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ORIGINAL ARTICLE

# Controlling of communication connection range using acoustic waves emitted from smartphones

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**Abstract**

The development of smartphones and other portable devices has expanded new ways of communication and collaboration both in private and business settings where there are used e.g. for sharing files and other information. However, this communication is not always secure and can be intercepted by a third party in the vicinity. This paper proposes an intelligent communication control mechanism where the shared information is accessible only within a physically limited space. Normally, existing communication methods based on radio waves (Wi-Fi or Bluetooth) are accessible to anyone within a specific range; thus, they are susceptible to breach and communication eavesdrop beyond walls. Our proposed method is based on an association scheme whereby the sending smartphone can restrict the communication range by controlling an acoustic wave's magnitude and frequency. Thus, unlike radio waves, it is possible to send the signal to devices located in a specific range, where the client devices exist, after recognizing the distance and angle between devices. Our experiments by sharing signals among smartphones indicate that it is possible to unidirectionally control the sharing range while sharply reducing any possibility to eavesdrop on the communication.

**Keywords** Acoustic waves · Co-location · Smartphone · Wi-Fi direct

## 1 Introduction

Data sharing and communication has traditionally been at the forefront of the disruptive technology since the heyday of the World Wide Web. Email, instant message, and VoIP services nearly obsoleted the need for typed letters and telegrams and have noticeably reduced the need for in-person communication. The development of client-server model and Device-to-Device (D2D) communication services further improved file sharing, albeit at the risk of copyright infringement. For instance, AirDrop, which can be used by products of Apple, is popular as D2D communication [1]. Further, cloud-based synchronization and sharing services such as Dropbox, iCloud and Google Drive are used for collaboration and data sharing to the next level. The benefits gained from client-server model communications include cost and time savings, knowledge and expertise dissemination. Contemporary communication methods were introduced due to advances in hardware and software. For example of D2D communications, Infrared Data Association (IrDA), Near Field Communication (NFC), or Wi-Fi Direct [2] have been used for data sharing. This further improved collaboration and data sharing.

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Traditionally, desktop computers and laptop were the main computing devices for personal and professional use. However, a recent development of powerful hand-held devices, such as tablets and smartphones, has shifted this trend since they are slowly replacing traditional file mechanisms both in private and in business settings. Mobile devices are commonplace while desktop computers are often relegated to computation intensive tasks. These mobile devices, unlike their desktop computer counterparts, are convenient for taking pictures, listening to music, viewing, and editing documents at anytime and anywhere. However, this flexibility comes at a cost, regarding for example, for file sharing. Conventionally, emails and other cloud services are employed for this task. However, for mobile devices using client-server model communications, it always requires an Internet connection. Additionally, in case of Internet traffic congestion, or in the presence of large files, it takes long to share, and requires a costly mobile data. Meanwhile, D2D communications, such as Wi-Fi Direct, do not require the Internet environment. Therefore, data sharing directly between devices is often preferable.

In this study, we propose a system which uses acoustic waves for an easy way to device communication via Wi-Fi Direct [3]. Our system establishes communications between the host device and nearby devices. The host device shares the information, which is needed to connect to a Wi-Fi Direct connection including the sender's IP address. The receivers use this information to locate and access the shared data on the host device via Wi-Fi Direct. This approach offer advantages over existing short distance inter-devices communication mechanisms. First, unlike existing radio waves based technologies, it is possible to granularly control the communication range by simply increasing or decreasing the acoustic waves' intensity. This in its turn improves security by reducing the possibility of hacker eavesdropping on the communication. Second, the proposed method is versatile and compatible with any systems that support sound processing as it only requires a microphone and speakers. Third, because we use Wi-Fi Direct for data sharing, our system provides fast data sharing while requiring very little handshaking time for co-located smartphones. Finally, acoustic waves do not require Internet services and/or extra communication hardware. Instead, they can propagate as long as air molecules exist. Thus, acoustic waves can be even used in underground indoor environments. The proposed approach can be especially useful for communications between co-located multiple smartphones.

In this paper, we describe the design and implementation of the sessions establishing system, using acoustic waves generated by smartphones. Moreover, we describe the resulting added security and reliability of the communication and explore its feasibility and practicality. The signal for establishing sessions should be encrypted. However, the main point of this research is controlling the range of communications. Thus, signal encryption is our future work.

This research was presented at 6th International Workshop on the Reliability of Intelligent Environments (WoRIE' 17) in 2017 [4]. In this paper, we additionally explained the proposed method. Furthermore, we added four more experiments, and showed the results in the Sect. 5.

## 2 Related work

In this section, we explain the conventional works related to our research.

### 2.1 Localization

When two devices need to be connected with each other, they first need to discover available devices. Thus, localization is related to our work [5]. Currently, the main technique of outdoor localizations is Global Positioning System (GPS) [6]. However, GPS cannot accurately be used indoors because it is sometimes difficult to receive the signal from the satellites. Using context awareness [7,8], the device can recognize where the device is, and what the user is doing. However, when the device tries to recognize the positions of other devices, it needs to obtain the positions through the networks. This can be useful at the places where the user frequently connects from. On the other hand, it is difficult to recognize the user's location or activity when he/she moves to a new location. There is a considerable amount of work on indoor localization using methods other than GPS [9]. Chung-Hao et al. [10] used Kalman-filter-based drift removal to achieve fast and precise localization using Radio Frequency Identification (RFID) readers and tags. In addition to the utilization of decay of wireless signals, one work uses the electrical field. Grosse-Puppendahl et al. [11] installed the electrical field sensors into the ceiling of the room and detected the location of a person by measuring the variation in the electrical field. Thus, the person does not need to wear any special device in the room. These indoor localization techniques necessitate the deployment of some equipment in the environment, which incurs an additional cost of measurement. Furthermore, the electrical field sensor is not robust for detecting multiple people. Fingerprinting is a technique to use for pre-determined wireless signal strength. He et al. [12] achieved higher precision than conventional methods by combining the information about both terminals and access points. Although these localization techniques have been improved to increase accuracy, they cannot distinguish two adjacent rooms even if their border is separated by walls that penetrate wireless signals. Moreover, these require extra devices or equipments.

## 2.2 Data sharing by the radio waves

File sharing is being done in many ways: email attachment, SMS attachment, skype attachment, FTP, sFTP, SCP, etc. In our research, we explore direct communication between physically co-located smartphones without the Internet connection. The development of cellular networks, such as long term evolution (LTE) or WiMAX, made it easier to share files. In fact, cellular networks are used in many relevant studies [13–15]. On the other hand, because D2D communicates between devices without the Internet, it can share data without depending on the environment [16–20].

The research of Wang et al. allows sharing data files without commercial networks [21]. In their study, the user switched the mobile devices to soft access point (AP) mode, and other devices connect to it and they can obtain the data files. However, the number of devices that can connect to the soft AP is limited, generally, from four to eight devices only. Thus, after obtaining the data files through the soft AP, the device turns from the receiver to a new soft AP. By multiple hops sharing, the devices in the same area can obtain the data files earlier. Furthermore, the study by Kanaoka et al. uses D2D communication [22]. In this study, the host device identifies the target devices by the gesture of shaking devices using an accelerometer. After detecting devices, the sessions of Wi-Fi Direct are established, and they can share data files, such as business cards. Mizumura et al. created a system that optimizes the time required for a file to reach multiple devices using Wi-Fi Direct [23]. Bluetooth is used for sharing the data files in the small range [24,25]. In all of these studies, the radio waves are used to detect the target devices. The radio waves can penetrate the wall, door, or glass. Besides, the radio waves can also spread widely. For example, the range of Bluetooth is approximately 10 m [26]. Thus, it is hard to define the co-location in a room, where many other devices exist. Users must manually find the target devices from a list on the screen. Even if some other unknown devices exist outside the room, the host device might find them because the range of the radio waves is huge. Moreover, Dhwani [27] is a system for short-range communicating short using NFC. Although NFC is commonly used in smartphones, the communication range of NFC is at most 10 cm and this is not sufficient for the assumed application in the range of 1 m.

Overall, most of the existing data sharing mechanisms do not allow the sender to directly control the range within which the shared data is accessible. Furthermore, it is usually required to use not so versatile equipment or hardwares to receive the shared data. D2D communication, especially Wi-Fi Direct, allows data sharing with no Internet connestion an Internet connection and at high transmission speed, even for large file size. Nevertheless, Wi-Fi direct does not allow to control the sharing range; rather, the shared data is broadcasted to any device in the vicinity

## 2.3 Data sharing by the acoustic waves

Communication using radio waves has also some weaknesses, as mentioned in Sect. 2.2. Therefore, some researchers have attempted to use acoustic waves to exchange the data instead of using radio waves to overcome these weaknesses. The advantage of using acoustic waves is that the required hardware, the microphone and speaker, are ubiquitous and available to many electronic devices; thus, there is no need to add any custom hardware. ChirpCast [28] is a system for distributing access keys using ultrasonic transmissions. Thus, ChirpCast can send to the straight direction only from the speaker. Moreover, the distance between devices must be close. In a system proposed by Kristian et al. [29], acoustic 20 kHz waves were used to exchange files. Its transmittable angle from the speaker is approximately ten degree, and the range from the speaker is approximately 80 cm. However, this system requires very high frequencies. Depending on the devices, substantially high frequency sound cannot be emitted by the speaker or recognized by the microphone of the off-the-shelf smartphones

BeepBeep [30] is a system for estimating the range between two devices using acoustic waves emitted from smartphones. Qiu et al. adopt BeepBeep to their system of file sharing by recognizing the positions of surrounding devices [31]. There is a question about which frequency is appropriate for audio-based communications using smartphones. In BeepBeep, audible 2–6-kHz audio is used. Since the average of an adult's audible range is at most 15–17 kHz [32], we have decided to choose the frequency which may or may not be heard and can be treated as a sound in the environments. Acoustic waves emitted from device is inaudible, thus does not disturb users' surroundings.

# 3 Proposed method

As explained in Sect. 2, conventional works have some disadvantages. To overcome these weaknesses, our approach uses acoustic waves to decide which client devices the host device connects to and to control the range of transmission. Unlike radio waves, acoustic waves can easily attenuate when the distance between devices is changed. Our approach uses speakers and microphones of off-the-shelf smartphones. Therefore, we must consider three points: the appropriate acoustic transmitting frequencies, the directionality of the acoustic waves (which depends on their frequency), and the magnitude of the acoustic waves. In this study, we decided to use audible acoustic waves near the ultrasonic range to reduce interferences from the surrounding.

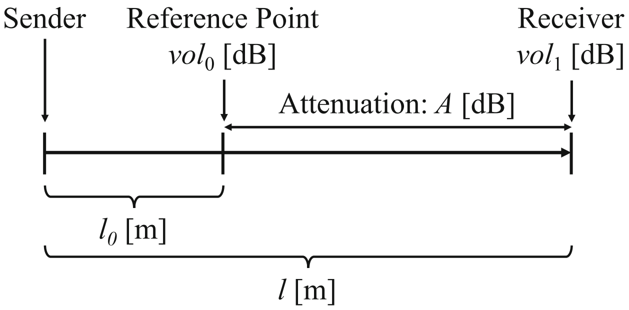

**Fig. 1** Communication between the sender and the receiver taking attenuation into consideration

### 3.1 Position recognition of surrounding devices

Before establishing device-to-device communications, the host device must select devices from devices existing around the host device. As explained in Sect. 2, in existing studies, the host device must use the radio waves, such as Bluetooth, to recognize the devices existing around the host device, and the user of the host device must select the devices to connect and share files. The propagation range of Bluetooth is approximately 10 meters. It is difficult to recognize the distance between the host device and the other devices because radio waves are less attenuated. Thus, in this study, we obtain the distance between the host device and the client device using acoustic waves, which are more attenuated than the radio waves.

First, we set the distance from the sender device to the reference point as $l_0$ m, and the distance from the sender device to the receiver device as $l$ m as shown in Fig. 1. The reason for deciding the reference point is obtaining an ideal value of attenuation at any point. Here, we assume that the acoustic wave sent from the sending device has a constant frequency and intensity. Moreover, we set the received acoustic waves intensity at the reference point and the receiver device as $\mathrm{vol}_0$ and $vol_1$, respectively. Based on the received acoustic waves intensity $vol_1$, the receiver calculates the attenuation $A$ from the reference point. The distance from the sender device to the receiver device, which is $l$, can be calculated with the formula of distance attenuation (Eq. 1).

$$A = 20 \times \log_{10}(l/l_0) \tag{1}$$

According to Eq. (1), $l$ is expressed by Eq. (2).

$$l = l_0 \times 10^{A/20} \tag{2}$$

According to (2), it is possible to calculate the distance between the devices. Based on the acoustic waves intensity ($vol_1$) received by receiver device, the attenuation $A$ is expressed by Eq. (3).

$$A = vol_0 - vol_1 \tag{3}$$

Thus, based on Eqs. (2) and (3), $l$ is expressed by Eq. (4).

$$l = l_0 \times 10^{(vol_0 - vol_1)/20} \tag{4}$$

### 3.2 Determination of acoustic waves used for signal

Using acoustic waves, since it is possible to explicitly designate the distance at which devices can connect, it is also possible to prevent recognition of a state of attempting to connect to mobile devices inside the intended range from mobile devices existing outside the co-location. Using the distance from the host device to the client device the output intensity of acoustic waves used for transmitting the signal is determined. We set the threshold of the reception strength required for the client device to receive the acoustic signal as $B$. Assuming that the output intensity of the acoustic waves from the host device is $V$, when Equation (5) is satisfied, devices existing in the range up to the client device can obtain the acoustic signal.

$$V = B + A \tag{5}$$

As shown in Eq. (1), explained in Sect. 3.1, the attenuation can be calculated from the distance from the host device to the client device. Equation (6) gives the intensity of the acoustic waves ($V$) to be transmitted by the host device.

$$V = B + 20 \times \log_{10}(l/l_0) \tag{6}$$

### 3.3 Controlling of connection angle changing acoustic waves frequency

The speaker of the smartphones, for example of LG V20 which we used for experiments in Sect. 5, are equipped with multiple points sound source. In this case, since there are more than two point sound resources, as shown in Fig. 2, acoustic waves cancel each other by phase differences as Eq. (8) [33].

$$\begin{aligned}\phi &= \frac{Q}{4\pi r_0}\sum_{i=0}^{N-1}\exp[-jkr_0 + iD\sin\theta]\\ &= \exp(-jkr_0)\frac{Q}{4\pi r_0}\sum_{i=0}^{N-1}\exp[-jkD\sin\theta]^i \qquad (7)\\ &= \exp(-jkr_0)\frac{Q}{4\pi r_0}\frac{\sin[\pi N(D/\lambda)\sin\theta]}{\sin[\pi(D/\lambda)\sin\theta]}\\ &\quad \exp[-j\pi(N-1)(D/\lambda)\sin\theta] \qquad (8)\end{aligned}$$

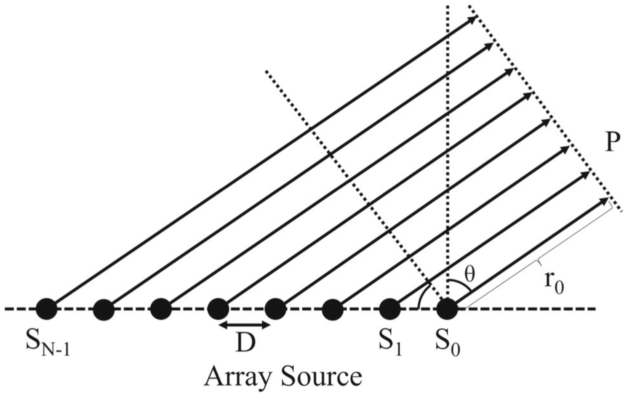

**Fig. 2** Emitting sound from multiple point sound sources

When $\theta$ is 0, using Eq. (9), directivity coefficient $R(\theta)$ is as shown in Eq. (10).

$$\phi = \exp(-jkr_0)\frac{QN}{4\pi r_0} \tag{9}$$

$$R(\theta) \equiv \left|\frac{\phi}{\phi_0}\right| = \left|\frac{\sin[\pi N(D/\lambda)\sin\theta]}{N\sin[\pi(D/\lambda)\sin\theta]}\right| \tag{10}$$

As shown in Eq. (10), the directionality of acoustic waves changes with frequency. While the high frequency acoustic waves are strongly directed from the speaker to the straight direction, the low frequency acoustic waves have less directivity. Using this property of acoustic waves, to connect devices which are inside the intended range, the host device controls the angle from the speaker using a proper frequency of acoustic waves.

Before sending the acoustic waves signal, the host device must recognize the range where client devices exist. In other words, the host device must recognize the angle between the rightmost client device and the leftmost client device. Each device presents at both edges transmits acoustic waves with strong directivity towards to the host device. By obtaining the azimuth of each device and finding the remainder, the host device can obtain the angle. Based on the obtained angle, the host device determines the frequency of acoustic waves to be output.

### 3.4 Positions of devices

Since the proposed method relies on the distance between the sender and the receiver, a communication path cannot be created if they move. Therefore, they need to be in a fixed location while an association is being established using acoustic signals. Once the association has been established, they can move within a certain range. We assume that only applications to allow several-second waiting time use the proposed system.

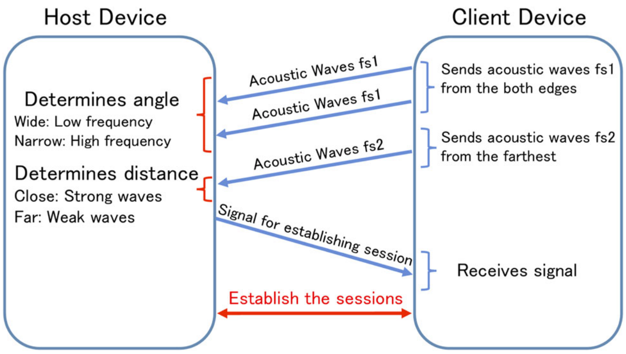

**Fig. 3** Outline figure of our system

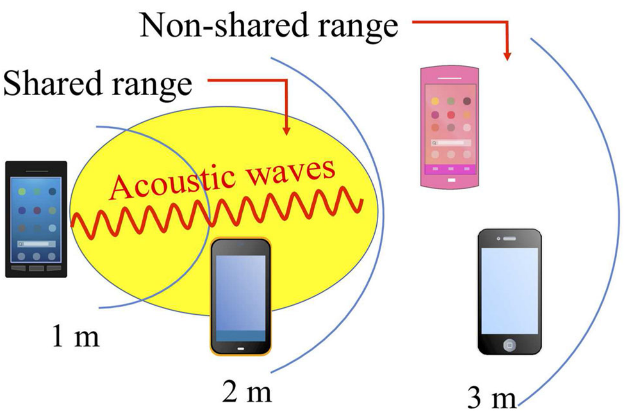

**Fig. 4** Dividing the space with acoustic waves

## 4 Design and implementation

In this section, we describe the design and implementation of our system. Unlike traditional Wi-Fi Direct use, we choose acoustic waves at frequency $fs$ in a non-audible range to human for establishing a communication sessions. This system comprises two components: a host device and a client device. When the user launches this application, the user can select one of them and connect to other devices. The host and client devices can establish the D2D connections to share files as shown in Fig. 3. The sent signal from the host device consists of the information, such as IP address of the sender, synchronization signal, and parity bits for error correction.

An essential part of the system is the control of the co-location by adjusting the magnitude and frequency of the emitted acoustic waves from the sender. When the magnitude of the signal is larger, the range of the common space becomes larger as well. Conversally, when the frequency of the signal is higher, the range of the common space becomes narrower. Space around the sender is divided into shared and non-shared range. Within the shared range, smartphones are shared with the procedure defined in the system as shown in Fig. 4.

### 4.1 Host device

The host device recognizes the distance to the client device and the position of the devices the user wishes to establish sessions with, and transmits the acoustic waves signal to establish those sessions. The state transition diagram of the host device is as shown in Fig. 5. With acoustic waves obtained from the client device, the host device recognizes the range (angle and distance) to be connected to. Depending on this range, the host device determines the appropriate frequency and output intensity for sending the acoustic waves signal. Using these acoustic waves, the host device sends the information necessary for the connection to client devices, and when connection requests are obtained from the client devices, Wi-Fi Direct connections are completed.

**Algorithm 1** Finding the range of signal transmission.

```
if $fs1 <= threshold$ then
    obtain $azimuth1$
end if
if $fs1 <= threshold$ then
    obtain $azimuth2$
end if
if $fs2 <= threshold$ then
    obtain $vol_1$ of $fs2$
end if
$angle \Leftarrow azimuth1 - azimuth2$
$l \Leftarrow l_0 \times 10^{(vol_0 - vol_1)/20}$
```

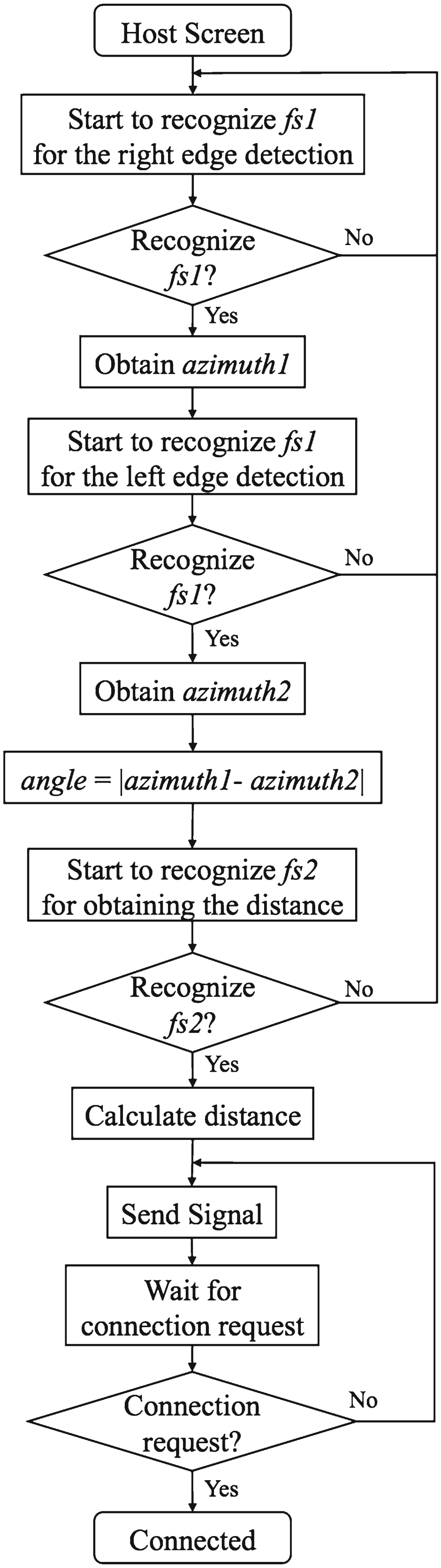

**Fig. 5** Flowchart of the host device

The determination of the acoustic waves to be used for signal for Wi-Fi Direct connection is as shown in Fig. 5. Then, we let the frequency of acoustic waves sent from client devices located at both edges of the range, where the user wishes to establish the sessions, be $fs1$, and let the frequency and volume of the acoustic waves sent from the farthest client device be $fs2$, respectively. As shown in Fig. 1, we set the distance between the client device and the reference point and the distance between the client device and the host device as $l_0$ and $l$, respectively. Moreover, we set the acoustic waves intensity received at the reference point and the one received by host device as $vol_0$ and $vol_1$, respectively. In this study, we set $l_0$ = 1 m. The host device obtains the angle and distance, as explained in Sect. 3. Then, we let the azimuths as $azimuth1$ and $azimuth2$ when the host device obtains the acoustic waves ($fs1$) from client devices located at both edges of the communication range. Based on the angle and the distance from the host device by the algorithm shown in Algorithm 1, the host device determines the frequency and intensity of the acoustic waves to establish the Wi-Fi Direct sessions. The signal is obtained by converting information necessary for session establishment into binary. The information to establish the Wi-Fi Direct sessions is encoded into an acoustic signal at a frequency $Fs$, modulated using On-Off Keying (OOK) encoding, and then transmitted at an interval $Td$. A 1 bit is modulated by emitting continuous acoustic

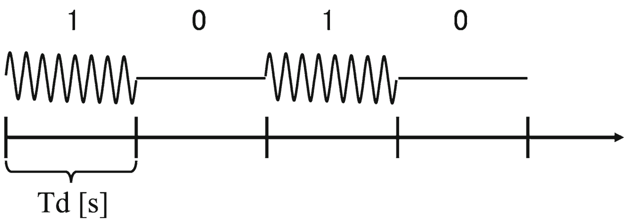

**Fig. 6** Modulating the signal using an On-Off Keying

waves for $Td$ milliseconds, while a 0 bit is modulated by discontinuing the acoustic waves for $Td$ milliseconds, as shown in Fig. 6. Using this encoding mechanism, the signal is represented by a sequence of acoustic waves (1 bit) and no-sounds (0 bit). Additionally, to enhance the error recovery capability, we inserted parity bits. In addition to the information bits, a preamble synchronization signal (SS) announces to the receiver the start of the transmission.

## 4.2 Client device

The client device must do a pretreatment for connecting to the host device. The state transition diagram of the client device is as shown in Fig. 7.

In order for the host device to recognize the range where the client devices exist, it is necessary for the host device to recognize the positions of client devices, which are located at the both edges of the range. Moreover, the host device must recognize the distance to the farthest client device. To satisfy these requirements, the client devices located at the both edges of the range and farthest from the host device send acoustic waves $fs1$ and $fs2$, respectively. Then, the volume of acoustic waves is $Vol0$. Based on the acoustic waves obtained from client devices, the host device recognizes distance and the positions of client devices and sends the acoustic waves signal to establish the sessions.

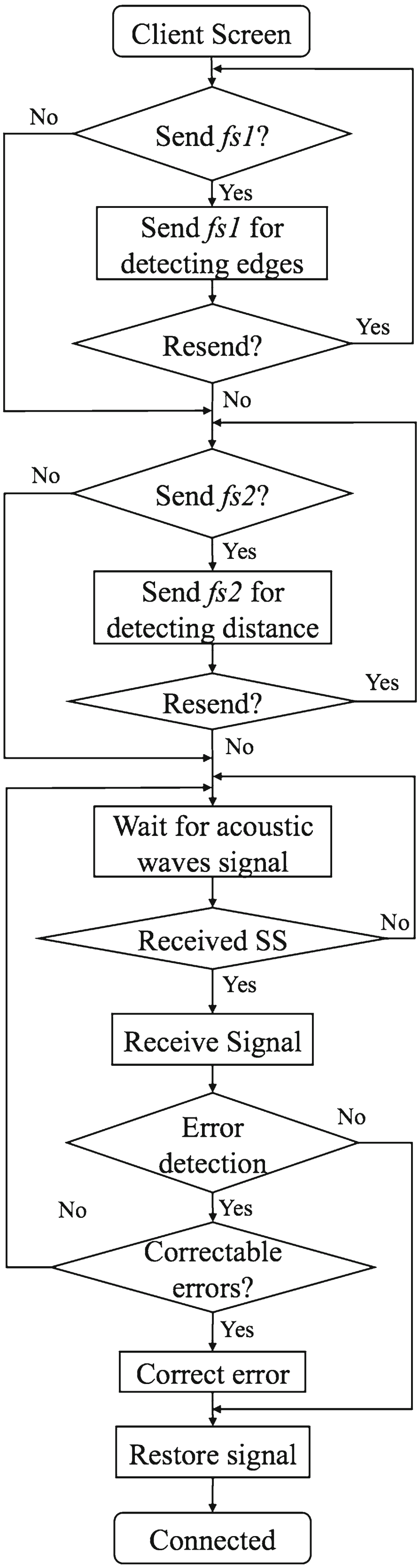

**Fig. 7** Flowchart of the client device

When the client device obtains the signal from the host device, the client device checks the following: Since the synchronization signal, which is 4 bits, exists at the head of the acoustic waves signal transmitted from the host device, after detecting the synchronization signal, the client device starts recognizing the acoustic waves signal and restores the information to establish the session. In addition to the information for a connection, the signal includes parity bits and synchronization signal. Parity bits judge whether the total error detection number is one or less digit, or plural digits. Since it is impossible to restore in the case of two or more digits of error detections, it does not attempt to establish a session and returns to the reception standby state and waits for the retransmission of the acoustic waves signal. When there is one or less error detection, error correction is possible at the client device. When an error is detected, error correction is performed. When no error is detected at par-

**Table 1** Description of environment used

| | |
|---|---|
| Speaker | LG V20 |
| Amplifier | Built-in |
| Microphone | LG V20 |
| Distance between speaker and mic | 1 cm |

**Table 2** Description of environment used

| | |
|---|---|
| Speaker | LG Nexus 5 |
| Amplifier | Built-in |
| Microphone | LG Nexus 5 |
| Distance between speaker and mic | 1 cm |

ity bits, it is determined that the acoustic waves signal has been properly received, and the client device restores from the binary digit string to the IP address and the states of the host device. After restoring the information for connection, the client device attempts to establish a Wi-Fi Direct session with the host device, and the devices can share files.

## 5 Experiments and results

In this section, we describe the preliminary experiments, evaluation, and these results. We conducted five experiments. Sect. 5.1 shows the frequency characteristic of LG Nexus 5 and LG V20, which are used for following experiments, as preliminary experiments. Section 5.2 shows the signal reception accuracy. Section 5.3 shows the results of attenuations by the distance between the microphone and the speaker. Section 5.4 shows how each acoustic waves spread. Section 5.5 shows the reception accuracy of acoustic waves signal.

### 5.1 Frequency characteristic of speaker

For experiments in the following sections, we used Android smartphones, LG Nexus 5 [34] and LG V20 [35]. Because our work is using acoustic waves, the specifications of microphones and speakers can affect the results. As preliminary experiments in this section, we measured the frequency characteristic of the speakers of the smartphones. We had three preliminary experiments. The result of the experiment conducted under the environment as shown in Table 1 is shown in Fig. 8. The result of the experiment conducted under the environment as shown in Table 4 is shown in Fig. 9. The result of the experiment conducted under the environment as shown in Table 3 is shown in Fig. 10. As shown in Figs. 8, 9, and 10, the smartphones do not emit strong acoustic waves over 20 kHz. Acoustic waves in audible range (low range) are strong enough. However, beeping audible acoustic waves interferes our daily life or is noisy. Thus, we need to choose the used frequency to be high enough but below the ultra sound region (Table 2).

There is a discussion about the heterogeneity of used devices. Since a sending device does not have any knowledge about receiving devices, it cannot determine the best frequency for them. An approach towards the problem is using the best allowable frequency for many kinds of devices. Although we have not implemented a strong error correcting code for the information to be transmitted, we can use error correction to accommodate imperfect receiving.

### 5.2 Signal reception accuracy

To verify our design in these experiments, we used two Nexus 5 smartphones. One serves as an acoustic waves' sender. It encodes and broadcasts its IP address. The encoding is done by modulating the waves signal at $fs = 18$ kHz, $Td = 200$ ms, and SS = 0xA. Another smartphone, the acoustic waves' receiver, listens to the incoming waves' signal and decodes the IP address of the sender to establish the communication. In these experiments, we measured the recognizable distance when changing the acoustic waves' transmission

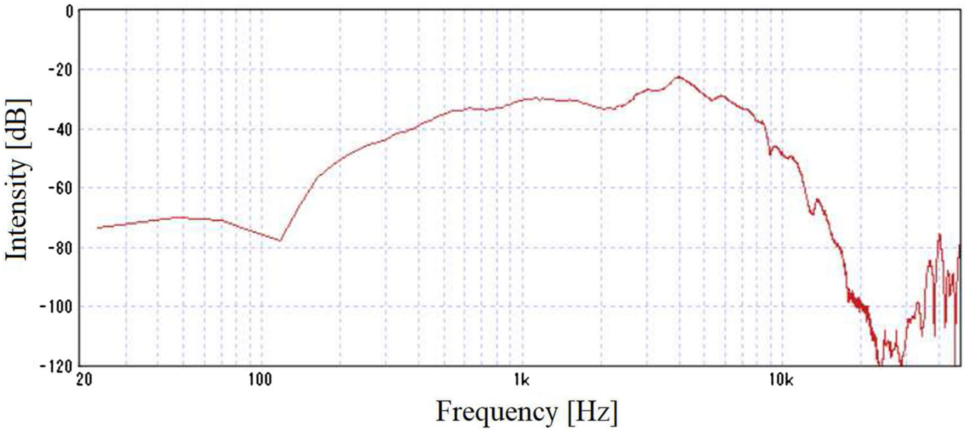

**Fig. 8** Frequency characteristics of speaker (V20–V20)

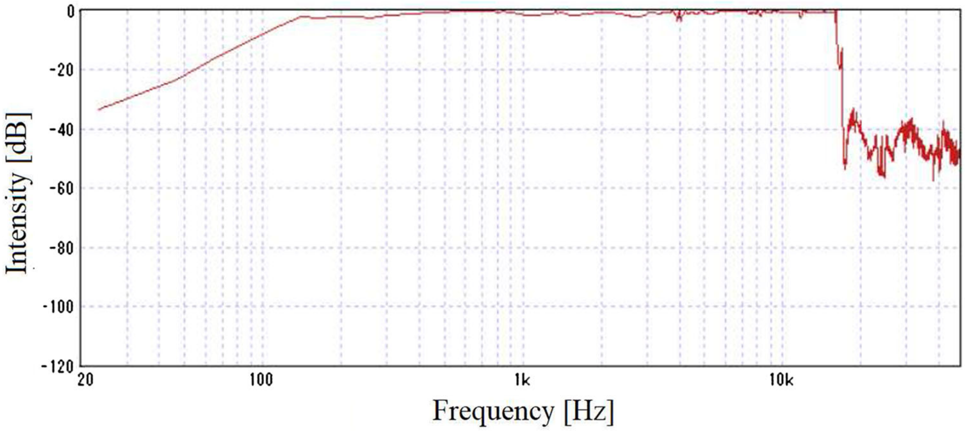

**Fig. 9** Frequency characteristics of speaker (Nexus 5–Nexus 5)

**Table 3** Description of environment used

| | |
|---|---|
| Speaker | LG V20 |
| Amplifier | Built-in |
| Microphone | LG Nexus 5 |
| Distance between speaker and mic | 1 cm |

output intensity. As the use case of the system is expected to be a noisy offices or a cafe, we experimented with 70 dB noise, which is at the same level as noise which can occur in our daily life surroundings [36]. In these experiments, we used a 70 dB white noise to verify our range-controlled communication. This white noise was created by a computer and emitted from a speaker put near the sender. In the noisy environment, we measured the recognition accuracy between the two devices, initially located at 0.50 m apart. Then, we increased the distance between the two devices in a 0.25 m increments up to 2.50 m, as shown in Fig. 11. This accuracy was measured in three acoustics from the sender devices: − 15, − 18, and − 21 dB. For each acoustic waves' intensity, we measured the recognition accuracy of the communication between the two devices and found that it is possible to control the range of communication between the two devices (Fig. 11). In these experiments, only the recognition accuracy for the first acoustic waves' receptions is reported and the results of the second acoustic waves' receptions to the recognition accuracy are not reported.

In our experiments, the sender was modulated at high acoustic frequency (18 kHz). Thus, the two devices can establish a communication only when they are aligned and the microphone of the host device is facing to the speaker of the client device. Indeed, high frequency acoustic waves do not propagate in all directions. Thus, this limitation further increases the communication security by reducing any possibility to intercept the communication unless the interceptor is in the direction of the sender.

### 5.3 Change in RSSI depending on distance

In this experiment, we measured the relationship between RSSIs of the client device and the distance between the devices when the acoustic waves of fixed frequency and fixed intensity are outputted from the host device. For these experiments, we used LG V20. The frequency for this experiment was 15 kHz, the output intensity of the acoustic waves' trans-

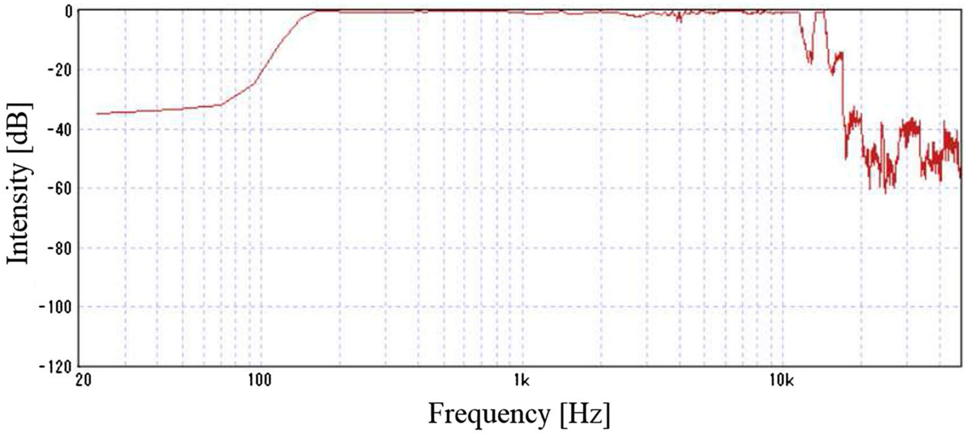

**Fig. 10** Frequency characteristics of speaker (V20–Nexus 5)

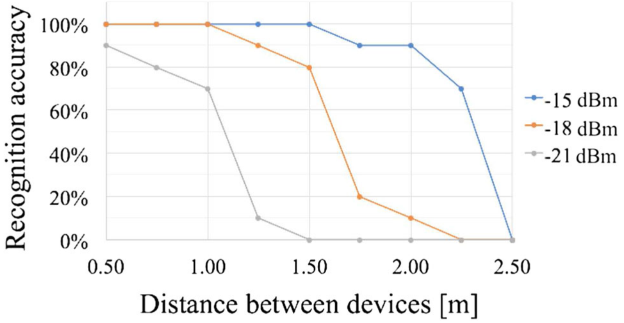

**Fig. 11** Reception accuracy using different intensity acoustic waves

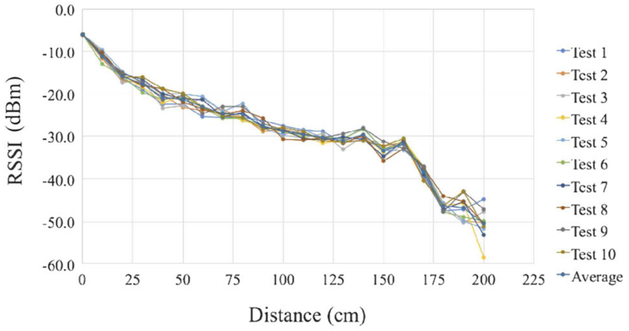

**Fig. 12** Acoustic waves attenuation by distance

mission source was − 6.01 dB. The results of RSSIs are shown in Fig. 12. As shown in Fig. 12, the attenuations of acoustic waves are large even when we moved the device for only 10 cm. Moreover, acoustic waves' look is steadily decaying. Thus, acoustic waves can be used for detecting distance and sending signals.

Furthermore, we measured the RSSIs of the radio waves to compare them with acoustic waves. Some of our motivations of using acoustic waves to connect to devices instead of the radio waves are that attenuation of the radio waves is unstable and that the radio waves have less attenuation than acoustic waves. To determine these, we experimented as follows: In these experiments, we used two devices as the radio waves' sender and receiver. We tethered the sender and measured the RSSIs of it. These experiments were conducted at two places. One of them was at the cafeteria: there were not many Wi-Fi signals, and the other was at the office building: there were many Wi-Fi signals. The results of these experiments are shown in Figs. 13 and 14 respectively. As shown in these figures, RSSIs are unstable. The measured wireless power of Wi-Fi signal fluctuated due to the interference by other Wi-Fi signals. While the radio waves sometimes have more than 10-dBm difference, the acoustic waves do not have much large variance. Moreover, compared with the acoustic waves, the attenuations of Wi-Fi signal are less. Thus, acoustic waves are better for co-location awareness.

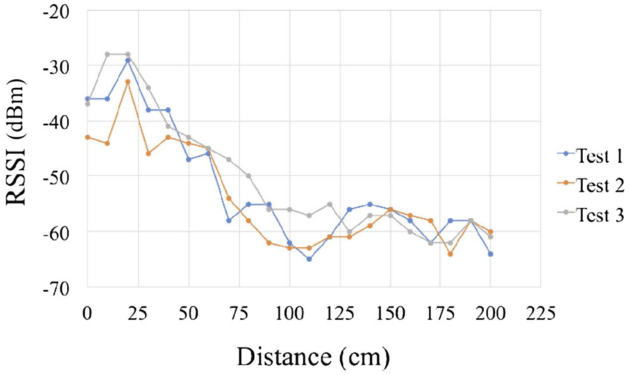

**Fig. 13** RSSI of the radio waves in the cafeteria

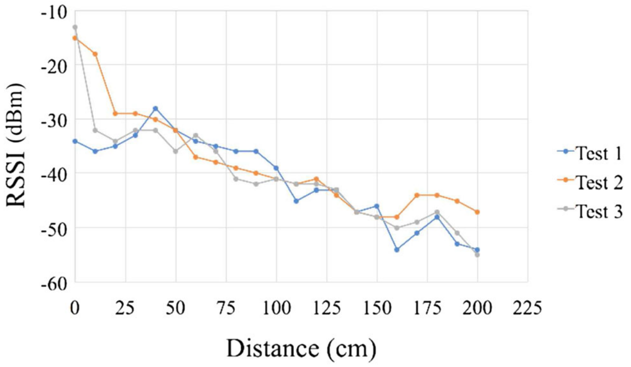

**Fig. 14** RSSI of the radio waves in the office building

## 5.4 Measurement of acoustic waves spreading

In this section, we ascertain how each acoustic waves frequency is spreading. For these experiments, we used LG V20. We measured the RSSIs at each point when we fixed the acoustic waves to a certain frequency and the intensity, and changed distance and angle. We changed the distance between devices by 10 cm at a time and the angle from the straight direction of the speaker face by 10 degrees at a time, and measured RSSIs at each point. We used 15 kHz and 18 kHz of acoustic waves. Fig. 15 shows the distribution of RSSI of 15 kHz acoustic waves, and Fig. 16 shows the distribution of RSSI of 18 kHz acoustic waves. When they were measured, the speaker of the smartphone was located at (0, 0), and faced to the vertical direction. Based on the experimental results, while 15 kHz acoustic waves equally spread, the attenuation of 18 kHz acoustic waves in the horizontal direction is large. Thus, the acoustic waves can be used for controlling the angle of the range.

## 5.5 Reception accuracy of acoustic waves signal

In this section, we show the reception accuracy of acoustic waves signal at each point. For these experiments, we used LG V20. We experimented four kinds of acoustic waves and

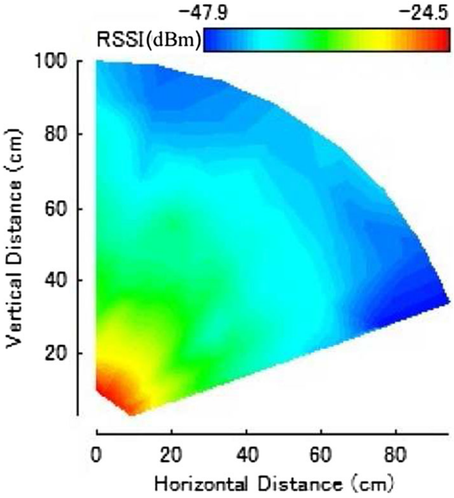

**Fig. 15** How acoustic waves spread using RSSI of 15 kHz acoustic waves

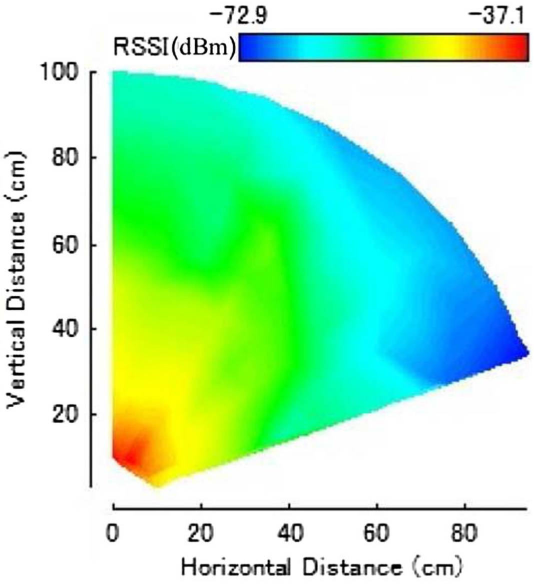

**Fig. 16** How acoustic waves spread using RSSI of 18 kHz acoustic waves

20 times each. The speaker of the smartphone located at (0, 0) and faced to the vertical direction, and the microphones are located at point A, B, C, and D, as shown in Fig. 17. Then, all microphones faced to the speaker. In these experiments, we emitted the acoustic waves of 15, 16.5, 17, and 17.5 kHz, which are supposed be spread for 90°, 60°, 30°, and 0°, respectively. Table 4 shows the results of each accuracy. According to the results, while the low frequency acoustic waves can propagate signals from 0 to 90 degrees, high frequency acoustic waves can only propagate signals in the straight direction. Thus, changing acoustic waves frequency can be used for controlling the range (angle).

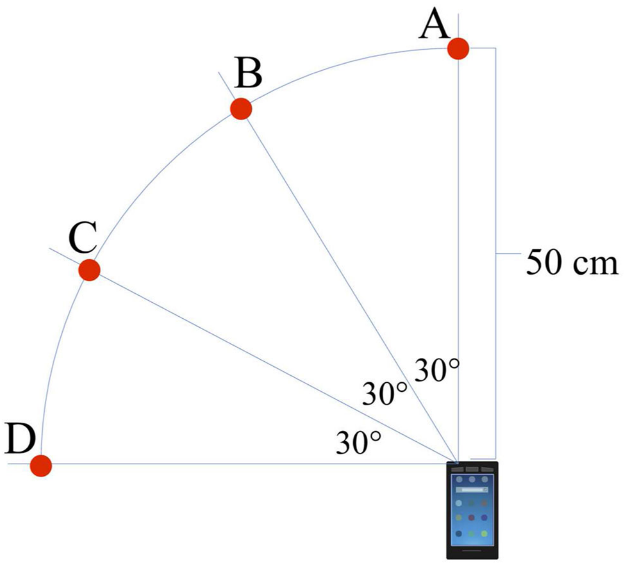

**Fig. 17** Environment of the experiment: positions of sender and receivers

**Table 4** Reception accuracy at each point changing frequencies

| | A (%) | B (%) | C (%) | D (%) |
|---|---|---|---|---|
| 15 kHz | 100 | 100 | 100 | 100 |
| 16.5 kHz | 95 | 90 | 85 | 15 |
| 17 kHz | 70 | 55 | 20 | 5 |
| 17.5 kHz | 55 | 15 | 5 | 0 |

## 6 Discussions

We now discuss the pros and cons of using audio signal for making associations between a sender and receivers. The alternative techniques are WiFi, ultra sound, and infrared. First, we compare the techniques in the easiness of controlling the communication range. WiFi covers a wide communication area, but the decrease in transmission power is not large in the distance between 1–2 m considered in this application. Ultra sound is also a kind of audio signal at a frequency above 20 kHz. In this sense, using ultra sound is an extension to our method. The reason for not using ultra sound is the dynamic range of speakers and microphones embedded in the current smartphones; not all smartphones can accommodate ultra sound. Therefore, we have chosen a conservative approach of using a frequency below 20 kHz. Infrared has strong directivity. It is useful for one-to-one communication, but it cannot be applied to one-to-many communications. Second, with respect to performance and reliability, audio signals can be disturbed by environmental noise, and thus they do not outperform other technologies. Finally, security of audio signal is weaker than encrypted WiFi signals. Therefore, our method can be used for non-critical applications such as distributing personal photographs or electronic business cards. This is the limitation of our work. The audio signals can be encrypted, but that remains for our future work.

Our system does not guarantee the end-to-end security mechanism. Therefore, as used in other computer systems, security software needs to be installed for mission-critical applications. This is also the limitation of our work.

Using acoustic signals is now new. However, we focus on a significant decrease in the received power with regard to the distance and we utilize the property to control the area of physical co-location. The experiment setup aimed at the investigation of the decrease in the received power by changing the intensity and frequency of the transmitted signal. There is still a strong constraint in the experiment and our future plan includes the investigation of sensitivity to orientation.

## 7 Conclusion and future work

In this paper, we have described a system to create an intelligent co-location for collaborative work with smartphones using acoustic waves' signal. Our preliminary study has shown that the range of communication can be controlled by modifying magnitude of the acoustic signal emitted at a sender. The system can adjust an output acoustic waves' intensity to control the connectable distance, which is shorter than a radio waves' propagate. Moreover, the system can adjust output acoustic waves' frequency to control the connectable angle. Acoustic waves can propagate as long as air molecules exist. Our proposed system defines arbitrary distance and angle from a host device as the co-location and distinguishes a device in the co-location from other devices in the same room. This improves security and versatility compared to existing radio based approaches. Because this system is using high frequency acoustic waves, directionality of the communication is much stronger. Thus, eavesdropping the communication between the two devices becomes difficult using off-the-shelf devices unless the eavesdropping device exists in the communication path. Our approach proves that acoustic waves transfer the signal to connect devices. However, at this point, in order to create a simple proof of concept prototype, we did not encrypt the signal of IP address. We will apply encrypting and Cyclic Redundancy Check to improving security and accuracy further more in our future work. Moreover, we will experiment more extensively, and find optimal frequencies for each angle.

In our future study, we will develop an Application Programming Interface (API) to allow an easy use of any systems. A lot of applications installed in our smartphones can share data through the API.

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