Inaudible Transmission System with Selective Dual Frequencies Robust to Noisy Surroundings

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Abstract—This paper proposes an inaudible communication method with high reception rate which is resistant to ambient noise using selective dual frequency. Dual frequencies allow combine more signals than a single frequency in a given frequency band, thereby reducing the error recognition rate. The proposed system also measures the frequencies occurring in the environment. After that, the system selectively uses frequencies in the unmeasured band to avoid interference and increase reception. Inaudible sound uses a high frequency of 16-22kHz, which humans hard to hear, but microphones can recognize. Thus, this method of transmission allows the use of speakers and microphones inside smart devices and consumer electronics. It can be used for near field communication instead of Bluetooth, NFC, Zigbee, and Wi-Fi. We provide a communication solution that increase the reception rate through different speaker outputs, variable frequency bands, and hardware direction. Experiments uses selective dual frequency resulted in the reception rate of at most 90% for distances of 12m, respectively.

I. INTRODUCTION

The evolution of smart devices and wireless communications has enabled work to be completed anywhere on the move. These smart devices use wireless communication technologies such as NFC, Bluetooth, Wi-Fi and LTE [1, 2, 3]. These methods require the installation of additional modules and incur costs. However, using speakers and microphones built into smart devices, it is possible to use protocol solutions for security and data transmission systems without installing modules. Inaudible frequency can provide Location Based Service (LBS) like Bluetooth [4, 5], and can implement functions such as payment and authentication [6, 7], voice recognition [8], audio watermarking [9, 10] and voice attack [11, 12]. Bluetooth requires a pairing process, which can cause the connection to fail depending on a type of OS of the device. However, these problems are solved with NFC using the 16-22kHz inaudible frequency. In general, smart devices can transmit and receive up to 22.05kHz and may receive and detect high frequencies up to 24kHz depending on the performance of the speaker.

Inaudible transmission has been mainly studied as a method of constructing packets by assigning patterns of communication [13]. This method uses an FSK modulation method using a single frequency, which is accompanied by a problem of erroneous recognition in a noise generating environment. If the hardware performance is good, the inaudible frequency shows a success rate close to 100% at more than 6m, but the performance decreases rapidly as distance increases [14]. Even if advances in IT devices have resulted in smaller devices that have improved performance, it is hard to see performance like the performance of large, high-performance microphones and speakers. Therefore, there is a need for a high efficiency inaudible communication method through software development as well as the development of high-performance small devices.

This paper solves the problems of reception rate and misrecognition by generating a new radio frequency based on the surrounding information. The transmitter measures the inaudible frequency bands occurring in the surroundings, then selects two frequencies where the frequency occurs less often. In addition, the proposed system uses dual frequencies, unlike the previous communication system using a single frequency. Dual frequencies can combine more signals than a single frequency. This combination of signals can reduce false recognition rates at the transmitter. As a result, we use dual frequencies to reduce false positives while maintaining the same reception as a single frequency. The maximum ranges of the dual frequencies for both environments that have the noise of 43dB and 71dB are 7.5m and 5.5m, respectively. Both of them have resulted in the increasing of reception rates over than 90%.

II. RELATED WORK

Due to the nature of sound wave communication, inaudible communication has directionality but does not pass through obstacles well. Therefore, research has been conducted in different environments. PhoneEar [17] inaudible communication experiment shows the difference in the reception rate while the user uses the smartphone in real life. Backdoor [18] inaudible communication study confirms the maximum SNR difference when the receiver and the transmitter are aligned in a straight line. Therefore, measuring the reception rate in various environments and measuring the reception rate according to the direction of the speaker and the microphone are indispensable elements in the development process. Also, since the inaudible communication is affected by ambient noise, white noise can significantly reduce system performance, and noise can be confused and mistaken for data signals. Inaudible frequencies generate noise in audible frequencies bands [19]. The audible frequency also affects the reception rate by generating noise in the inaudible frequency band. This in turn means that the audible frequency also affects the inaudible frequency band. For this reason, it does not work
properly in noisy places, as certain signals can generate errors due to unexpected sounds occurring in the environment.

Inaudible transmission uses various modulation schemes such as FSK, ASK, PSK, and OFDM [15]. Most of the frequencies constitute and transmit FSK modulation type packets. The ASK, QPSK and OFDM are used. However, since the ASK method changes the amplitude, the reception rate is greatly degraded when the audio size decreases in the inaudible communication process. The QPSK results in a very high error rate in our target spectrum, due to the limited sample rate on commodity devices [16]. It also has a hearing problem for people in the process of changing phases. In the OFDM scheme, fast and accurate communication is possible, but its reception distance is short, which limits its use in real life. For this reason, we use the FSK modulation method, which is the most used in inaudible sound wave communication because it allows dual frequency signal that has the same signal length as single frequency, but various signal combinations are possible, allowing many kinds of signal transmission.

Generally, the longer the signal, the higher the reception rate, but the longer the transmission time. Also, the simpler the signal, the higher the reception rate, but it can be mistaken for ambient noise. As a way to solve this problem, our system proposes the use of multiple frequencies. By transmitting two or more different frequencies in the inaudible frequency band at the same time, it is possible to reduce the false recognition rate without increasing the length of the signal. But it should be noted that the more frequencies of signals transmitted at the same time in the process of using multiple frequencies, the more the frequencies to be transmitted and the receiver must receive all the signals. If the transmitter transmits a large number of frequencies, the receiver must receive all the signals, which may lower the reception rate.

III. PROPOSED SYSTEM DESIGN

We propose a wireless data communication method based on the mixed signal of inaudible frequency (high frequency) using the smartphone's speaker and microphone. The transmitter encodes the dual frequency and transmits it for 1 sec, and the receiver decodes and restores the signal received through the microphone. Figure 1 shows the general structure of the proposed application system. The transmitter collects various types of noise such as construction noise, traffic noise, and life noise in a real environment through a microphone before transmission. This is to grasp the frequency data generated in the surroundings and communicate by avoiding the noise frequency band. Preventing the overlapping of frequencies can increase the reception rate and reduce erroneous recognition. The transmitter analyzes all input sounds through an internal microphone, detects the trigger signal using a Fast Fourier Transform (FFT), and decodes the corresponding frequency. In this process, the two frequencies having the lowest frequency of occurrence are selected from the input frequency data, and the selected frequency is transmitted. The transmitted dual frequency is received at the receiver through the microphone and provides the receiving information and events to the user through the display.

Figure 1. System functional components

The audible frequency band that a person can hear is generally 20Hz to 20kHz. However, the actual audible frequency varies according to the auditory cell age. Most people have difficulty recognizing signals above 16kHz and do not detect 17kHz. The available frequency bands differ depending on the performance and frequency characteristics of the microphones and speakers. According to the Nike St-Shannon sampling theory, it can receive up to 22.05 kHz when the sampling frequency is 44.1kHz. Modern smart devices can receive up to 24kHz, but most small devices typically hear up to 22.05kHz. Therefore, the standard sampling frequency of this system is 44.1kHz.

Speaker performance has been developed to output high and low pitches evenly, but there is a difference in output between the high and low bass depending on the speaker type. So, you can see that the output of certain frequencies is higher and most small smart devices have a similar feature. Therefore, it is recommended to use the frequency band with large output value as communication signal. We found a frequency band with a high reception rate through experiments. In addition, in order to ensure the reliability of data transmission with the appropriate conditions, two frequencies having the lowest frequency among the frequencies of 17kHz to 21kHz occurring in the surrounding environment are used first.

Transmitting two frequencies simultaneously can cause interference between frequencies. And there is a difference
between the frequency input from the smart device and the frequency actually generated. This means that the spacing between frequencies affects the reception. Experiments show that the frequency you are transmitting produces a frequency difference of about 50Hz. Experiments show that the frequency of transmission shows an error of about 50Hz in a quiet environment and an error of about 80Hz in a noisy environment. Therefore, we must adjust the spacing to at least 100Hz so that the frequencies to be transmitted are not interfered. And depending on the performance of the device, it is necessary to keep the interval at least 200Hz.

When using a Mary Frequency Shift Keying (MFSK) modulation scheme, the probability of misinterpretation is less than when a single frequency is used. In addition, the number of signal combinations increases so that various communication signals can be used. As more signals are sent at the same time, the problem of false recognition can be solved. However, since the performance of a small-sized smart device is limited, the output of the speaker decreases as the number of output signals increases.

\[ S_{MFSK}(t) = \cos(2\pi f_m t), \quad 0 \leq t \leq T_s, \quad m = 1, \ldots, M = 2^k \]  

(1)

Experimental results show that the decibel difference between single frequency use and dual frequency use is very low, about 1dB at 1m distance, but more than 3dB when using over triple frequency. Therefore, in a closed indoor environment, a frequency modulation scheme of \( k=2 \) is used, which can reduce the erroneous reception while exhibiting a high reception rate.

\[ 1 - (p^r \cdot r^2) \]

\[ 1 - (p \cdot r) \]

Figure 2. Reception rate according to misrecognition frequency occurring in the surrounding environment

Figure 2 shows the probability of misrecognition according to the types of frequencies occurring in the environment. The \( p \) is the probability that no noise will occur in the environment and \( r=0.99 \) be the probability that the device recognizes one frequency. When receiving a single frequency, the error recognition rate is \( p \cdot r \). If you use dual frequencies, the device must recognize two frequencies, and the error recognition rate will be \( p^r \cdot r^2 \). This means that dual frequencies reception is misidentified with a much lower probability than a single frequency reception. The more frequencies a device receives in the environment, the more pronounced the difference in misrecognition rates between single and dual frequencies.

The length of the communication signal and the configuration of the packet signal greatly influence the reception rate in maintaining the signal for data transmission. The longer the signal length, the simpler the packet, the higher the reception rate. The exact frequency detection distance depends on the duration of the tone, which also affects the communication distance. Therefore, the system continuously sends the same signal and sets the signal length to 1 sec so that there is no inconvenience to the user. In addition, the audible frequency is also affected by indoor and outdoor environments and is also affected by obstacles. Table 1 shows the parameters set in this system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation frequency</td>
<td>17kHz-21kHz</td>
</tr>
<tr>
<td>Number of frequencies</td>
<td>Dual frequencies</td>
</tr>
<tr>
<td>Tone duration</td>
<td>1sec</td>
</tr>
<tr>
<td>Frequency gap</td>
<td>200Hz (100Hz)</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>44.1kHz (48kHz)</td>
</tr>
<tr>
<td>Ambient noise</td>
<td>43dB±α</td>
</tr>
</tbody>
</table>

Table 1

Sound communication is affected by many things, including surrounding structures, noise, and hardware performance. Therefore, to achieve the best performance, we recommend experimenting in an enclosed space, quiet environment with no structure. Interference usually occurs in the same frequency band. But it is different from what we know. Inaudible frequency bands are affected by the audible frequencies of other bands. This can cause noise in the inaudible frequencies and reduce the loudness of the sound. Therefore, based on the parameter values in Table 1, we experiment in an enclosed space of 15m * 10m.

IV. PERFORMANCE EVALUATION

The system configures an Android application that sends and receives a sound at a sampling rate of 44,100Hz to two Galaxy S8 units. The system uses an FFT library and is designed to transmit and receive simultaneously. Based on the above conditions, the sender collects the surrounding frequency data and then sends two frequencies based on this data and the receiver receives the signal.

We keep the distance between devices at 1m and measure the speaker output of each frequency band in a room with 43dB of noise. Experiments are performed at intervals of 200Hz for the 16-22kHz frequency band, and the volume of the speaker is output to the maximum. 100 times for each frequency, and the speaker and microphone are placed on the opposite straight line.
Figure 3. Maximum volume output at each frequency band utilizing a device

Figure 3 shows the volume level of each frequency. Speaker volume typically decreases from 22.05 kHz or 24 kHz, depending on speaker performance and frequency sample rate. However, the experimental results decrease at 19.6 kHz and show different sound outputs in each frequency band. The difference in sound output is up to approximately 19 dB even within the 16-20 kHz band. And the speaker shows better sound output at 17-18 kHz. This experiment was carried out with Galaxy S8, and similar data values were obtained even with Galaxy S6, Galaxy S7, Galaxy Note 4, and Samsung Metal 9 notebook. We have found that, as a result, a high sound output can be achieved in a certain band of frequencies. This means that due to the recent miniaturization of smart devices, hardware products with similar specifications are utilized. Therefore, when communicating using an inaudible frequency, we prefer to choose a frequency of 17-18 kHz. This is a way to increase reception on speakers and microphones used in handled devices such as smartphones, tablets and laptops.

Figure 4 shows the number of false recognitions by distance for single and dual frequencies. The frequency of the 16-22 kHz band with the frequency interval of 100 Hz was randomly generated to make noise, and the number of false recognitions was measured. The experiment measured the number of misperceptions when 10,000 random noises were generated per distance. And we did 50 experiments like this and averaged the measured results. As a result, when using single frequency, it was misidentified more than 160 times up to 6.5 m. In the case of 10 m, more than 120 errors were recognized. However, when using dual frequency, the number of misrecognitions was 2-3 times. In a noisy environment, it can be concluded that using a dual frequency rather than a single frequency can significantly reduce misperception.

The selective dual frequency inaudible system has several conditions for frequency selection. We repeated the experiments and prioritized the algorithms to ensure high frequency reception. In the first place, the device selects frequencies that do not occur in the environment. Second, choose a frequency band with high speaker output. The system should allow the two frequencies to be at least 200 Hz apart to avoid interference, but should not be too far apart. If the two frequencies are too far apart, the output of each frequency band will be reduced.

Figure 5. Experiment environment to speaker and microphone orientations.

Figure 6. Reception rate according to speaker and microphone orientations.
Figure 5 and Figure 6 show the reception rate according to the direction and distance of the speaker and microphone. Also, it can be seen that the reception rate difference is high starting from the angle of 90 degrees of the two terminals. This shows the characteristics of a sound wave communication in which the reception rate is lowered when no sound is heard. It can be confirmed that the reception rate is 80% or more in any direction within 2m. And if the length and direction of the transmitted data are the same, the reception rate is reduced due to the loss of the path. Since sound waves are directional, the reception rate increases when the speaker and the microphone face each other. In addition, the reception rate is different depending on the hardware performance.

Figure 7 shows the reception rate in a quiet indoor environment and a noisy indoor environment based on the proposed method. The reception rate was over 90% up to 12m in a quiet room of 20dB, and up to 7.5m with a reception rate of more than 95% in a quiet office. In addition, it receives up to 7m with a reception rate of more than 80% even in an environment of about 71dB such as a noisy office. This results in the same reception performance as a single frequency, while reducing false recognition rates in a quiet environment and a noisy indoor environment based on the proposed method. The reception rate was over 90% up to 12m in a quiet room of 20dB, and up to 7.5m with a reception rate of more than 95% in a quiet office. In addition, it receives up to 7m with a reception rate of more than 80% even in an environment of about 71dB such as a noisy office. This shows the characteristics of a sound wave communication, which shows high performance in a closed space. Therefore, many accurate standards are needed, such as the performance of the hardware in use, ambient noise, the size of the enclosed indoor space, and the type of wall.

V. CONCLUSION

This paper proposes a method of maintaining high reception even in noisy environments. Experimental results show over 80% reception up to 7m even in an environment of approximately 75dB. It shows a reception rate of 90% or more up to 10m in an environment with noise of about 20dB or less. Depending on the surrounding environment, the use of a selective dual frequencies enables higher reception and lowers error rates than conventional systems. If this method is configured as packet communication, more secure communication is possible.

Inaudible transmissions are affected by laboratory space and ambient noise, but changing the way you communicate and increasing the performance of your hardware can replace traditional short-range communications. Therefore, we plan to standardize the real environment and speaker output for easy use in the real world. In addition, by increasing the reception using multiple communication sensor modules, we are studying intelligent inaudible frequency transmission based on variable data such as ambient noise, multi-frequency and modulation. The recovery rate is expected to increase if the received signal is recovered through learning.

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