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Three Cs detection method using Wi-Fi radio wave statistics

Nobuo Suzuki*, Kentaro Tajiri, Miyu Sato
Kindai University, 11-6 Kayanomori, Iizuka, Fukuoka 820-8555, Japan

Abstract

Many infection preventing measures have been taken in COVID-19 situation. In particular, the approach called Three Cs avoidance is drawing attention. Three Cs means closed spaces, crowded places, and close-contact settings. This approach is taken in many business scenes regardless of individual situation. Such Three Cs are effective, but it is difficult for humans to always be aware of them. Various detection systems have been proposed to help understanding Three Cs situation. Most of them use cameras, CO2 sensors and so on. However, such system is costly due to introduce new equipment. Therefore, we propose a method for detecting Three Cs using only the existing widely used Wi-Fi equipment. Our method introduces unique detection parameters and performs statistical evaluation. As a result of constructing the system and evaluating it, we confirmed that it was possible to detect Three Cs with an accuracy of 86% or more.

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1. Introduction

The spread of COVID-19 has become one of major social problems in recent years. Many infection preventing measures have been taken. An approach called Three Cs avoidance to reduce denseness between humans is drawing attention [1,2]. Three Cs means crowded place, close-contact setting, and closed space. This approach is being taken in many business situations regardless of individual scenes. Although such Three Cs are effective, it is difficult for humans to always be aware of them. Therefore, various automatic detection systems have been proposed to help understanding Three Cs situation. Most of them use dedicated devices such as cameras and CO2 sensors. However, such systems are costly due to introduce new equipment. Therefore, we propose methods to detect Three Cs only with the existing widely used Wi-Fi equipment. These methods divided into two stages, crowded place and close-contact setting, and closed place. The detection of Three Cs is performed by combining the detection results of each measure. As a result of constructing the detection system and evaluating it, we confirmed that the Three Cs can be detected with an accuracy of 86% or more.
This paper first describes existing research and clarify the position of this research. Next, it gives the details of the proposed Three Cs detection method. Finally, the results of the evaluation are shown and discussed.

2. Three Cs detection systems

Some methods for detecting Three Cs have been studied so far. They can be roughly classified into two categories. One uses dedicated IoT sensors and another uses only general-purpose devices such as smartphones without using special sensors. Table 1 shows those systems.

| No. | Name                                      | Organization         | Category                  | Features                                                                 |
|-----|-------------------------------------------|----------------------|---------------------------|--------------------------------------------------------------------------|
| 1   | Three Cs visualization system              | Uhuru                | Dedicated devices         | Combination of VOC sensor, noise sensor, and human sensor.               |
| 2   | Conference room Three Cs visualization system | Optex                | Dedicated devices         | Combination of attendance sensor, CO2 sensor, and door open/close sensor.|
| 3   | Signage alert                              | TechnoFace           | Dedicated devices         | Count the number of people using a camera.                               |
| 4   | Three Cs checker                           | Rapid Program        | General-purpose device    | Smartphone app                                                           |
| 5   | Three Cs sensor                            | Univ. of Tokyo       | General-purpose device    | Works with positive person tracking app.                                 |
| 6   | Sports gym dense detection system          | Osaka Univ.          | General-purpose device    | Calculate the distance between people from the video.                   |
| 7   | Event venue number of persons distribution system | Osaka Inst. of Technology | General-purpose device    | Detect by using Wi-Fi packets.                                           |

The following systems use dedicated IoT sensors. Uhuru has announced a Three Cs visualization system [3]. A VOC sensor, a noise sensor, and a human sensor are combined to visualize the degree of Three Cs density. It alerts people to heads-up preventing infection by visualizing the density of people. Optex has developed a Three Cs visualization system for conference rooms by combining special sensors such as attendance sensors, CO2 sensors, and door open/close sensors [4]. TechnoFace has developed a system that uses a camera to count the number of people and display a warning on a digital signage [5]. These methods are expensive and difficult to introduce easily because they use dedicated IoT sensors and digital signages.

Next, following systems use only general-purpose devices such as cameras and Wi-Fi without using special sensors. Rapid Program has announced a smartphone app called "Three Cs Checker" that detects Three Cs situations [6]. This system judges Three Cs as follows. It measures the noise level with a microphone of a smartphone, and judges closed space when it exceeds a certain level. This system decides crowded place if the number of Bluetooth devices exceeds a certain number after it check the number of such devices around the persons. It is close-contact setting when the received signal strength (RSSI) of nearby Bluetooth devices exceeds a certain level. The University of Tokyo has proposed "Three Cs sensor" that detects Three Cs situations on their campus area [7]. COCOA [13], a positive person tracking app released by Japanese government, searches for the number of Bluetooth devices installed to determine the population density within a certain area. Osaka University has proposed a dense detection system using a camera for a sports gym [8]. The system recognizes people from the video, and the distance between people is calculated to estimate density. This system also tracks the person after detection to prevent the detection error of the hidden person and achieves 83.6% accuracy. Osaka Institute of Technology has proposed a method to acquire the distribution of the number of people at the event venue by detecting Wi-Fi packets [9]. This makes it possible to grasp the congestion situation and predict the occurrence of congestion. These are low cost due to the
realization of software only, but most of them have not been objectively evaluated so that their performance is unknown.

On the other hand, our proposed method uses only general-purpose devices such as Wi-Fi without using special sensors. It was also built in a real environment and evaluated its performance.

3. Proposed Three Cs detection method

First, we review the definition of Three Cs condition. The Ministry of Health, Labor and Welfare of Japan requests the measures to prevent infection as follows [1].

- Crowded place: Keep 2 meters distance from the neighbors.
- Close-contact setting: Do not have more than 10 people in the room.
- Closed space: Open the windows of the room you are periodically.

The existing research defines the following conditions as Three Cs for these definitions. Rapid Program acquired the noise level by the microphone of the smartphone and defined as closed space when the noise level exceeds 40 dB [6]. It checks the number of Bluetooth devices around, and if it exceeds 40, it defines crowded place. It also defines close-contact setting when there are 4 or more devices with RSSI -55 or more of nearby Bluetooth devices. However, the objective evaluation of these judgment standard values has not been performed, and the evaluation is only sensuous. Next, University of Tokyo determined crowded place by estimating the population density. It estimated crowd place when the number of transmissions from the positive person tracking application through Bluetooth was 5 times in a minute [7]. This system didn’t also conduct the objective evaluation. Uhuru [3], Optex [4], and TechnoFace [5] didn’t make their own judgment of Three Cs, but used estimated Three Cs by visualizing it. Our method examines specific criteria based on the definition of the Ministry of Health, Labor and Welfare of Japan, and proposes a realization method on an actual system.

According to the definition of the Ministry of Health, Labor and Welfare of Japan, crowded place can be estimated by whether the distance between people is 2 meters or more. Close-contact setting can be estimated by counting the number of people nearby. Closed space can be estimated by determining whether a nearby door is open or closed. We tried to estimate these conditions using information on Wi-Fi radio waves. Specifically, we collected Wi-Fi Received Signal Strength Indicator (RSSI) and the statistical characteristics of this data to detect Three Cs.

3.1. Extracting Received Signal Strength Indicator from Wi-Fi packets

This section describes the method of extracting Received Signal Strength Indicator (RSSI) from Wi-Fi packets. Wi-Fi packets are captured [12] and RSSI information contained in the packet headers called Radiotap are extracted. The receiving radio strength between the target smartphones can be obtained as a result [11]. In general, the higher the value of this receiving radio wave strength, the closer the distance between the terminals. The lower the value, the distance between the terminals tends to be distant.

Fig. 1. Our Three Cs detection system configuration.
The system needs to use a function called NIC as a monitor mode in order to extract Wi-Fi packets. Since Windows and ordinarily Linux OS don’t have this function, we realized by installing Kali-Linux on Raspberry Pi at this time. Fig. 1 shows the system configuration to sense RSSI using Wi-Fi and estimate Three Cs.

3.2. Crowded place and close-contact setting

This section focuses on crowded place and close-contact setting in Three Cs. Methods to detect close-contact setting detection has been proposed so far. Yo et. al. proposed an accompanying indicator to identify the accompanying groups for the purpose of automating information sharing in groups on SNS [10]. This indicator provides how much people acted together using the absolute and relative position of the terminals. For example, we can estimate that people would like to share pictures if they act together when they take pictures. The accompanying indicates that people stay with others when they are doing a certain action, and the indicator of how long they accompany is called an accompanying indicator. Equation (1) shows the accompanying indicator, where \( t \) is the current time, \( d \) is the distance depending on the location, \( td \) is the most recent time that has entered that distance, and \( d(t) \) is the distance between the terminals in the current time. The accompanying indicator \( A(t) \) is the function of these parameters.

\[
A(t) = 1 - \frac{1}{1 + \int_{td}^{t} \frac{1}{d(t)} \, dt}
\]  

(1)

The distance between the terminals is determined by RSSI of Bluetooth communication. The accompanying indicator is not a simple human distance, but it can be used as a more accurate close-contact setting degree by using time elements. Therefore, we added crowded place element to this accompanying degree to express the degree of crowded place and close-contact setting in this study. The degree of crowded place can be estimated by calculating the accompanying indicator per person from the number of people around. We call it the degree of crowded place and close-contact setting (CPCS). The greater CPCS, the greater the degree of crowded place and close-contact setting. Equation (2) shows this condition, where \( n \) is the number of people around it.

\[
T(t) = \frac{A(t)}{n}
\]  

(2)

d(t) is a distance between people, and is equivalent to the distance between smartphones. The distance is estimated using the radio wave strength of Wi-Fi emitted by the smartphone. We prepared 9 terminals, acquired RSSI for each distance, and measured the average and maximum RSSI value for each distance. Fig. 2 and 3 show the measurement situation, and Table 2 shows the measurement results. We decided to determine the distance based on the maximum RSSI value. For example, the distance between the terminal 1 and 2 was set to D12, and the RSSI value from the terminal 1 to the terminal 2 was -44 dBm. The closest maximum RSSI value can be estimated to be 100cm of -44.5dbm at this situation. Furthermore, we performed the measurement in chronological order because CPCS formula assumed chronological change. In other words, the measurement of each distance was conducted as time proceeding.

Table 2. Measurement result of Wi-Fi RSSI and distance with multiple devices for learning.

| Terminal No. | Terminal Name | Distance (cm) and RSSI value (dBm) every 10 seconds |
|--------------|---------------|---------------------------------------------------|
| 1            | SPC35         | -34.2    -38.6    -43.6    -54.4    -56.7    -58.2 |
| 4            | SPC40         | -38.6    -40.0    -41.4    -41.8    -45.2    -43.0 |
| 5            | SPC34         | -39.6    -42.0    -43.0    -44.2    -46.0    -47.8 |
| 6            | SPC39         | -34.2    -44.6    -45.0    -46.0    -47.2    -49.5 |
| 8            | SPC44         | -41.2    -42.0    -44.1    -45.8    -46.7    -47.9 |
| Ave.         |               | -37.6    -41.4    -43.4    -46.4    -48.4    -49.3 |
| Max.         |               | -41.2    -44.6    -45.0    -54.4    -56.7    -58.2 |
CPCS was calculated by assigning this measurement result into Formula (2). Table 3 shows the result. Here, we determined that it was sparse place if the distance between the terminals was 200 cm or more, and crowded place if it was 150 cm or less according to the actual crowd and sparse situations as shown in Fig. 2.

Table 3. CPCS with multiple devices for learning.

| Terminal No. | Terminal Name | Crowd (-150cm) | Sparse (200-300cm) |
|--------------|---------------|----------------|-------------------|
| 1,4,5        | SPC35,40,34   | 0.27           | 0.18              |
| 4,5,6        | SPC40,34,39   | 0.28           | 0.24              |
| 5,6,8        | SPC34,39,44   | 0.28           | 0.22              |
| 6,8,1        | SPC39,44,35   | 0.26           | 0.20              |
| 8,1,4        | SPC44,35,40   | 0.27           | 0.20              |
| Ave.         |                | 0.27           | 0.21              |

It is crowded when CPCS is 0.27 and sparse when 0.21 from this result. Therefore, we decided crowd or sparse based on the intermediate value 0.24. The estimation formula is shown in Equation (3).

\[
\text{if } T(t) > 0.24 \text{ then crowd else sparse} \tag{3}
\]

3.3. Closed space

Closed space means a situation where the return flow of the air is hindered by closing the door of the room [1]. Therefore, the closed space can be detected by estimating the opening and closing state of the door in the room. We tried to detect the opening and closing of the room door by the Wi-Fi radio wave. Generally, there are many reflections of radio waves when the door is closed. On the other hand, the radio wave is radiated outside when the door is open, so the amount of radio wave reflection is few. Therefore, the conditions of the opening or closing of the door changes the received signal strength of Wi-Fi radio wave. It is also possible to improve accuracy by observing changes in time-based receiving signal strength.

First, we measured RSSI when the door in the actual room was opened and closed. Fig. 3 shows the floor plan of the room, and the measurement results in Fig. 4. Wi-Fi packet was collected at interval of 60 seconds when the door was opened and closed, and RSSI was extracted from the packets.
Next, the standard deviation was calculated by Formula (4) in order to grasp the changing RSSI over periods of time, where \( i \) is the number of each measurement, \( x_i \) is Wi-Fi RSSI at the time of the measurement, and \( \bar{x} \) is the average value of Wi-Fi RSSI. Table 4 shows the result.

\[
S = \sqrt{\frac{1}{n} \sum_{n=1}^{n} (x_i - \bar{x})^2} \tag{4}
\]

We evaluated the median value of closing the door and the average value of the median of opening, the minimum value of closing, and the maximum value of opening. Then we realized the minimum value of closing the door was the highest performance. It was 0.8914 and the accuracy was 86%. Therefore, this value was determined to be a threshold value for estimation of opening or closing the door.
Table 4. Standard deviation of RSSI when the door is opened or closed the door.

| Measured number | Close  | Open  |
|-----------------|--------|-------|
| 1               | 1.0653 | 0.4441|
| 2               | 1.1008 | 0.2053|
| 3               | 0.9533 | 1.0382|
| 4               | 1.1160 | 0.8031|
| 5               | 1.0001 | 0.8278|
| 6               | 1.2071 | 1.1202|
| 7               | 0.8914 | 0.7065|

4. Evaluation

4.1. The evaluation of Crowded place and Close-contact setting

The measurement was conducted in the actual situation using the crowd and sparse estimation criteria for CPCS defined in Section 3.2. Then the accuracy was also evaluated. First, Wi-Fi RSSI was measured using terminals different from learning ones. CPCS was estimated using the measurement results. Table 5 and 6 show the result. The accuracy was 88% according to the result, so we could realize this method was sufficiently effective.

Table 5. Measurement of Wi-Fi RSSI and distances on evaluation terminals.

| Terminal No. | Terminal name | Distance (cm) and RSSI value (dBm) every 10 seconds |
|--------------|---------------|--------------------------------------------------|
|              |               | 50       | 100     | 150     | 200     | 250     | 300     |
| 2            | SPC33         | -38.0    | -40.4   | -42.1   | -44.0   | -46.3   | -48.4   |
| 3            | SPC52         | -40.8    | -42.4   | -44.1   | -45.2   | -47.4   | -48.0   |
| 7            | SPC36         | -37.0    | -40.1   | -41.0   | -43.6   | -43.3   | -44.0   |
| 9            | iPhone7       | -35.0    | -42.4   | -44.4   | -45.6   | -47.4   | -48.0   |
| Ave.         |               | -30.2    | -33.1   | -34.3   | -35.7   | -36.9   | -37.7   |

Table 6. CPCS on evaluation terminals.

| Terminal No. | Terminal name                  | Crowd (-150cm) | Evaluation | Sparse (200-300cm) | Evaluation |
|--------------|--------------------------------|----------------|------------|--------------------|------------|
| 2,3,7        | SPC33, 52, 36                  | 0.28           | Correct    | 0.22               | Correct    |
| 3,7,9        | SPC52, 36, iPhone7              | 0.26           | Correct    | 0.21               | Correct    |
| 7,9,2        | SPC36, iPhone7, SPC33           | 0.29           | Correct    | 0.25               | Incorrect  |
| 9,2,3        | iPhone7, SPC33, 52              | 0.26           | Correct    | 0.20               | Correct    |

4.2. The evaluation of Closed space

We evaluated the accuracy by measuring in the actual situation using the criteria for closed space defined in Section 3.3. The evaluation was begun from measuring Wi-Fi RSSI with multiple times separately from the learning cases. The standard deviation was calculated using the measurement results, and the opening or closing of the door was estimated based on the criteria value 0.8914. Table 7 shows the result. The accuracy was 83% from the result, and we realized that this method was sufficiently effective.
Table 7. The evaluation in case of opening and closing the door.

| Number of measurements | Close Evaluation | Open Evaluation |
|------------------------|------------------|-----------------|
|                        | Correct          | Incorrect       |
| 1                      | 0.9706           | 0.8981          |
| 2                      | 1.0556           | 1.0539          |
| 3                      | 0.8914           | 0.7065          |
| 4                      | 1.0173           | 1.0327          |

5. Conclusion

This research proposed a method to estimate Three Cs by using the received signal strength of Wi-Fi radio wave. Three Cs were divided into crowded place and close-contact settings, and closed space in our method. Then we proposed the appropriate method for each case.

On the other hand, this method learned the estimation criteria based on a specific environment. The actual usage environment always changes. There is a problem that calibration processing is required when the environment changes. We plan to develop automatic calibration method in the future.

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