Real-Time Passenger Counting in Streetcars Using High Sound Frequency Signals

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***Abstract*—Various technologies using wireless access points, camera recognition, transportation cards, and Bluetooth beacons have recently been proposed for use in measuring congestion in public transportation. However, existing methods have the problem of low measurement accuracy or providing congestion information in only four stages. Thus, this paper proposes a real-time passenger counting technology for streetcars that uses high sound frequency signals to solve these problems and counting passenger more accurately. Because high-frequency signals have a smaller signal transmission range than Bluetooth beacon, their use can solve the problem of misrecognition of people located outside the streetcar, and the number of passengers can be measured with the same level of accuracy as when using the Bluetooth Low Energy (BLE) signal. To verify the performance of the proposed system, we conducted a comparative experiment with a BLE beacon-based system. The proposed method showed high accuracy and could thus be used immediately to measure real-time congestion in streetcars.**

***Keywords*—streetcar, congestion estimation, high sound frequency, smart device, Bluetooth beacon**

I. INTRODUCTION

As smart devices are increasingly used and indoor positioning technology has developed, congestion measurement methods for public transportation (e.g., subways and buses) using this technology have been proposed. Congestion measurement involves counting the passengers on transportation, and as doing this with the human eyes has limitations, camera recognition and real-time congestion measurement technology using Artificial Intelligence (AI) have been proposed [1]. However, this method does not show the exact number of passengers on transportation because it displays congestion information in only four steps. To measure the number of passengers without using visual information, a method of predicting from statistics on the use of transportation cards containing integrated circuit chips has also been proposed [2]. However, this method has the problem of low accuracy when some passengers use other payment methods, such as cash and tickets, instead of transportation cards.

Recently, transportation congestion has begun to be measured by counting passengers' smart devices rather than passengers themselves. The methods of counting people's smart devices on transportation use the wireless Access Points (APs) connected to such devices and Bluetooth Low Energy (BLE) beacon signals. A wireless AP uses the AP installed in the subway to calculate the number of smart devices on transportation and to measure congestion thereon, but the smart devices must be connected to the AP for communication [3]. Thus, this method is difficult to use for transportation in Japan, Canada, the USA, and Australia without wireless APs.

The method using BLE beacons involves installing beacons in transportation and counting the number of smart devices receiving the beacon signal. Since Apple's iBeacon was launched in 2013, BLE technology has been widely used [4] as the maximum reach of the BLE signal is up to 70 m, allowing for more accurate tracking of indoor user locations [5]. Beacon-based technology is used in user location tracking [6], electronic attendance systems [7], service information provision [8], and theft prevention technology [9]. A system for checking the number of public bus passengers using beacons [10, 11] and indoor density analysis using beacons and high-frequency signals [12] have been proposed. However, because the BLE signal has a wide range, even people located outside transportation are often mistakenly recognized [13].

Therefore, this paper proposes a system for identifying the numbers of people aboard streetcars and measuring the real-time passenger counting of streetcars by installing speakers on them and delivering high sound frequency signals to passengers' smart devices. Streetcar passengers will download the proposed application on their respective smart devices, and the application will receive high sound frequency signals from the speakers installed within the streetcar. The high sound frequency signals will consistently generate a pair of frequencies in the range of 18–22 kHz that will hardly be heard by the passengers, among the frequencies that can be outputted from the speaker [14]. To increase the transmission range of the high sound frequency signals, we propose a new type of signal that combines the methods used by Kim *et al.* [15] and Won *et al.* [16] by modifying the dual signals proposed by the existing studies. When the proposed application receives a high sound frequency signal, it automatically sends the signal value, smart

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device information, ride time, and drop-off time to the passenger counting server. The server receives the user's boarding and disembarkation information and stores it in a database, and may easily measure passenger congestion for each usage time of the corresponding streetcar.

To verify the performance of the proposed method, we compared the performance of the proposed technology with that of an existing Bluetooth-based system in the streetcar. In the first experiment, one participant boarded at and disembarked from random sections of a streetcar (one to five stations) 10 times, and whether the smart device accurately recognized the participant's streetcar section boarding and disembarkation was determined. In this experiment, both the Bluetooth-based and proposed methods showed 100% boarding and disembarkation recognition accuracy. In the second experiment, 10 of the 15 participants boarded at and disembarked from each station 10 times. The five people who did not do so were located at each station and only launched the application. In this experiment, unlike the Bluetooth-based method, the proposed method had no misrecognition. Thus, the proposed method is a useful technology that can easily count streetcar passengers and measure real-time streetcar congestion by increasing the accuracy of signal reception using a pair of high sound frequency signals. The proposed method can also be applied to subways and public buses in addition to streetcars.

This paper is organized as follows. In Section II, we describe the existing research using inaudible high frequencies of audible sound. In Section III, we explain the flow of real-time passenger counting in streetcar using high frequency signal and the proposed application. In Section IV, we show a comparative experiment and results with method using Bluetooth beacons for performance verification of the proposed application. Lastly, in Section V, we present the conclusions and establish future research and directions.

II. Related Work

In this section, we describe the existing research using inaudible high frequencies of audible sound. Most of the recent studies use high sound frequencies as a signal from 18 kHz to 22 kHz in the audible frequency range. Since modern smartphones allow to record sound with 48,000 samples/s, according to the Nyquist-Shannon theorem sounds with a maximum frequency of 24kHz can be technically detected [17]. Bihler presented three types of smartphones used at the time, and verified the performance of detecting the signal of each smartphone by generating a 24 kHz signal at a distance of 2 m as shown in Table I.

TABLE I. ID Transmission in a Quiet Office Setting (2 m Distance)

Receiv. Device	IDs Sent	True Pos	False Pos	Detection Rate
HTC ADP 1	235	201	2	85.5%
Sony x10 mp	320	304	1	95.0%
HTC Desire	1023	928	10	90.7%

Bihler proposed 20 kHz and 22 kHz ultrasonic signals as trigger signal to replace Near Field Communication (NFC) [18]. He used a 8-bit 3.2 MHz Freescale microcontroller and a simple piezo speaker for generating the trigger signal and used Frequency Shift Keying (FSK) technology as the signal, using 20 kHz signals as 0 and 22 kHz signals as 1 [19]. With a transmission duration of 26 ms per bit, an 8 bit identification number could be transmitted in 208 ms. At this time, he used Hamming Code Schema to deal with errors that could be caused by ambient noise during data transmission [20]. Using this trigger signal which is composed of high sound frequencies, Bihler proposed a smart device-based museum guide application, which has since greatly influenced the research on signal processing between smart devices using high sound frequency. Quan proposed a high sound frequency signal as an acoustic background fingerprint used for security authentication of mobile devices [21]. Park proposed the Inaudible Dual Tone Data Transmission (IDTD) method as a method for communication between objects [22] and Chung proposed a new method of transmitting 32 bit data within 1.5 m as a data transmission method between smart devices using high sound frequency [23].

Inaudible sound that cannot be heard by people within the audible frequency is also used for fall detection and indoor Echo-location. Lian proposed a fall detection method by detecting a 20 kHz continuous wave signal with a speaker and microphone installed in the house, instead of smartphones with accelerometers and gyroscopes, Radio Frequency Identification (RIFD), and various sensors [24]. He continued to apply the Singular Value Decomposition (SVD) to reduce the feature dimension to 1, so as to input to a Hidden Markov Model (HMM) for training [25]. Lian's proposed method represents an accuracy of 91% when used at 1 m distance and 45 dB which correspond to 80% of the speaker's maximum power output. Gabriele used 18 kHz to 22 kHz signals to index 2 bits signals and proposed dual-function communication and echo-location with low-cost hardware [26]. This echo-locator revealed that the echo-locator could guarantee low absolute errors in a range between approximately 1 and 6 m, and in the same interval the communication performance can yield a BER as low as 0.02%.

III. Real-Time Passenger Counting in Streetcars Using High Sound Frequency Signals

In this section, we describe the flow of real-time passenger counting in streetcars using smart devices and high sound frequency signals. We also explain the generation of high sound frequency signals used to count passengers and how smart device applications recognize high sound frequency signals. The overall flow of the proposed method is shown in Fig. 1. In Fig. 1, the speaker and the personal computer installed in the streetcar generate and output high frequencies for counting the passengers ①. The passengers' smart device applications collect the sounds around them and analyze high frequencies through Fast Fourier Transform (FFT) ②.

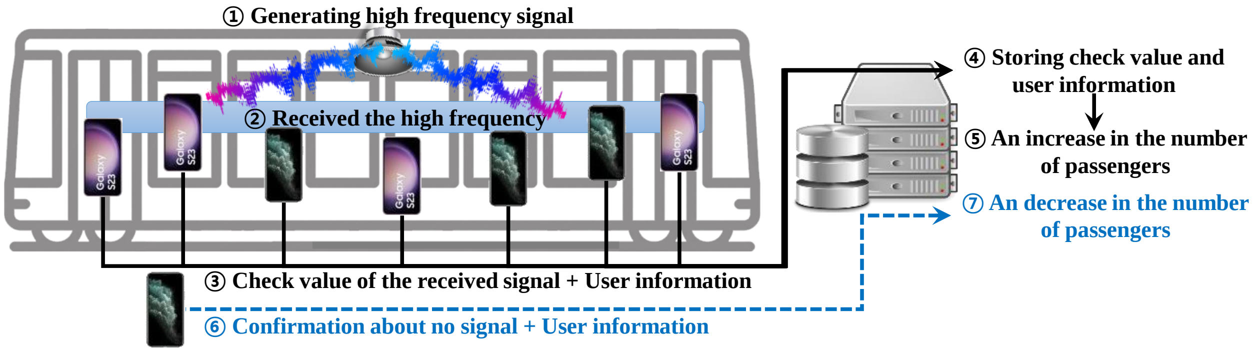

Fig. 1. Flow of real-time passenger counting in streetcars using high sound frequency signals.

When the application detects high sound frequencies, it sends a received high frequency value and user information to the server ③. The server stores the high frequency value and user information in a database ④ and increases the number of people aboard the streetcar by one ⑤. At this time, the high sound frequency signal shown in Fig. 1 is continuously generated in the streetcar. When a passenger rides the streetcar, the passenger's smart device application detects a high frequency from the surrounding sound and continuously receives high sound frequency signals while aboard the streetcar. When the passenger disembarks from the streetcar, the application confirms that no more high sound frequency signals are received and sends this information to the server ⑥. The server receives the information and reduces the number of passengers in the streetcar by one ⑦.

The high sound frequency values used in the existing study ranged from 18 kHz to 22 kHz, and we used a new signal transmission method—that of Kim *et al.* [15] and Won *et al.* [16], which has a wide transmission range. Won *et al.* [16] expanded the transmission range by proposing the use of 1 s signal intervals, and Kim *et al.* [15] proposed a pair of signals to vary the signal values. The method proposed in this paper uses one signal in the range of 18–19.9 kHz and another signal in the range of 20–21.9 kHz. The high sound frequency signal is selected in units of 100 Hz. It can generate 20 types of 400 signal combinations at 18–19.9 kHz, and 20 types at 20–21.9 kHz. Fig. 2 shows the high sound frequency signals for counting streetcar passengers and measuring streetcar congestion using the proposed method as time and frequency values.

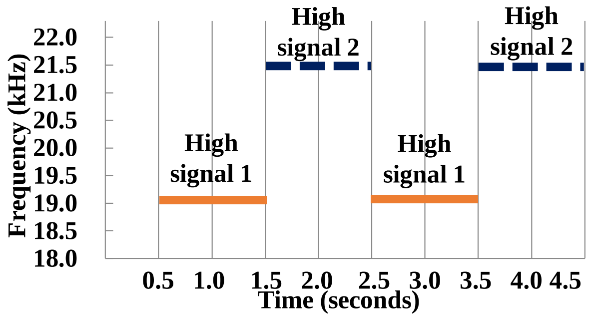

Fig. 2. Example of the proposed high sound frequencies for passenger counting in streetcars.

In Fig. 2, a pair of high sound frequency signals, signal 1 (19.0 kHz) and signal 2 (21.5 kHz), are given. These values are generated repeatedly for 1 s at 1 s intervals. The frequency signal for counting streetcar passengers can be used for the statistical analysis of streetcar passengers using a fixed value assigned to a streetcar.

The proposed application for collecting passenger boarding and disembarkation information checks whether high frequencies above 18.0 kHz are generated through the built-in microphone. If high frequencies are detected, the application sends the passenger boarding and disembarkation information to the server according to the pseudo code shown in Fig. 3.

```
While(receive A_t) Do
  a ← 0;   F_t ← FFT(A_t);   sortByBin(F_t);
  If ( first HF value of F_t is over 20.0 kHz) Then
    a ← first HF value of F_t;   receive A_t+1
    F_t+1 ← FFT(A_t+1);   sortByBin(F_t+1);
    If ( first HF value of F_t+1 is over 20.0 kHz and
        a = first HF value of F_t+1) Then
      sleep(m)   EXIT WHILE
    END If
  END If
END WHILE
While(receive A_t+m) Do
  b ← 0;   F_t+m ← FFT(A_t+m);   sortByBin(F_t+m);
  If ( first HF value of F_t+m is over 18.0 kHz and
      first HF value of F_t+m is under 19.9 kHz) Then
    b ← first HF value of F_t+m;   receive A_t+m+1
    F_t+m+1 ← FFT(A_t+m+1);   sortByBin(F_t+m+1);
    If ( first HF value of F_t+m+1 is over 18.0 kHz and
        first HF value of F_t+m+1 is under 19.9 kHz) Then
      If ( b = first HF value of F_t+m+1) Then
        SendReceivedCheckValue;   EXIT WHILE
      END If
    END If
  END If
END WHILE
```

Fig. 3. Pseudo code for high sound frequency detection for streetcar passenger counting.

In Fig. 3, $\boldsymbol{A_t}$ is the signal value collected by the smart device at time $\boldsymbol{t}$, and $\boldsymbol{F_t}$ is the frequency **bin** value obtained through FFT from $\boldsymbol{A_t}$. High frequencies are sorted by **bin** (sortByBin), and if there is a high frequency of 20.0 kHz or more among them, the high signal value is entered into $\boldsymbol{a}$, and whether the value is correct at the next signal $\boldsymbol{A_{t+1}}$ is checked again. If value $\boldsymbol{a}$ is a match, the code sleeps for $\boldsymbol{m}$ s and leaves the while statement. After that, the repeat statement is executed again, and the system gets F_{t+m} from the audio value of A_{t+m} obtained through FFT. After checking for high frequencies between 18.0 kHz and 19.9 kHz, the frequencies representing high **bin** values are entered as signal values b, and whether the value is correct at the next signal is checked again. At this time, when the signal values a and b are acquired by the frequency signal, the application sends the reception signal values to the server for boarding confirmation. The passenger counting server increases the number of passengers at the streetcar table by one using the received values and user information, and stores the new number by one. The application then continuously receives a high sound frequency signal while the passenger is on the streetcar. When the passenger disembarks from the streetcar, the application confirms that values a and b are no longer present in the first and second while statements. The application sends the disembarkation information to the server, which reduces the number of passengers on the streetcar by one.

IV. Experiments and Evaluations

In this section, we describe comparative experiments with existing Bluetooth beacon-based methods and their results to verify the performance of the proposed method. Basbei4 was used as the Bluetooth beacon, and Marshall Amberton was used as the speaker for high sound frequency output with the iPhone 14 Pro Max. We created iOS and Android based application to generate the proposed high sound frequencies. The Intel® Core™ i5-750 CPU and 8G Ram were used for the boarding counting and passenger counting server. For the server environment, Apache 2.2.14, MySQL 5.1.39, and PHP 5.2.12 were used. There were 15 participants in the experiment, and the experiment was conducted on IYOTETSU Line 3 in Matsuyama, Japan, which is famous for the Botchan Ressha, as shown in Fig. 4. Route 3 (Red line) in Fig. 4 was used for the experiment because it was suitable for the experiment as many tourists take it, the section is short, and it has relatively fewer stations (11 stations: 01, 02, 21, 20, 19, 18, 17, 16, 22, 23, and 24). In the first experiment, the two participants boarded and disembarked at anywhere from one to five stations, and the boarding and disembarkation were measured 10 times. One participant's boarding and disembarkation were measured using a Bluetooth beacon, and the other participant's boarding and disembarkation were measured using the proposed method. Both participants used the iPhone 13 Pro and boarded and disembarked at the same stations. At this time, five beacons and five speakers were used because all the streetcars had to have a beacon and a speaker. Fig. 5 shows the results of the first experiment.

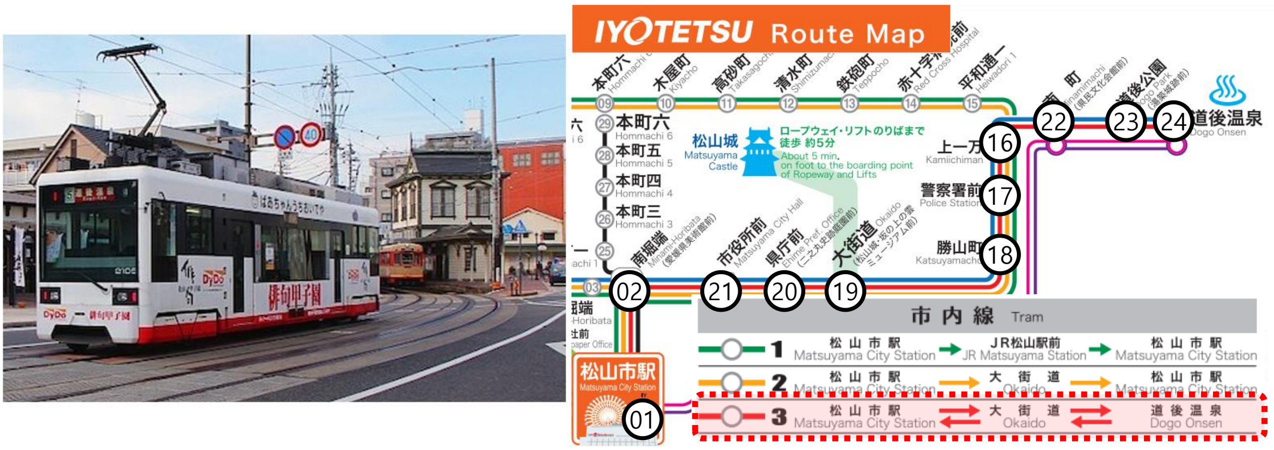

Fig. 4. Photo of a streetcar in Matsuyama, Japan, and route map for the passenger counting experiment.

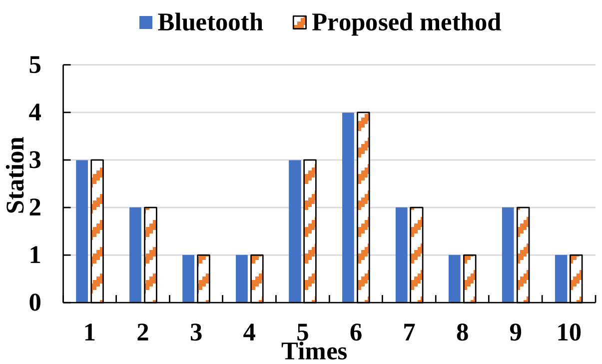

Fig. 5. Accuracy results of the Bluetooth beacon and the proposed application regarding the number of times the participants boarded the streetcar and disembarked from it.

In the first experiment, two participants boarded and disembarked at 11 stations, as shown in Fig. 4, by dividing them into 3(01-02-21-20), 2(20-19-18), 1(18-17), 1(17-16), and 3(16-22-23-24), respectively, from one to five times. The six to ten times were also divided into 11 stations by dividing them into 4(24-23-22-16-17), 2(17-18-19), 1(19-20), 2(20-21-02), and 1(02-01) in the opposite direction to board and disembark. Both the Bluetooth beacon and the proposed method showed 100% measurement accuracy 10 times, without misrecognition or non-recognition.

In the second experiment, 10 participants boarded the streetcar at the same time, disembarked at the next station, and boarded the streetcar and disembarked from it again. In this experiment, 10 beacons and speakers for 10 streetcars were required to proceed from the first station to the last station because each participant had to board five times and disembark five times, so the experiment was conducted by returning to five stations after going to such stations. The direction of boarding was 24, 23, 22, 16, 17, and 18, and the direction of disembarkation was the reverse (see Fig. 4). Then, at each station, one participant launched the proposed application but did not actually board the streetcar. Eight of the 15 participants were iPhone 12–14 users, and the remaining seven were Galaxy 20–22 users. The proposed application was developed for iOS and Android, respectively. Fig. 6 shows the results of the experiment on the measurement of the number of people who boarded the streetcar at the same time using the Bluetooth beacon and the proposed method.

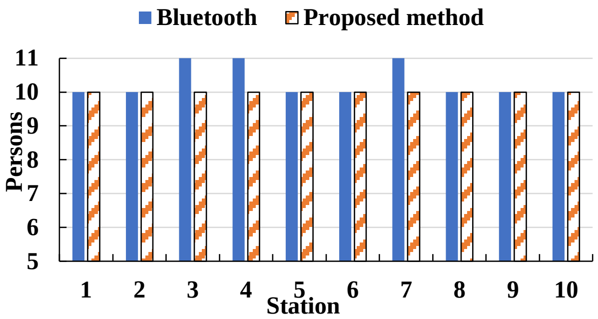

Fig. 6. Results of the Bluetooth beacon and the proposed method application regarding simultaneous streetcar boarding and disembarkation.

In Fig. 6, the results of the second experiment on boarding and disembarkation obtained using the Bluetooth beacon show that 11 people boarded the streetcar at the third station (from station 22 to station 16), fourth station (from station 16 to station 17), and seventh station (from station 17 to station 16). This is expected to be measured as if the participant had boarded the streetcar, even though the participant did not, due to the closer distance between stations 22 and 16, 16 and 17, and 17 and 16 and the wider signal range of the beacon. On the other hand, as the proposed method has a relatively small signal reach, it was possible to accurately determine that all 10 participants boarded and disembarked at all the stations, without misrecognition. Thus, the proposed method showed high accuracy in the first and second experiments, and unlike the Bluetooth beacon, it had no misrecognition.

V. Conclusion

In this paper, we propose a technology that can accurately count the people boarding streetcars and disembarking from them using their smart devices and high sound frequency signals, and thus measure real-time streetcar congestion. We present a method of cross-using a pair of high sound frequency signals to maintain high accuracy while keeping the reach distance, instead of using the signals used in the previous research. To verify the performance of the proposed method, we conducted comparative experiments with the Bluetooth beacon-based method. As a result, unlike the Bluetooth beacon, the proposed method showed no misrecognition, and its performance was excellent. Therefore, the proposed method for real-time passenger counting in streetcars using smart devices and high sound frequency signals can replace the one used and presented in the previous research. In addition, it is a useful technology because the data collected for congestion estimation can be used to statistically analyze the usage status during the week and the weekend.

In our future research, we will conduct large-scale congestion measurement experiments using the proposed method. Although the present study was able to confirm the accuracy of high sound frequency signals through a small-scale experiment involving 15 participants, we expect that there may be unrecognition and misrecognition as the number of passengers increases. The streetcar used in the experiment was a single train with boarding gates located at both ends. Many countries around the world, including Malaysia, Germany, and Portugal, have streetcars consisting of two to four trains. Therefore, we will conduct further studies and experiments that can apply the proposed high sound frequency signals in a space consisting of two to four trains.

Conflict of Interest

The author declares no conflict of interest.

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References

[1] Science Japan. (February 2022). Visualization of congestion in trains. Tokyu and Hankyu, Tokyo Institute of Technology perform demonstration experiment. [Online]. Available: https://sj.jst.go.jp/news/202202/n0224-03k.html

[2] S. J. Lee and S. I. Shin, "A study on improving subway crowding based on smart card data: A focus on early bird policy alternative," *Journal of Information Technology Services*, vol. 19, no. 2, pp. 125−138, 2020.

[3] Seoultech, Seoul Metropolitan Government. (December 2021). Seoul transportation corporation awarded the 'Top 10 railroad technology award' for subway congestion calculation service through big data convergence. [Online]. Available: https://globalrail.seoultech.ac.kr/community/news/?do=commonview&bnum=57346&bidx=512926

[4] S. Shao, N. Shuo, and N. Kubota, "An iBeacon indoor positioning system based on multi-sensor fusion," in *Proc. 2018 Joint 10th International Conference on Soft Computing and Intelligent Systems (SCIS) and 19th International Symposium on Advanced Intelligent Systems (ISIS)*, Toyama, Japan, December 2018, pp. 1115−1120.

[5] P. Bellavista, A. Corradi, M. Ferrari, L. Foschini, P. C. M. Picone, and R. Montanari, "Performance evaluation of frameworks for iBeacon-based localization using Bluetooth low energy," in *Proc. 2019 Summer Simulation Conference (SummerSim)*, Berlin, Germany, July 2019, pp. 1−7.

[6] F. Pascale, E. A. Adinolfi, M. Avagliano, V. Giannella, and A. Salas, "A low energy IoT application using beacon for indoor localization," *Applied Sciences*, vol. 11, no. 11, 4902, May 2021.

[7] M. S. Uddin, S. M. Allayear, N. C. Das, and F. A. Talukder, "A location based time and attendance system," *International Journal*

of Computer Theory and Engineering, vol. 6, no. 1, pp. 36−38, February 2014.

[8] J. Lee and J. Chung, "Study on smart order app UX from brand communication perspective," *Advanced Science Letters*, vol. 22, no. 11, pp. 3684−3687, November 2016.

[9] M. B. Chung, "Antitheft technology for smart carts using dual beacons and a weight sensor," *Mobile Information Systems*, 7770768, July 2022.

[10] M. B. Chung, "Number-of-passengers counting system on public buses using beacon technology and smart devices," in *Proc. 2023 8th International Conference on Intelligent Information Technology*, Da Nang, Vietnam, February 2023, pp. 229−233.

[11] B. Zorić, M. Dudjak, and D. Bajer, "Predicting public transport arrival time and congestion based on BLE beacon crowdsourced data," in *Proc. 2022 IEEE Zooming Innovation in Consumer Technologies Conference (ZINC)*, Novi Sad, Serbia, May 2022, pp. 81−86.

[12] M. B. Chung, "Density estimation system of space users using high frequencies of speaker," *Mobile Information Systems*, 7684710, May 2020.

[13] B. Yang, L. Guo, R. Guo, M. Zhao, and T. Zhao, "A novel trilateration algorithm for RSSI-based indoor localization," *IEEE Sensors Journal*, vol. 20, no. 14, pp. 8164−8172, July 2020.

[14] M. D. Fletcher, S. Lloyd Jones, P. R. White, C. N. Dolder, T. G. Leighton, and B. Lineton, "Effects of very high-frequency sound and ultrasound on humans. Part II: A double-blind randomized provocation study of inaudible 20-kHz ultrasound," *The Journal of the Acoustical Society of America*, vol. 144, no. 4, pp. 2521−2531, October 2018.

[15] J. B. Kim, J. E. Song, and M. K. Lee, "Authentication of a smart phone user using audio frequency analysis," *Journal of the Korea Institute of Information Security and Cryptology*, vol. 22, no. 2, pp. 327−336, April 2012.

[16] K. Won, S. Yeoum, B. Kang, M. Kim, Y. Shin, and H. Choo, "Inaudible transmission system with selective dual frequencies robust to noisy surroundings," in *Proc. 2020 IEEE International Conference on Consumer Electronics (ICCE)*, Las Vegas, NV, USA, March 2020, pp. 1−6.

[17] C. E. Shannon, "Communication in the presence of noise," in *Proc. the IRE'49*, January 1949, vol. 37, no. 1, pp. 10–21.

[18] P. Bihler, P. Imhoff, and A. B. Cremers, "SmartGuide—A smartphone museum guide with ultrasound control," *Procedia Computer Science*, vol. 5, pp. 586−592, August 2011.

[19] J. Boiko, V. Tolubko, O. Barabash, O. Eromenko, and Y. Havrylko, "Signal processing with frequency and phase shift keying modulation in telecommunications," *Telecommunication Computing Electronics and Control*, vol. 17, no. 4, pp. 2025−2038, August 2019.

[20] R. W. Hamming, "Error detecting and error correcting codes," in *Computer Arithmetic*, vol. 2, American Telephone and Telegraph Company, 2015, pp. 3−16.

[21] Q. Quach, N. Nguyen, and T. Dinh, "Secure authentication for mobile devices based on acoustic background fingerprint," in *Proc. Fifth International Conference on Knowledge and Systems Engineering, KSE 2013*, 2014, vol. 244, pp. 375−387.

[22] S. Park, Y. Do, J. Park, D. S. Kim, and H. Choo, "Inaudible dual tone data transmission for home appliances," in *Proc. 2014 IEEE Fourth International Conference on Consumer Electronics Berlin (ICCE-Berlin)*, Berlin, Germany, September 2014, pp. 131−134.

[23] M. B. Chung, "Short distance data transmission method using inaudible high-frequencies between smart devices," *Telecommunication Systems*, vol. 70, no. 4, pp. 583−594, August 2018.

[24] J. Lian, X. Yuan, M. Li, and N. F. Tzeng, "Fall detection via inaudible acoustic sensing," in *Proc. ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, September 2021, vol. 5, no. 3, pp. 1−21.

[25] P. Choudhary, A. Tripathi, A. K. Singh, and P. C. Vashist, "Upper half face recognition using hidden Markov model and singular value decomposition coefficients," in *Proc. Advances in Computational Intelligence and Communication Technology, CICT 2019*, June 2020, pp. 549−561.

[26] G. Allegro, A. Fascista, and A. Coluccia. (February 2022). Acoustic dual-function communication and echo-location in inaudible band. *Sensors*. [Online]. 22(3). 1284. Available: https://www.mdpi.com/1424-8220/22/3/1284