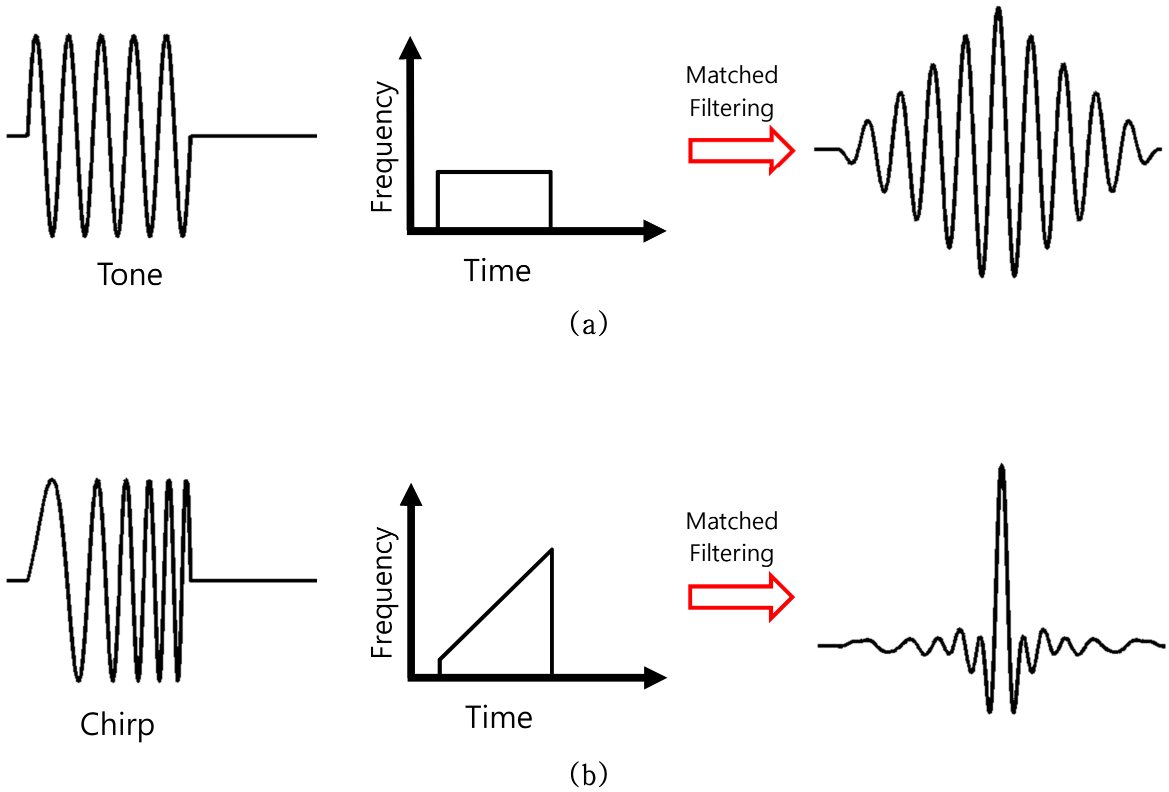


Figure 6. Experiment of application of matched filtering. (a) is the result of tone signals with consistent frequency, and (b) is the result of chirp signal with a linearly increasing frequencies.

We have produced from 1 kHz to 20 kHz sounds in the scale of amplitude of ±1 in the place a certain distance away in order to designate the chirp signals with the most appropriate frequency range to two smartphones and recorded it. Figure 7 represents a graph of result when receiving the recorded sound. Samsung Galaxy S5 was used for the experiment of recording and producing chirp signals at the same time. As a result of experiment, there was no prominent difference. However, the area between 2kHz and 6kHz and the area between 8kHz and 12kHz had less difference between the amplitude scale and original sound. Therefore, these two areas

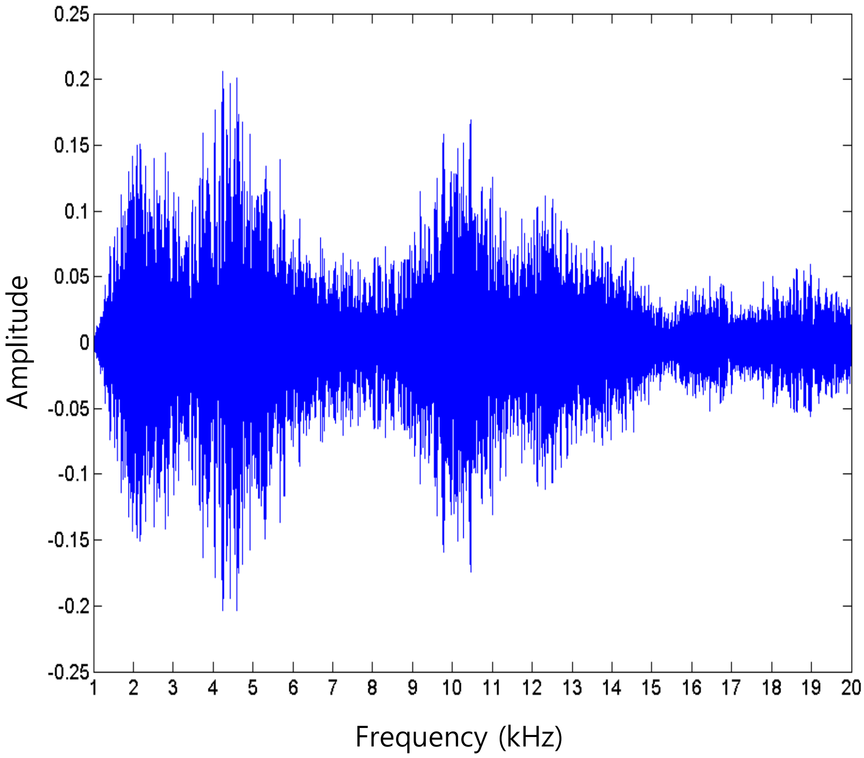
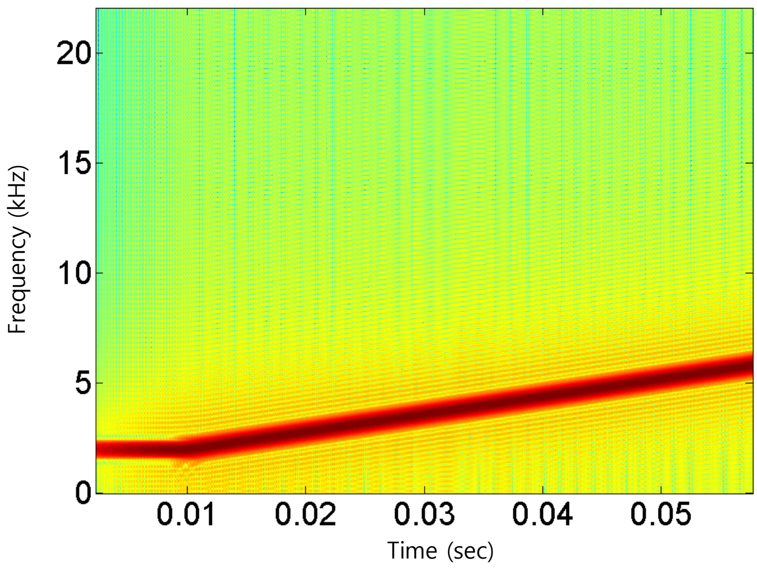


Figure 7. Graph of changes in amplitude from changes in frequency (1 kHz ~ 20 kHz).

used chirp signals. In addition, it was confirmed that noise as small as mouse click sound was produced when transmitting chirp signals from the smartphone's speakers while proceeding the experiment [21]. We have added fade-in signals that the sound scale was linearly increased during 0.01 second on the beginning and the ending of chirp signals to relieve noise since there was a chance of deforming original sound.

As a result, the final configuration of chirp signals used in our experiment was shown in Figure 8.

(a)



(b)

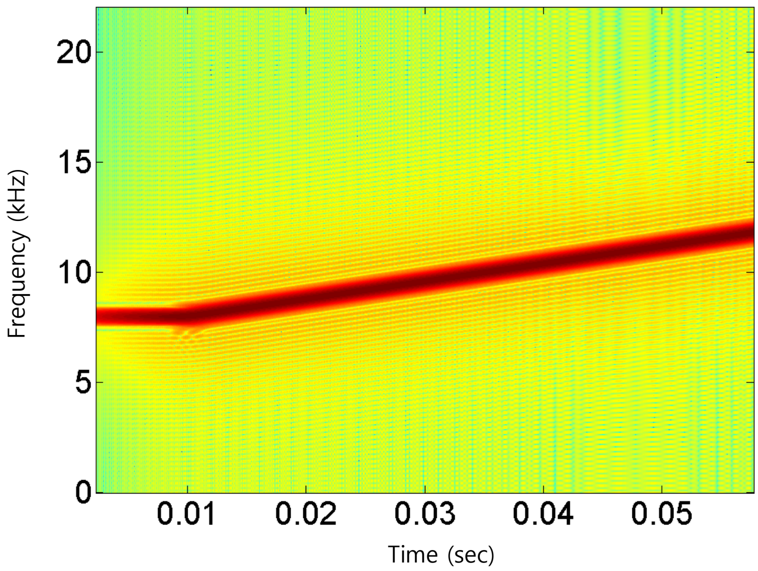


Figure 8. Graph of changes in frequency according to the time frame of chirp signals used in the experiment. Two of the chirp signals had warm-up zone during 0.01 second. (a) and (b) had area of frequency to be linearly increased in the area between 2 kHz and 6 kHz and between 8 kHz and 12 kHz, respectively.

5.2 Chirp Signal Detection

Figure 9 is the result of recording chirp signals produced by two smartphones at the same time. Since it represent the result of recording signals at the same time, it was confirmed that sound combined with two of the chirp signals was recorded. We have used matched-filter and confirmed when two of the chirp signals were received through filtering with original signals, respectively, when two signals were recorded at the same time.

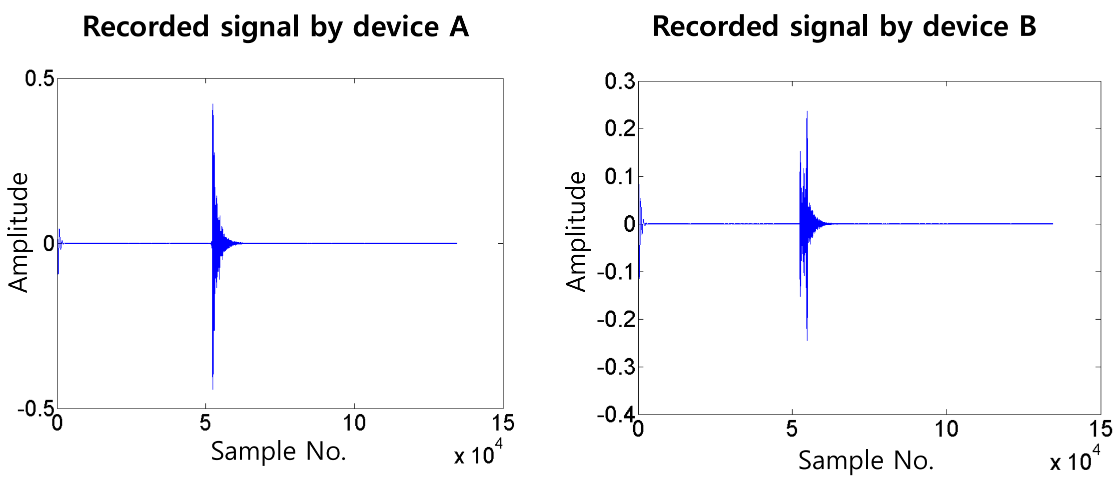


Figure 9. Example of graph for simultaneously produced chirp signals recorded by each of A and B.

Figure 10 is a graph representing the result values from matched-filtering after comparing the recorded signals with original signals. It was able to confirm that the area with the highest correlation value was where the signal was received. However, error was rapidly increased as the distance between devices became further apart according to the result of experiment. This was because the correlation value of reflected waves was turned out to be highest due to multipath effect [22] that sound was reflected and delivered indoor. Therefore, we have found the peak point of filtered signals and regarded the first peak point [23] among all the peak points within 1000 samples as of the maximum peak point as the area where chirp signal was received.

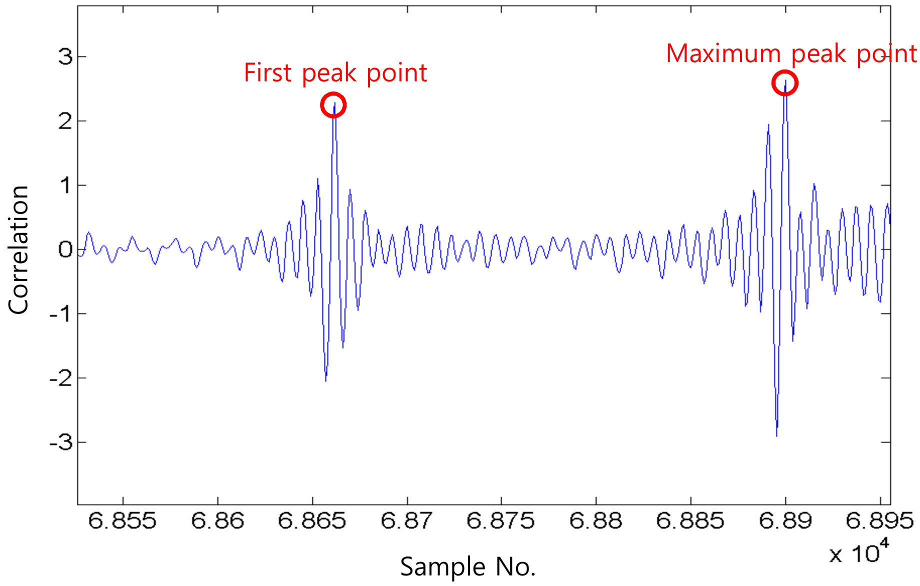


Figure 10. Finding first peak point from the result of matched filtering due to multipath effect.

5.3 Device Orientation

As for the smartphone recently released, more than two mics are distributed on the front and back sides in order to prevent howling phenomenon and to improve the sound quality. Therefore, there might be a difference depending on types of smartphones. However, there usually a difference of distance from mic for more than 10 cm on the front and backside. Hereupon, K value in the equation (13) turns out to be different depending on what types of microphone are being used.

As for many of the Android smartphones including Samsung Galaxy S5 used in the experiment, regular speaker is located on the back as shown in Figure 11. Therefore, if the smart phone on the desk was placed with front cover facing towards the user as shown on front orientation in the Figure 11 in experiment, speaker tends to be located closer to the desk. This causes multipath effect and sound distortion phenomenon when speakers produce chirp signals.

Figure 11. Front and back side of Samsung Galaxy S5 used in the experiment.

We have directly confirmed how a distance error for more than tens of meters was incurred even after finding the first peak point when smartphones used regular speakers on the front orientation. However, most of the people tend to place smartphones with front cover facing towards the user on the desk. Considering such characteristics of users, restriction insisting that accurate result was to be derived on the experiment only when placing the smartphone upside down would be of a huge obstacle on this study aiming to provide commercial applications. Therefore, we have solved this issue by producing chirp signals on the communicating speaker instead of backside speaker on the location of front orientation.

In case of having front orientation shown in Figure 11 after the system determined the posture of smartphones being placed by using gravity sensor z-axis value, front communicating speaker was used, but backside speaker was used in case of back orientation in order to produce chirp signals. If the smartphone was placed with front side facing towards users, gravity sensor value was turned out to be +9.8 m/s^2 as gravity acceleration [24]. If the smartphone was placed upside down, gravity sensor was turned out to be -9.8 m/s^2. Therefore, it is feasible to select posture-customized usage of speaker after determining the posture before producing chirp signals.

VI. EVALUATION

6.1 Hardware Configuration

For the evaluation of system applied with the method we have suggested, two devices of Samsung Galaxy S5, one of the COTS (Commercial Off-The-Shelf) devices, were used. Both devices used Android 4.4.2 versions and were equipped with blue tooth, Wi-Fi, 2GB RAM, and 2.5 GHz quad-cores CPU [25]. In addition, as for speakers producing chirp signals, the regular speaker was located on the backside, while communicating speaker was installed on the front side. As for mic receiving chirp signals, both top and bottom areas of the mic were used. As a result of the experiment, it was confirmed that an error of distance measurement was turned out to be less when using the mic located further in distance from speakers. Therefore, when using

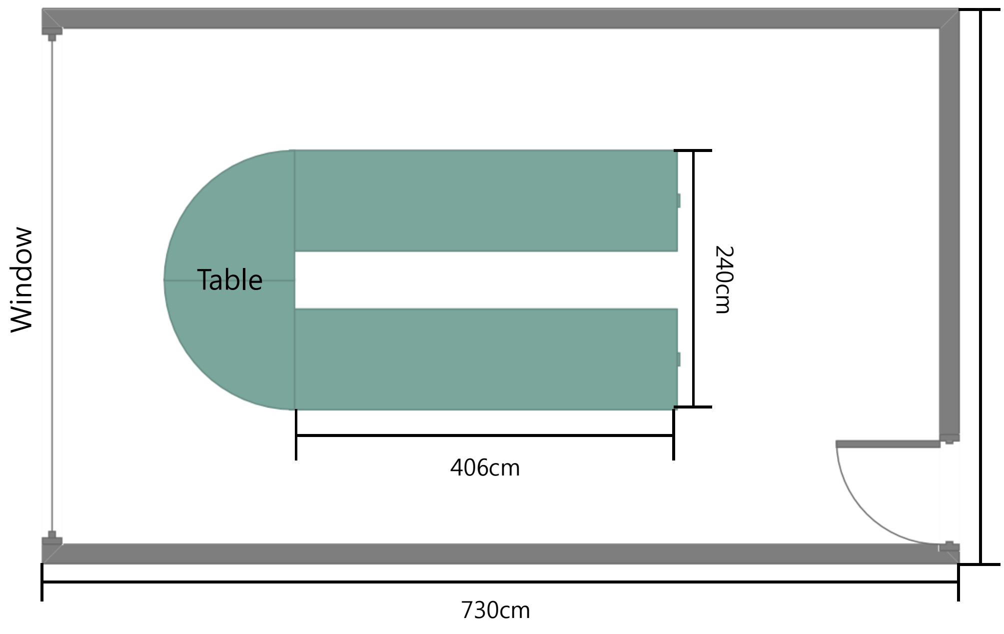


Figure 12. Meeting room on the experiment.

the front side communicating speaker, the mic on the bottom was utilized. If using the backside regular speaker, the mic on the top was utilized.

6.2 Test Case Design

We have proceeded an experiment at the meeting with length of 730 cm and width of 530 cm as shown in Figure 12. The temperature in the meeting room was maintained between 17 and 20 ℃, and the smartphone was placed on the U-shaped table with length of 406 cm and width of 240 cm on the experiment. In addition, all other artificial noises were limited except for chirp signals.

We have classified total three cases depending on where to place the smartphone as shown in Figure 13 for the experiment:

Case 1 (Back-Back): All smartphones are placed upside down making screens to face the table.

Case 2 (Back-Front): One smartphone is placed on the table with front side facing upward while the other facing the table.

Case 3 (Front-Front): All smartphones are placed on top of the table with front side facing up.

For each case, smartphones were separated 100 cm, 200 cm, 300 cm, and 400 cm apart from each other, and 30 distance measurements were accordingly made for each of the cases. In addition, chirp signal in the size of 0 decil-Bell full scale ($dBfs$) was used on case 1 and case 3. On case 2, chirp signal in the size of 0 $dBfs$ was used for device using regular speakers, and the one in the size of -30 $dBfs$ was used for device using backside speaker. The reason why sound in different intensity was used was that sound of less intensity was produced if communicating speaker played the same sound of $0\,dBfs$. Therefore, it was because chirp signal in small intensity was drowned out by the large intensity sound causing the matched-filtering to be poorly conducted.

Case 1

Gravity sensor z-axis: (-9.8 / -9.8)

Case 2

Gravity sensor z-axis: (-9.8 / +9.8)

Case 3

Gravity sensor z-axis: (+9.8 / +9.8)

Figure 13. Case 1, Case 2, Case 3 devices orientation.

6.3 Experimental Result

Speed of sound influenced by air temperature was applied after confirming the temperature [26] in each experiment by using the following equation:

$$c = 331.3 + 0.606 * T \tag{14}$$

T indicates Celsius temperature of air (℃). In addition, we have calculated the absolute value of difference between distance value estimated in the experiment and real distance value as a distance error:

$$Distance\ Error = |Real\ Distance - Estimated\ Distance| \tag{15}$$

As a result of the experiment, there were cases that a distance error was turned out to be up to tens of meter. Therefore, the average value was significantly increased by only one huge error value if calculating the average distance error in the entire experiment. Hereupon, less than 10 cm was treated as a basis determined as an allowable distance error, the average value and standard deviation of distance error values satisfying these requirements were calculated. In addition, accuracy represented in the unit of percentage as to how much value was relevant to the range of allowable distance error determined in each experiment was calculated as well. Figure 14 indicates a graph of the accuracy, Figure 15 indicates the average distance error, and Figure 16 indicates the standard deviation of the case 1, 2, and 3.

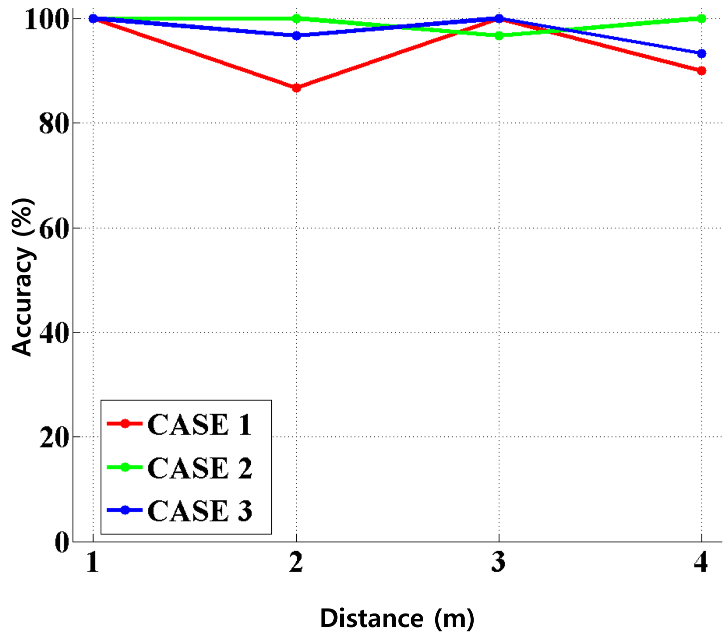


Figure 14. Accuracy of case 1, 2, 3.

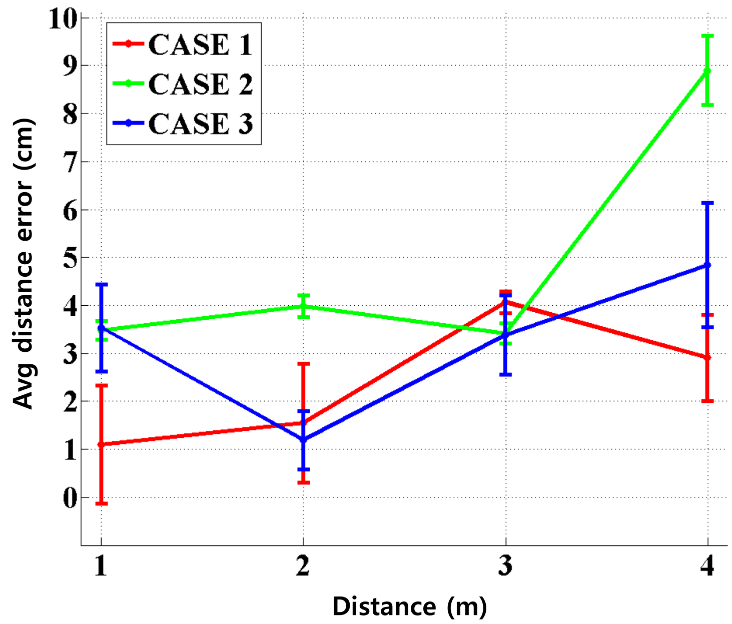


Figure 15. Average distance error of case 1, 2, 3.

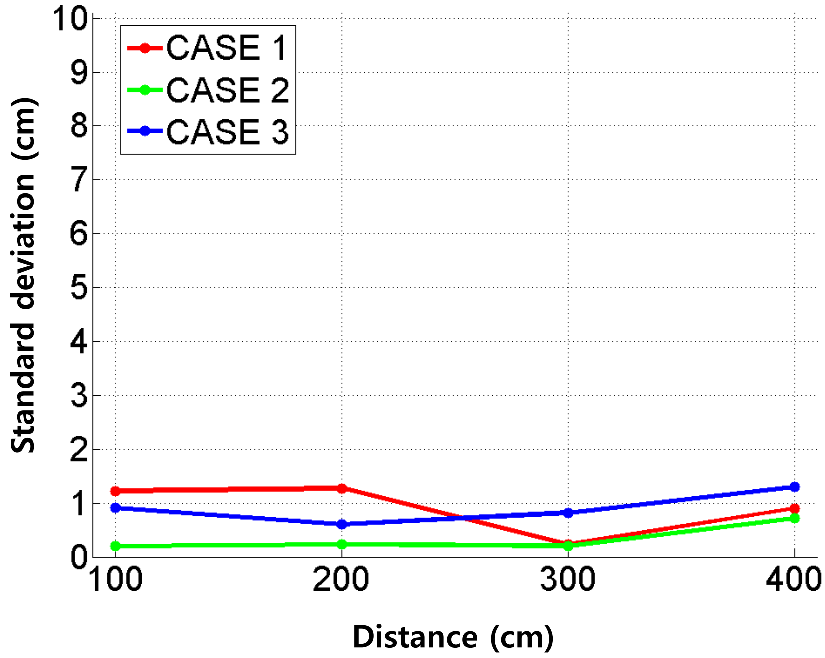


Figure 16. Standard deviation graphs of case 1, 2, 3.

6.3.1 Case 1 Result

In case 1, K value as a value of adding the distance of speaker and mic of two devices was $25cm$. In addition, the experiment was proceeded in the temperature of 20 ℃ in all the conditions of changes in distance (changes in distance between devices in $1m$ interval from $1m$ to $4m$), and both devices used 0 $dBfs$ chirp signals.

As a result of experiment, at least 87 % of accuracy was derived as shown in the Figure 14, and the average of distance error was 4.07 cm maximum as shown in the Figure 15. And the standard deviation was 1.26 cm maximum as shown in the Figure 16. Figure 17 is the box plot

[27] on the results of case 1. Therefore, it was confirmed that less than 5 cm of distance error was derived in all the conditions.

6.3.2 Case 2 Result

K value was 26 cm, and the experiment on the interval of 1 m and 2 m was proceeded in the temperature of 19 ℃. In addition, the experiment on the interval of 3 m and 4 m was proceeded in the temperature of 18 ℃. Both devices showed the accuracy of 96.67 % and 66.67 %, respectively, in the interval of 1 m and 2 m if producing 0 $dBfs$ chirp signal. However, distance error was turned out to be beyond 10 cm, the allowable error range in each of the 30 trials of experiment in the interval of more than or equal to 3 m. Therefore, each of the devices using the front speaker and backside speaker used 0 $dBfs$ and -30 $dBfs$ chirp signals only in case 2. As a result, minimum of 96.67 % of accuracy was obtained, and the average of distance error was shown as 8.9 cm maximum. The standard deviation was turned out to be 0.71 cm maximum. Figure 18 is the box plot graph on the result of case 2. Therefore, it was confirmed that less than 5 cm of distance error was obtained in all the cases except for distance of more than 9 cm in 4 m.

6.3.3 Case 3 Result

K value was fixed at 27 cm in case 3. All the experiments conducted on the change in intervals were proceeded in the temperature of 17℃. As a result of experiment, accuracy of more than 93 % was shown in all the experiments, and the average distance error was 4.8 cm maximum. The standard deviation was turned out to be 1.3 cm maximum. Figure 19 is the box plot graph on the result of case 3. It was confirmed that less than 5 cm of distance error was obtained in all the conditions except for more than 6 cm of distance error in the 4 m.

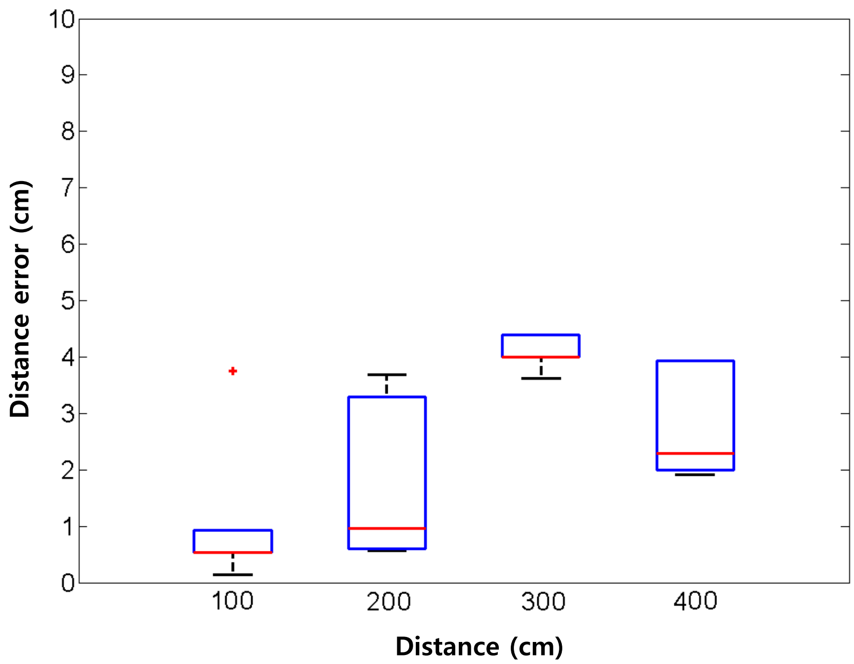


Figure 17. Case 1 box plot.

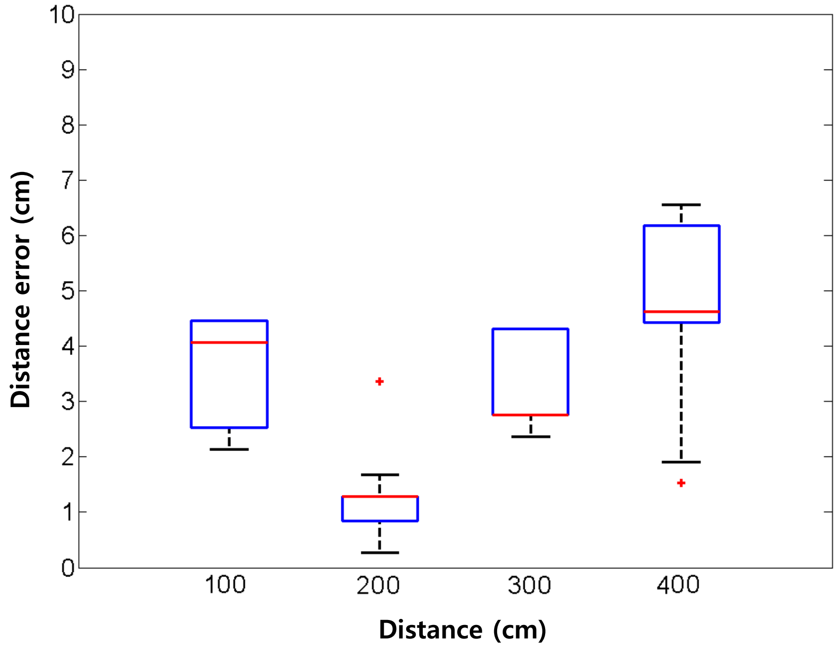


Figure 18. Case 2 box plot.

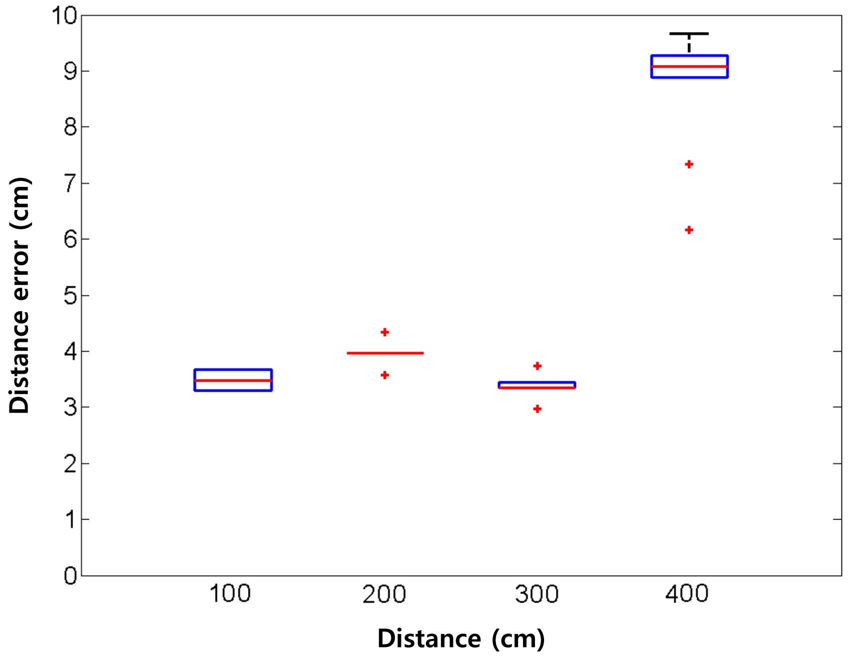


Figure 19. Case 3 box plot.

VII. CONCLUSION

We proposed an accurate, asynchronous, and robust distance measurement method as a software-only solution. In this work, we used two devices of Samsung Galaxy S5, one of the COTS devices, and suggested a system which can measure distance between devices only with installation of application and configuration of network without modifying hardware. In other words, our proposed method enables the development of highly-accurate infrastructure-less localization system for smartphones. In addition, it was confirmed that measurement of distance was available within allowable error range in the environment where accurate synchronization was not performed beyond the weakness of previous method with much limitation on time error such as TOA or RSSI method. Hereupon, feasibility of how the smartphone could replace the previous devices in the field of sensor network having been experimented. Furthermore, it was possible to fulfill requirements of the basis in infrastructure-less smart meeting system that we have been studying on.

Experiment was conducted in the general indoor meeting room representing less than 10 cm of distance error with more than 87 % of accuracy from less than 4 cm distance between devices in every experiment. This experiment was conducted in the situation limiting all sources of the noise as much as possible. However, it is planned to proceed a follow-up study in the environment with noise as similar as the one from real meeting. Furthermore, more than three smartphones are to be used planning to proceed various experiments in a similar situation with meeting in the future work.

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요 약 문

CHIRP 신호를 이용한 비동기적 거리측정 방법

스마트폰이 대중화 되면서 이를 활용한 다양한 애플리케이션 시장이 급성장하고 있다. 특히 스마트폰이 다양한 센서들을 내장하고, 컴퓨터 못지 않은 데이터 처리능력을 갖춤으로써 기존의 센서 네트워크를 구성하는 디바이스들을 스마트폰으로 대체하는 연구들이 활발히 진행 중에 있다. 이러한 스마트폰 기반 네트워크를 구성하기 위해서는 네트워크를 구성하는 디바이스들 간의 거리측정이 우선적으로 이루어져야 한다.

우리는 기존의 대표적인 거리 측정방법인 RSSI (Received Signal Strength Indicator)와 TOA (Time of Arrival) 측정 기법의 한계점을 극복한 chirp 신호를 이용한 새로운 비동기적 거리측정 기법을 제안한다. 또한 우리는 COTS (Commercial Off-The-Shelf) 디바이스 중 하나인 Samsung Galaxy S5 2 대를 사용하여 하드웨어나 OS Kernel 등의 수정이 필요없는 Infrastructure-less 한 시스템을 제안한다. 실험 결과, 10cm까지의 거리오차를 센서 네트워크를 구성할 수 있는 최대 허용 가능한 오차로 보았을 때, 최소 87 % 이상의 정확도로 모두 10 cm 이내의 거리오차가 발생하였다.

핵심어: 센서 네트워크, 거리측정, Localization, 스마트폰, CHIRP 신호, 스마트폰 기반 애드혹 네트워크