A Proposal on Direction Estimation between Devices Using Acoustic Waves

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Abstract. How can you easily find a partner in rendezvous whom you have not met before (e.g., a new friend on social network service, a customer in delivery service)? One answer is to display the distance and direction to the partner on your smartphone. Although conventional work has provided keys to perform distance estimation with only commodities like smartphones, direction estimation requires pre-planned infrastructure or special hardware. In this paper, we newly propose a direction estimation method, which monitors Doppler Effect of acoustic waves generated by user's simple motion. Moreover, we implemented the proposed method, and measured its performance under real-world conditions. The experimental results show that the estimation error ranges within 18.0 degrees, which is practical for the above use cases.

Keywords: Direction Estimation, Acoustic Wave, Smartphone, Doppler Effect.

1 Introduction

The increasing popularity of Internet services, e.g., SNS (Social Network Service) and BBS (Bulletin Board System), has allowed communication with many people, and created a need for new forms of rendezvous. One example is meeting an SNS friend whom you have not met before. Other examples are rendezvous between a customer and a deliveryman in delivery service and between a worker registering a part-time job via Internet and the supervisor. Even in cases of rendezvous with a person without real world acquaintance like these examples, partner searching must be facilitated.

One of the ways of achieving such rendezvous is to provide the accurate distance and direction to the partner. A well-known solution is to share locations obtained from GPS (Global Positioning System). However, the accuracy of location, which includes error of several meters, is insufficient to find a partner in such rendezvous. Alternatively, by the transmission and reception of acoustic waves between user devices, like smartphones and mobile phones, the correct distance can be estimated [1]. In terms of direction, multiple methods to estimate the direction have been proposed [2]-[8]. However, these methods require not only the user devices, but also pre-planned infrastructures, like Wi-Fi AP (Access Point), or special hardware,

A. Puiatti et al. (Eds.): MobiQuitous 2011, LNICST 104, pp. 25–36, 2012.

like a directional radio antenna and microphone. So, too much initial cost causes bottleneck to deploy.

One of the ways to estimate direction without initial cost is the transmission and reception of radio signals or acoustic waves between devices via Wi-Fi and Bluetooth antennas and microphone/speaker, which are equipped with commercially available devices. However, it is difficult to estimate direction only by simple transmission and reception alone, because of omni-directional nature intrinsic to radio signals and acoustic waves transmitted from commercially available devices. Meanwhile, the known problem with distance and direction estimations using radio signals and acoustic waves is the increase in estimation error due to reflection from objects, such as walls and ceilings [1]. The estimation error may also increase, when a device misrecognizes noise as acoustic wave. To facilitate rendezvous not only outdoors, like in shopping malls and parks, but also indoors, e.g. in cafés or station yards, the increase in estimation error at the reflection wave and noise sites must be prevented.

This paper newly proposes a direction estimation method between devices using acoustic waves, to realize a precision required for the rendezvous without any pre-planned infrastructures and special hardware. In order to do this, the proposed method exploits Doppler Effect on transmission and reception of acoustic waves. Meanwhile, to prevent the estimation error from increasing due to reflection waves and noise, the devices tries to remove them using acoustic wave information, including the transmission count and the transmission interval of acoustic waves. Moreover, we implement the proposed method as a smartphone application and measure its performance. Through the experiment, we evaluate from the viewpoint of the impact of the distance between devices, reflection wave, noise and crowdedness on the estimation error, since these should be taken into account for the real world use.

This paper is organized as follows. Chapter 2 shows related work, while Chapter 3 newly proposes a direction estimation method between devices using acoustic waves. Chapter 4 describes the implementation of the application of the proposed method, and Chapter 5 evaluates it using the implemented application. Chapter 6 concludes this paper.

2 Related Work

Some methods to estimate the direction between devices have been proposed. These methods are classified into two approaches. The first one uses pre-planned infrastructures, and the second one transmits and receives signals directly between devices.

In the first approach using infrastructures, each device initially obtains its location from infrastructure, and then the devices exchange respective locations. A well-known solution to obtain location is GPS (Global Positioning System). The application to share locations obtained from GPS [2] has been available. Since the sufficient GPS satellites have been introduced and most user devices have GPS receivers, the application needs hardly initial cost. However, the accuracy of location, which includes error of several meters, is insufficient to find a partner without real world acquaintance in the rendezvous. In addition, the location may include more error in urban areas and indoors.

The other methods to obtain location from infrastructure use Wi-Fi AP (Access Point) [3], UWB (Ultra Wide Band) AP [4] or ultrasound transmitters and receivers [5] [6]. These methods require the introduction of multiple infrastructures and location of the infrastructures beforehand. In these methods, the location of the device is obtained through measuring distances to more than three infrastructures. The distance is measured by ToA (Time of Arrival) during the transmission and reception of radio signals or ultrasounds between a device and each infrastructure. These methods can obtain more precise location than GPS. In particular, the precision of location in methods [5] [6] is about 10 cm, because the speed of sound is relatively slower than that of radio signal. Also, the location even in urban and indoor areas can be obtained. However, excessive initial cost of infrastructures is required.

In terms of the second approach to transmit and receive signals directly between devices, the direction is estimated using a directional radio antenna or microphone [7] [8]. In concrete terms, a device calculates the DoA (Direction of Arrival) of a signal transmitted by the other device, and then the device estimates the direction to be that of DoA. However, it is difficult to apply these methods to commercially available devices, since those devices are not equipped with directional radio antennas and microphones.

As abovementioned, though several methods to estimate direction have been proposed, some lack sufficient direction precision, or others require excessive initial cost of infrastructures and a special hardware. Therefore, in the next chapter, we propose a new direction estimation method, which realizes a precision required for the rendezvous without initial cost.

3 Direction Estimation between Devices Using Acoustic Waves

We newly propose a direction estimation method between devices using acoustic waves. Acoustic waves are usually chosen to elevate the accuracy, because of their relatively slower speed than radio signals. The proposed method is based on the following approaches:

Approach 1: We use Doppler Effect for the direction estimation (See Section 3.2 for more details). For producing the Doppler Effect, a user motion is used (See Section 3.1 for more details).

Approach 2: For recognition of the Doppler Effect, the pulse-pair method [9] or FFT (Fast Fourier Transform) method is generally used. We use the former, since its processing load is lower. In concrete terms, the devices transmit and receive multiple pulse-type acoustic waves and detect the change between transmission and reception intervals of acoustic waves (See Section 3.2 for more details).

Approach 3: To reduce the estimation error due to reflection waves and noise, the device tries to remove them, using acoustic wave information including the

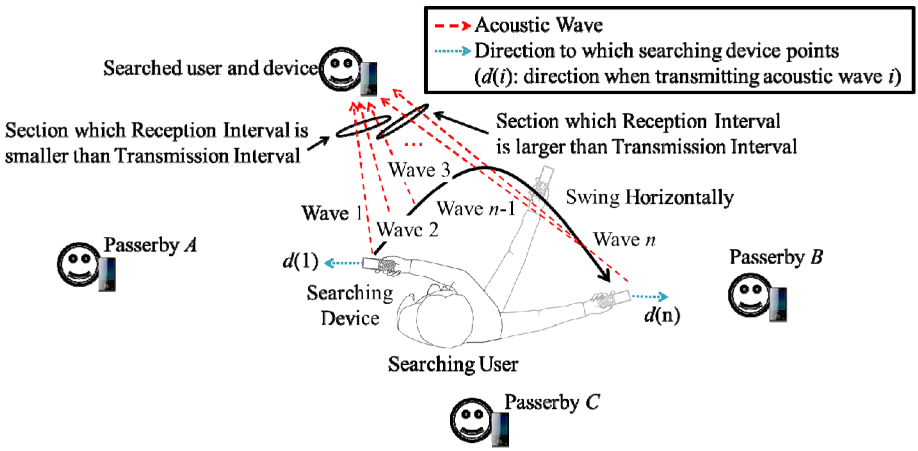

Fig. 1. The outline of direction estimation based on Doppler Effect

transmission count and the transmission interval of acoustic waves (See Section 3.3 for more details). This information is exchanged beforehand via Bluetooth, Wi-Fi and so on.

In the rest of this paper, we refer to a user requiring direction to a partner and his/her partner as searching and searched users, respectively. Similarly, we refer to the devices of the searching and searched users as searching and searched devices, respectively. The basic procedure of the proposed method is as follows:

Basic Procedure 1: The searching and searched devices exchange the acoustic wave information.

Basic Procedure 2: While the searching device is transmitting acoustic waves, a Doppler Effect is produced by the searching user motion. Also, the searching device detects its direction to which it points, when transmitting each acoustic wave. The detection is performed with magnetic sensor or gyrocompass.

Basic Procedure 3: After receiving acoustic waves, the searched device calculates the reception interval of the acoustic waves, whereupon it notifies the calculated reception interval back to the searching device.

Basic Procedure 4: The searching device estimates the direction by the change of transmission and reception intervals based on the Doppler Effect.

The rest of this Chapter is organized as follows. Section 3.1 explains the user motion to generate the Doppler Effect, while Section 3.2 describes the direction estimation based on the Doppler Effect. Section 3.3 states the procedure used to calculate the reception interval of acoustic waves, and Section 3.4 shows the whole procedure for the direction estimation of the searching and searched devices.

3.1 Searching User Motion for Generation of Doppler Effect

When the searching user requires direction to the searched user, he/she is naturally unaware of the location of the searched user. So, generating a Doppler Effect to all directions is required. One example of the user motions is to swing the searching device horizontally as if drawing a half circle, as illustrated in Fig. 1. In specific term, the searching user stretches the arm while holding the searching device, and then swings it horizontally through 180 degrees.

3.2 Direction Estimation Using Acoustic Waves Based on Doppler Effect

The outline of direction estimation based on the Doppler Effect is depicted in Fig. 1. The searching device transmits multiple pulse-type acoustic waves at a transmission interval, during swing. Also, the searching device detects its direction pointing to, when transmitting each acoustic wave. As a result, the searched device receives the acoustic waves at an interval different from the transmission interval. Based on the Doppler Effect, in the section in which the searching device is approaching the searched device, the reception interval is smaller than the transmission interval (hereafter, referred to as the approaching section). Conversely, in the section that the searching device is withdrawing from the searched device, the reception interval is larger than the transmission interval (hereafter, referred to as the withdrawing section). By detecting these sections from the change between the transmission and reception intervals (hereafter, referred to as change of interval), the direction can be estimated, when the searched user is located not only in front of the searching user like Fig. 1, but also to the right, left and back sides of the searching user like passers-by *A*, *B* and *C* in Fig. 1.

The concrete procedures are as follows. First, the searching device calculates the change between the transmission and reception intervals. Second, it estimates the direction by the change of interval. Now, the acquisition of transmission interval is possible by generation of a music file, which plays acoustic waves at a specified interval. According to the reception interval, the searched device calculates it and notifies it to the searching device. Calculation of the reception interval is described in Section 3.3. In the rest of this section, let the transmission count of acoustic waves be n and the direction to which the searching device points in transmission of acoustic wave i (i=1, 2, … , n) be $d(i)$. Also, let the transmission and reception intervals between the acoustic waves i and j be $SI(i, j)$ and $RI(i, j)$ (i=1, 2, … , n-1, j=i+1, i+2, … , n), respectively. We assume that the searching device is swung clockwise, as shown in Fig. 1. In the last part of this section, we show how the proposed method can estimate direction during swing in counter clockwise manner.

Calculation of the Change of Interval: The searching device calculates the change of interval $CI(i)$ with the transmission and reception intervals as follow: $CI(i) = SI(i, i+1) - RI(i, i+1)$.

Direction Estimation: The procedure of direction estimation with the change of interval $CI(i)$ is illustrated in Fig. 2. In the procedure, there are 4 patterns of the direction: front, right, left and back.

If the change of interval $CI(i)$ is initially negative, and then becomes positive, this means that the approaching and withdrawing sections occur in turn. Thus, the searched device is located in front of the searching device (Line 4 in Fig. 2). In this

```
1.  if(CI(1) < 0)
2.     for(i = 1; i < n; i = i + 1)
3.       if(CI(i) > 0)
4.         D = d(i); break;  ←  Front
5.       end
6.       if(i == n − 1)
7.         D = d(n);  ←  Right (Clockwise)
8.       end            (Left (Counter Clock wise))
9.     end
10. else
11.    for(i = 1; i < n; i = i + 1)
12.      if(CI(i) < 0)
13.        D = d(i) + 180; break;  ←Back
14.      end
15.      if(i == n − 1)     Left (Clockwise)
16.        D = d(1);  ←     (Right (Counter Clock wise))
17.      end
18.    end
19. else
```

Fig. 2. The procedure of direction estimation with change of interval of acoustic waves

case, the searching device detects the acoustic wave of boundary between both sections, and then estimates the direction at that of the searching device in transmitting the detected acoustic wave.

Conversely, when the change of interval $CI(i)$ is initially positive (including zero) and becomes negative, it means that the withdrawing and approaching sections occur alternately, and the searched device is located at the back side of the searching device (Line 13 in Fig. 2). In this case, the searching device detects the acoustic wave of the boundary and estimates the direction at the right back of the direction of the searching device in transmitting the detected acoustic wave.

Where all the values of the change of interval $CI(i)$ are negative (positive), this indicates that only the approaching (withdrawing) section occurs, whereupon the searched device is judged to be on the right (left) side of the searching device (Line 7 (Line 16) in Fig. 2). Here, the searching device estimates the direction as one of the searching device in transmitting the last acoustic wave n (first acoustic wave 1).

Now, we assume that the searching user swings the searching device clockwise. The difference between clockwise and counter clockwise is judgment whether the searched device is located to the right or left side at Lines 7 and 16 in Fig. 2. However, the estimated direction is same in both cases, so the direction can be estimated if swung counter clockwise.

3.3 Calculation of Reception Interval of Acoustic Waves

We describe how the searched device calculates the reception interval of acoustic waves. Now, the calculation is realized by recording acoustic waves as the file once, and then analysing the file, as shown in [1]. This enables us to prevent errors between the actual time of reception and the time of recognition of reception of the acoustic wave.

```
A = {1,2,···,n}; i = 1; Bi = φ
while(A ≠ φ)
   A' = A
   if (Bi == φ)
      x = min(A'); Bi = Bi ∪ {x}; A' = A' − {x};
   else
      while(A' ≠ φ)
         y = max(Bi); z = min(A'); A' = A' − {z};
         if (| SI(y, z) − RI(y, z) |< Threshold)
            Bi = Bi ∪ {z};
         end
      end
      A = A − Bi; i = i + 1; Bi = φ;
   end
end

temp = 0;
for(j = 1; j < i; j = j + 1)
   if (temp <| Bi |)
      temp =| Bi |; index = j;
   end
end
```

(Division of Set of Acoustic Wave) Abstracting sets of acoustic waves of which transmission and reception intervals of acoustic waves differ less than threshold

(Removal of Reflection Wave) Acoustic waves except the member of the maximum set are removed

Fig. 3. The procedure of removal of reflection wave

The concrete procedures are as follows. Both devices initially exchange the acoustic wave information. Next, the searched device detects the reception time of the acoustic waves, and then calculates the reception interval of them. After that, it tries to remove the reflection waves and noise with the acoustic wave information.

Exchange of Acoustic Wave Information: The Acoustic wave information, including the transmission count n, transmission interval $SI(i, j)$ and the frequency of acoustic waves f, is exchanged between both devices beforehand.

Detection of the Reception Time of Acoustic Wave: The reception time is detected by correlation between the recorded file and a reference signal in the time domain. The reference signal can be generated with the acoustic wave information. The time of the maximum peak of correlation is concluded as the reception time $R(i)$ (i=1, 2, … , n).

Calculation of Reception Interval of Acoustic Wave: The reception intervals between the arbitrary two acoustic waves i and j (i=1, 2, … , n-1, j=i+1, i+2, … , n) are calculated as follows: $RI(i, j) = R(j) – R(i)$.

Removal of Reflection Waves and Noise: The searched device tries to remove reflection waves and noise based on the following approach. If the transmission and reception intervals of two acoustic waves differ by more than a threshold, at least one of the two acoustic waves is a reflection wave. If the arm length is 70cm, the change of distance between both devices by the swing depicted in Fig. 1 is indicated as a maximum 140cm. Thus, the change of transmission and reception intervals peaks at 4.3ms (≒140cm / the speed of sound), so the threshold is set as 4.3ms.

The searched device tries to remove reflection waves and noise, based on the procedure shown in Fig. 3. Initially, set A composed of n acoustic waves is divided

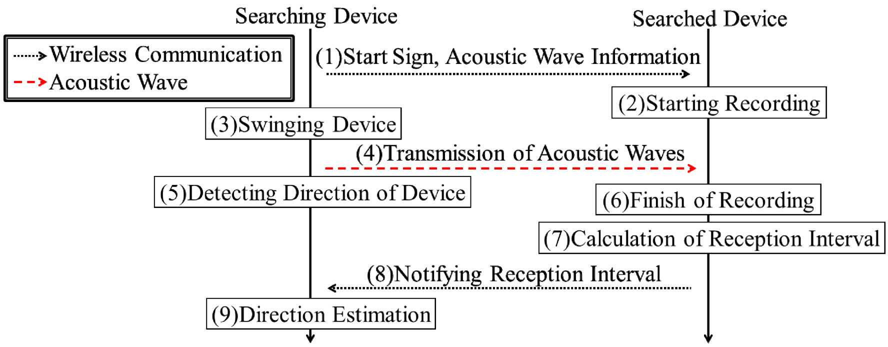

Fig. 4. The whole procedure of searching and searched devices

into sets composed of acoustic waves, which the transmission and reception intervals of the two waves have differences less than the threshold (from Lines 1 to 15 in Fig. 3). Then, if the number of abstracted sets exceeds 1, the acoustic waves, except the member of the maximum set B_{index}, are removed (from Lines 17 to 22 in Fig. 3).

Finally, the searched device notifies the reception interval and the set B_{index} to the searching device. Now, the set B_{index} is used by the searching device, only if some acoustic waves are removed. In that case, the number of transmission interval exceeds that of the reception interval, whereupon the searching device recalculates the transmission interval adaptive to the reception interval with the set B_{index}.

3.4 Whole Procedure for Direction Estimation of Searching and Searched Devices

We explain the whole procedure of the searching and searched devices using Fig. 4. First, the searching device notifies a start sign and the acoustic wave information to the searched device (Fig. 4 (1)). After receiving this, the searched device starts to record (Fig. 4 (2)). After that, when the searching device is swung (Fig. 4 (3)), it transmits acoustic waves (Fig. 4 (4)). At the same time, it detects its direction in transmission of each acoustic wave (Fig. 4 (5)). After finishing recording (Fig. 4 (6)), the searched devices calculates the reception interval (Section 3.3) (Fig. 4 (7)), and then notifies the reception interval (Fig. 4 (8)). On receiving the reception interval, the searching device estimates the direction (Section 3.2) (Fig. 4 (9)).

4 Implementation

We implement the proposed method as an application on smartphones (Android 2.1), in order to evaluate it. We show the implementation outline.

- Bluetooth is used as the form of radio communication to notify the acoustic wave information and the reception interval.

- A chirp signal is selected as an acoustic wave, with sampling frequency and signal length of 44.1 kHz and 50ms, respectively.
- Some parameters, such as the frequency range of the chirp signal, the transmission count and the transmission interval, can be selected via the application setting menu.
- A magnetic sensor is used to detect the direction in which the searching device points.
- To adjust the detection timing of the direction in which the searching device points and transmission of each acoustic wave, the timer is set in line with the transmission interval.
- To adjust the start timing of swing and transmission of acoustic waves, the application shows the countdown on the display.
- The estimated direction is shown via an arrow on the display of smartphone. After the estimation, the arrow is dynamically adjusted to point to the estimated direction by detecting the direction to which the searching device points continuously.

5 Experiment and Evaluation

To evaluate the proposed method, we measure its performance, through the implemented application. First, we evaluate the distance between devices within which the proposed method works enough for practical use, since an acoustic wave attenuates according to propagation distance. Now, if we supposed rendezvous outdoors and indoors, such as in shopping malls, parks, cafés and station yards, factors, such as reflection waves, noise and crowdedness would impact on the results. Thus, we also evaluate from the viewpoint of impact of reflection waves, noise and crowdedness.

5.1 Experimental Method

We use estimation error as an evaluation metric, which is calculated as the absolute difference between the estimated and actual directions.

We set the parameters as follows: frequency range of the chirp signal of 14-16kHz, the transmission count of 15 and the transmission interval of 200ms. In the experiment, the directions in which the searching user turns is six patterns: the front, right and left 45 degrees, right and left 90 degrees and back, based to the direction relative to the searched user, as illustrated in Fig. 5. Also, the searching user swing clockwise.

The experimental conditions are shown in Table. 1. In the first experiment, the distances between devices are set as 10m, 20m and 30m outdoors. The second experiment is performed in a room that is approximately 8m x 8m to generate reflection waves. The third experiment is performed, while playing a music file on a PC. The loudness level near the searched device shows 80dB, which is compatible to a noisy urban city in daytime [10]. The frequency of the music file ranges under 5kHz. The fourth experiment is performed near a station. Many people pass through between devices. The loudness level near the searched device shows 80dB. The estimation error is measured 30 times under each condition.

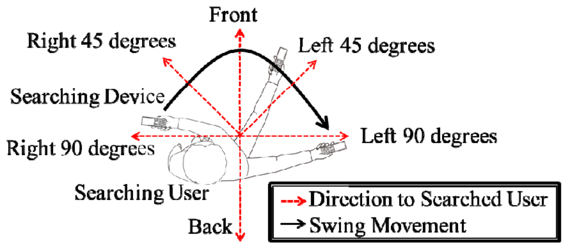

Fig. 5. Directions of searching user based on direction to searched user

Table 1. Experimental Condition

Experimental Content	Distance between Devices	Place	Remarks
1. Distance between Devices	10m, 20m, 30m	Outdoors	Quiet
2. Reflection Wave	10m	Indoors (Room by 8m x 8m)	Quiet
3. Noise	10m	Indoors (Room by 8m x 8m)	Loudness level 80dB (Playing music file)
4. Crowdedness	10m	Outdoors	Passers-by (Loudness level 80dB)

5.2 Experimental Results

We illustrate the experimental results of distance between devices in Fig. 6 (a), and also depict those of the impact of reflection waves, noise and crowdedness in Fig. 6 (b). The vertical and horizontal axes imply estimation error and the direction in which the searching user turns, respectively. Each plot includes averaged values of 30 trials under each condition. Also, the plot averaged for the direction in which the searching user turns is shown at the far left in the Fig. 6 (a) and (b). Now, for comparison, the result of 10m outdoors is also plotted in Fig. 6 (b).

Distance between Devices: From the experimental results, we can see little difference in estimation error among distances. For instance, the averaged values range from 9.6 (P1 in Fig. 6 (a)) to 12.6 degrees (P2 in Fig. 6 (a)). Meanwhile, it is confirmed that the estimation error increases due to attenuation of acoustic waves, when we measured it in case of distance of 40m. Thus, the proposed method works enough for practical use, where the distance between devices is within 30m.

Impact of Reflection Wave, Noise and Crowdedness: The experimental results of Fig. 6 (b) show that all estimation errors are kept within 18.0 degrees.

In terms of reflection waves, the averaged value is 12.2 degrees (P4 in Fig. 6 (b)), while that of the first experiment with 10m is 9.6 degrees (P3 in Fig. 6 (b)), meaning the impact of reflection wave is small. Hence, it is indicated that reflection waves are sufficiently removed by the procedure in Section 3.3.

In the case of noise, the averaged value is 11.8 degrees (P5 in Fig. 6 (b)), so that we can say that the impact of noise is also small. This is because the frequency of acoustic waves (14-16kHz) is different from that of the music file (under 5kHz).

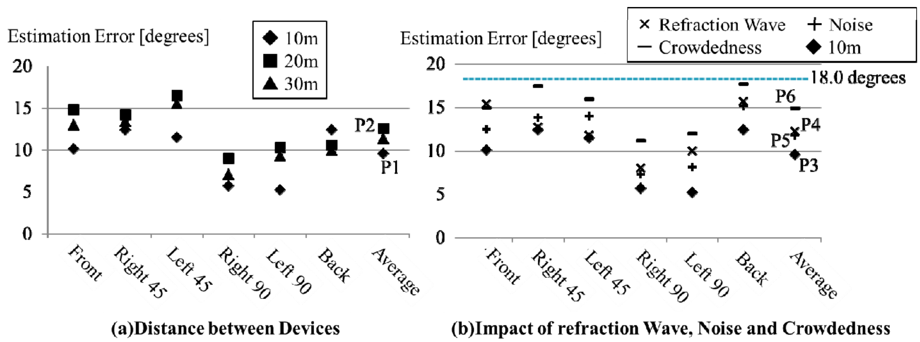

Fig. 6. Experimental results of Estimation Error

Similarly, since the frequency of noise made by humans and cars is different, the impact of noise in shopping malls and parks is also considered small. Just in case if there is noise with high frequency, by scanning frequency of present noise, it is possible to select the frequency different from present noise.

Regarding crowdedness, the experimental results show that the averaged value is 14.9 degrees (P6 in Fig. 6 (b)), meaning the impact is slightly larger than that in other cases. This is due to interception of some acoustic waves by passers-by. As a result, the number of acoustic waves used for the estimation is reduced. However, the estimation error is still kept within 18.0 degrees.

Direction of Searching User: The estimation errors in the cases of right and left 90 degrees are smaller than that in other cases. For example, all plots of the former case in Fig. 6 (a) range under 10.3 degrees, while those in the latter case range over 10.0 degrees. This is because only approaching or withdrawing section occurs in the former case. Conversely, the both sections occur in the latter case, so the detection of boundary between both sections is required. In this detection, there is few change of distance near the boundary, as shown in acoustic waves 2 and 3 in Fig. 1. Hence, the estimation error is a little increased.

5.3 Evaluation

The experimental results show that the direction estimation is possible where the distance between devices is within 30m. In the rendezvous, it is likely to approach the partner within 30m by sharing the rendezvous place. Otherwise, by combining the proposed method with existing location services like GPS, it would be possible to lead a user to near the partner. Meanwhile, the estimation error is kept within 18.0 degrees under conditions where reflection wave, noise and crowdedness are factors. By obtaining the direction of an error of within 18.0 degrees, the direction in which the partner would be located is limited to 1/10 (=18.0*2/360). In case that there is only one person in the estimated direction, this person must be specified as the partner. Otherwise, if there are multiple persons in the estimated direction, we can make a short list of the candidate persons by 1/10. This enables the user to easily find his/her partner. Therefore, the proposed method is practical for the rendezvous with the person who is not acquaintance in the actual world.

6 Conclusion

We proposed a direction estimation method enabling users to have a rendezvous for the first time which requires neither any additional infrastructures nor special hardware on user devices. In the proposed method, Doppler Effect produced by a user movement is used for the direction estimation. Meanwhile, to prevent the estimation error from increasing due to reflection waves, the device removes reflection waves with acoustic wave information. We implemented the mechanism as a smartphone application and evaluated its performance under real-world conditions. The experimental results show that the estimation error is kept within 18.0 degrees under the condition even where reflection wave, noise and crowdedness occur. This implies that the direction in which the partner would be located is limited to 1/10 (=18.0*2/360) in the rendezvous. As this enables the user to find a partner easily, the proposed method is practical for the rendezvous.

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