



HOKKAIDO UNIVERSITY

Title	Doppler Estimation of Multicarrier Acoustic Signals Based on the Accordance of Complex Amplitude Estimates
Author(s)	Toyooka, Yuta; Nakamura, Masanari; Hashizume, Hiromichi et al.
Citation	IEEE sensors journal, 25(16), 31232-31241 https://doi.org/10.1109/jsen.2025.3586867
Issue Date	2025-08-15
Doc URL	https://hdl.handle.net/2115/96006
Rights	© 2025 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Type	journal article
File Information	Sensors_20250702.pdf

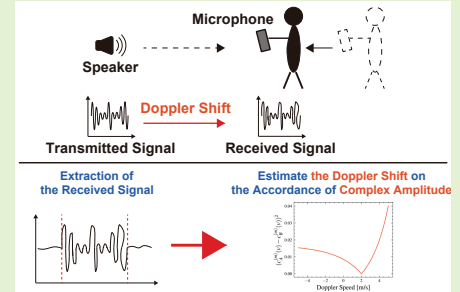


Doppler Estimation of Multicarrier Acoustic Signals Based on the Accordance of Complex Amplitude Estimates

Yuta Toyooka, Masanari Nakamura, Hiromichi Hashizume, and Masanori Sugimoto

Abstract—In positioning and communication systems utilizing multicarrier acoustic signals composed of multiple sinusoidal waves, performance degradation arises due to Doppler shifts caused by receiver motion. Consequently, it is essential to estimate the magnitude of the Doppler shift while simultaneously mitigating the influence of multipath propagation. To address this challenge, the proposed method extracts the segment of the received signal prior to the arrival of multipath components and identifies the concordance point of two sets of complex amplitude groups obtained using the extracted signal and two sets of reference signal groups. This approach reduces the computational burden by minimizing the number of multiplications required during the search process, enabling efficient estimation with lower complexity compared to conventional methods that search through reference signals. Evaluation experiments demonstrated that, when moving a microphone at velocities ranging from -2.0 to 2.0 m/s, the proposed method achieved Doppler shift estimation with a standard deviation of less than 0.064 m/s at signal-to-noise ratios of 21.2 dB or higher.

Index Terms—acoustic data transfer, doppler estimation, complex Amplitude, multi-carrier signal



I. INTRODUCTION

IN recent years, the widespread adoption of mobile devices such as smartphones, which are typically equipped with standard speakers and microphones, has drawn significant attention to positioning and communication technologies utilizing acoustic signals. Acoustic-based positioning and communication offer several advantages, including the potential for higher measurement precision compared to electromagnetic waves, owing to the slower propagation speed of acoustic signals in air. Additionally, these methods require no supplementary hardware on the receiver side, making them particularly appealing. Consequently, numerous techniques leveraging these advantages have been the focus of extensive research [1], [2]. Applications of acoustic communication have also been explored in other challenging environments, such as underwater scenarios, where the characteristics of signal propagation differ significantly from air, as discussed in recent studies [3], [4].

When the receiver is in motion during the transmission of acoustic signals, the occurrence of Doppler shifts induces phase rotation in the received signal, thereby degrading positioning and communication performance. Therefore, the

estimation of the Doppler shift magnitude is required.

As a method for estimating the magnitude of Doppler shifts, a commonly employed approach involves preparing multiple reference signals corresponding to all possible Doppler shift magnitudes and determining the Doppler shift that maximizes the inner product with the received signal. While this reference signal search method has the advantage of being applicable to arbitrary signals, it suffers from the drawback of high computational complexity.

Sato et al. [5] proposed the Extended Phase Accordance Method, which reduces computational complexity by employing two sinusoidal waves as the transmitted signal and searching for a frequency that ensures the amplitude ratio calculated from the received signal matches a known amplitude ratio. While this method is applicable to OFDM (Orthogonal Frequency Division Multiplexing) signals, it faces the challenge of requiring prior measurement of the received amplitude ratio between each pair of sinusoidal waves.

In response, we propose a method for estimating the Doppler shift magnitude of multicarrier acoustic signals composed of multiple sinusoidal waves, which is applicable even when the received amplitude ratios are unknown. The proposed method extracts the signal up to the arrival of the first multipath component and estimates the Doppler shift magnitude by identifying the concordance point between two sets of amplitude groups derived from the extracted received signal and two sets of reference signal groups. This approach eliminates the need for prior measurement of the received

Yuta Toyooka, Masanari Nakamura, and Masanori Sugimoto. Hokkaido University Sapporo, 060-0814, Japan, Email: {yutasapporo89, masanari, sugi}@ist.hokudai.ac.jp

Hiromichi Hashizume, National Institution for Academic Degrees and Quality Enhancement of Higher Education, Tokyo, 187-8587, Japan, Email: has@nii.ac.jp

amplitude ratios.

Furthermore, in the Doppler shift magnitude search process of the proposed method, the number of multiplication operations is reduced compared to methods that search through reference signals. Consequently, faster estimation is achieved.

The main contributions of this paper are as follows:

- We proposed a method for rapidly estimating the Doppler shift magnitude caused by receiver motion in multicarrier acoustic signals, while effectively mitigating the influence of multipath propagation.
- Through evaluation experiments conducted in a real-world environment, we confirmed that when a microphone is moved at velocities ranging from -2.0 to 2.0 m/s, the proposed method achieves a Doppler shift estimation precision with a standard deviation of less than 0.064 m/s at an SNR of 21.2 dB or higher.
- We discussed the relationship between the choice of reference frequencies and the estimation performance of the proposed method through simulations.

The structure of this paper is as follows. In section II, we present related studies on Doppler shift estimation methods using acoustic signals. In section III, we discuss the proposed Doppler shift estimation method based on searching for concordance points of complex amplitude groups. In section IV, we evaluate the performance of the proposed method in noisy environments through simulation experiments. In section V, we compare the proposed method with other Doppler shift estimation methods through evaluation experiments, demonstrating its performance. In section VI, we provide a discussion on the experimental results and the parameters of the proposed method, and we conclude the paper in section VII.

II. RELATED WORK

This section introduces Doppler shift estimation methods using acoustic signals. The proposed method is applicable to Doppler shift estimation for acoustic signals with multiple superimposed sine waves, such as OFDM. Therefore, in this paper, we review existing Doppler shift estimation methods using acoustic signals and categorize them into four types based on the transmitted signal: single-frequency signals, sequences with good/low cross-correlation properties (Kasami sequences), chirp signals, and OFDM. We then compare their characteristics and conditions of application.

First, we introduce Doppler shift estimation methods using a single-frequency signal as the transmitted signal. Kuang et al. [6], [7] proposed a method for estimating Doppler shift by utilizing the periodic displacement in continuous single-frequency signals. This method improved the ranging performance of moving objects through Doppler correction; however, it had the drawback of being sensitive to environmental noise such as multipath interference. To address this issue, Kuang et al. [8] combined STFT with a wavelet packet filter bank, resulting in a Doppler shift estimation method that reduces the impact of multipath interference. Next, we introduce methods that apply the FFT (Fast Fourier Transform) to the received signal and estimate the Doppler shift frequency as the frequency that shows the maximum amplitude in the

amplitude spectrum [9]–[11]. Widodo et al. [9] added a 36 kHz sine wave to a spread spectrum sound and used the frequency that exhibited a maximum value within the range of 35.84–36.16 kHz to estimate the position based on the Doppler shift frequency. Khyam et al. [10] selected a pilot carrier from an OFDM signal and estimated the Doppler shift by significantly amplifying its amplitude compared to other carriers. Aguilera et al. [11] added a single-frequency signal of the same frequency as the center frequency of the chirp signal to estimate the Doppler shift using the added single-frequency signal. Methods using a single-frequency signal are more susceptible to interference in multipath environments and have more limited ranging and communication performance compared to OFDM or chirp signals. Additionally, when adding a single-frequency signal to the target signal for Doppler shift estimation, it is necessary to consider the interference with the target signal, as well as the impact on energy distribution and SNR.

Concerning techniques that employ a Kasami sequence, Alvarez et al. [12] developed a multi-filter bank that can simultaneously compute the correlation coefficients of Kasami sequences for frequency-shifted candidate signals and performed position determination. In evaluation experiments, they confirmed that Doppler speed estimation could be achieved with a 90th-percentile value of 0.8 m/s when a robot rotated with angular velocities ranging from 0.5 to 3.5 rad/s.

Regarding methods using a chirp signal, McCarthy et al. [13]–[15] proposed a method that transmits periodic chirp signals and estimates the Doppler shift by utilizing changes in the arrival period of the received signal, performing ranging. In these methods, Doppler shift is calculated for each reception time, and as a result, the obtained speed corresponds to the average speed within the reception interval, making it challenging to accurately estimate the instantaneous speed. Misra et al. [16] utilized the change in the sweep rate of the chirp signal caused by the Doppler effect and proposed a Doppler shift estimation method using a matched filter-type correlator bank, where the sweep rate is used as a parameter. Evaluation experiments showed that the average speed error for Doppler velocities ranging from 1.1 to 5.0 m/s was less than 1.20 m/s. Ashhar et al. [17]–[19] proposed a method where up-chirp and down-chirp signals are alternately transmitted, and after estimating the reception times, the difference between the estimated reception times is used to calculate the Doppler shift. In evaluation experiments, the average absolute error for distance estimation without Doppler correction was 16.93 mm, while applying the proposed method reduced the average absolute error to 3.83 mm. Methods using chirp signals as the transmitted signal generally exhibit better characteristics in terms of PAPR (Peak to Average Power Ratio) compared to methods using OFDM, and they often provide superior Doppler shift estimation performance. However, OFDM offers efficient multiplexing and high data communication capacity, providing excellent advantages in communication performance. Therefore, Doppler shift estimation methods using signals with multiple superimposed sine waves, which can be applied to OFDM, are also often required in various scenarios.

Finally, we discuss methods using signals with multiple superimposed sine waves, such as OFDM. Sato et al. [5] proposed the Extended Phase Accordance Method, a Doppler shift estimation method that requires fewer computations. This method uses two known sinusoidal waves (frequencies of 39.75 kHz and 40.25 kHz) as the transmitted signal and assumes that their amplitude ratio upon reception is known. For the received signal, the inner product with a predefined reference signal is calculated to obtain the amplitude values. If the frequency of the Doppler-shifted received signal does not match the reference signal, the amplitude ratio will differ from the known ratio; however, the amplitude ratio when the reference signal frequency is adjusted can be theoretically predicted. Based on this prediction, the Doppler shift magnitude that matches the known amplitude ratio is determined, enabling estimation with reduced computational complexity compared to methods involving reference signal searches. Measurements in real-world environments reported that when the transmitter was moved at speeds of $-1.5 \text{ m/s} \sim 1.5 \text{ m/s}$ over a distance of $1.0 \text{ m} \sim 1.8 \text{ m}$, Doppler velocity estimation was achieved with a standard deviation of less than 25 mm/s .

Although the Extended Phase Accordance Method assumes a known amplitude ratio, this requires prior measurement. Therefore, this paper proposes an extended method that can be applied even when the amplitudes of individual sinusoidal waves are unknown. This enables fast Doppler shift estimation without the need for prior measurements.

III. PROPOSED METHOD

A. Overview

In this section, we propose a method for estimating the Doppler shift magnitude of multicarrier acoustic signals composed of multiple sinusoidal waves. The proposed method involves transmitting a multicarrier signal consisting of M single-frequency components ($M \geq 1$) from a single speaker and receiving it with a single moving microphone. We prepare $2M$ reference frequencies for the received signal and compute the inner product with the complex sinusoidal waves corresponding to these reference frequencies. This process yields two sets of received amplitudes for each carrier, and the Doppler shift magnitude is estimated by searching for the concordance point between these two sets of amplitudes. The proposed method eliminates the need for prior measurement of the transmitted amplitudes for each carrier and reduces the number of multiplications required during the search process compared to methods that explore reference signals as discussed in Section III-D.

B. Transmitted Signal and Received Signal

The transmitted signal $s(t)$ is a composite signal of length T , consisting of M superimposed single-frequency signals with distinct frequencies.

$$s(t) = \sum_{m=1}^M A_m \cos(2\pi f_m t) = \sum_{m=1}^M A_m \cos(\omega_m t) \quad (1)$$

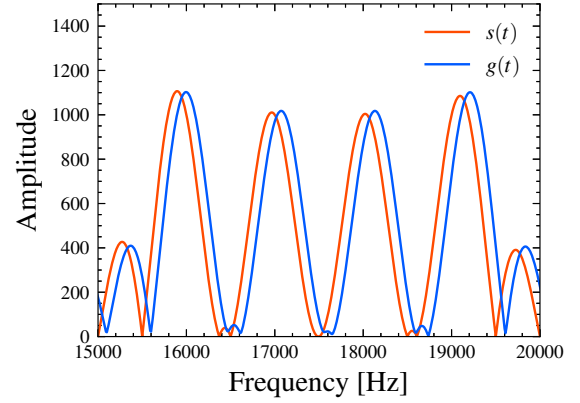


Fig. 1: Frequency spectra of the transmitted and received signals (Doppler speed: 2.0 m/s)

where A_m is the transmission amplitude of each sinusoidal wave, and f_m is the transmission frequency of each carrier. The received signal $g(t)$ can then be expressed as follows:

$$g(t) = \sum_{m=1}^M a_m \cos(\omega'_m t + \phi_m) + n(t) \quad (2)$$

where a_m is the received amplitude of each sinusoidal wave, ϕ_m is the phase at $t = 0$, and $n(t)$ is the noise. In the following, we ignore noise to simplify the explanation of the proposed method. ω'_m is the frequency-shifted version of ω_m , obtained from the following relationship:

$$\omega'_m = \frac{c - v_{mic}}{c} \omega_m \quad (3)$$

where c is the speed of sound, and v_{mic} is the radial speed of the microphone relative to the speaker. Figure 1 shows the frequency spectra of the transmitted signal $s(t)$ and the received signal $g(t)$ affected by the Doppler shift.

C. Doppler Shift Estimation Method

The analytic signal $g_a(t)$, obtained by applying the Hilbert transform to the received signal $g(t)$, is expressed as follows:

$$g_a(t) = \sum_{m=1}^M a_m \exp(j(\omega'_m t + \phi_m)) \quad (4)$$

where j is the imaginary unit. Next, we define arbitrary reference frequencies F_i ($1 \leq i \leq 2M$) and divide them into two groups: $F^{(A)} = [F_1, F_2, \dots, F_M]$ and $F^{(B)} = [F_{M+1}, F_{M+2}, \dots, F_{2M}]$. Using the Phase Accordance Method [20], we estimate the reception time and extract the analytic signal $g_a(t)$ using a rectangular window of length $T/2$ centered at the reception time. After sampling this signal with an ADC to obtain a discrete signal, the inner product with complex sinusoidal waves of arbitrary reference angular frequencies $\Omega_i (= 2\pi F_i)$ is computed, yielding the following output dp_i :

$$\begin{aligned}
dp_i &= \langle g_a(t[n]), \exp(j\Omega_i t[n]) \rangle \\
&= \frac{1}{N} \sum_{m=1}^M \sum_{n=0}^{N-1} a_m \exp(j(\omega'_m t[n] + \phi_m)) \exp(-j\Omega_i t[n]) \\
&= \sum_{m=1}^M \sum_{n=0}^{N-1} a_m \exp(j\phi_m) \frac{\exp(j(\omega'_m - \Omega_i)t[n])}{N} \\
&= \sum_{m=1}^M c_m d_{mi}
\end{aligned} \tag{5}$$

$$\begin{aligned}
c_m &= a_m \exp(j\phi_m) \\
d_{mi} &= \begin{cases} 1 & (\omega'_m = \Omega_i) \\ \frac{1 - \exp\left(\frac{j(\omega'_m - \Omega_i)N}{f_s}\right)}{N \left(1 - \exp\left(\frac{j(\omega'_m - \Omega_i)}{f_s}\right)\right)} & (\omega'_m \neq \Omega_i) \end{cases}
\end{aligned} \tag{6}$$

where f_s is the sampling frequency of the ADC, N is the number of samples in the received signal, and $t[n] = \frac{n}{f_s}$. By performing the calculations of Eq. (5) and Eq. (6) for all F_i and dividing the resulting dp_i values into $F^{(A)}$ and $F^{(B)}$, the results can be expressed in matrix form as follows:

$$\begin{aligned}
\begin{pmatrix} dp_1 \\ \vdots \\ dp_M \end{pmatrix} &= \begin{pmatrix} d_{11} & \cdots & d_{M1} \\ \vdots & \ddots & \vdots \\ d_{1M} & \cdots & d_{MM} \end{pmatrix} \begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix} \\
&= D_A \begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix}
\end{aligned} \tag{7}$$

$$\begin{aligned}
\begin{pmatrix} dp_{(M+1)} \\ \vdots \\ dp_{2M} \end{pmatrix} &= \begin{pmatrix} d_{1(M+1)} & \cdots & d_{M(M+1)} \\ \vdots & \ddots & \vdots \\ d_{1(2M)} & \cdots & d_{M(2M)} \end{pmatrix} \begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix} \\
&= D_B \begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix}
\end{aligned} \tag{8}$$

Eq. (7) and Eq. (8) are rearranged as follows:

$$\begin{aligned}
\begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix} &= D_A^{-1} \begin{pmatrix} dp_1 \\ \vdots \\ dp_M \end{pmatrix} \\
&= \mathbf{c}_A(v)
\end{aligned} \tag{9}$$

$$\begin{aligned}
\begin{pmatrix} c_1 \\ \vdots \\ c_M \end{pmatrix} &= D_B^{-1} \begin{pmatrix} dp_{(M+1)} \\ \vdots \\ dp_{2M} \end{pmatrix} \\
&= \mathbf{c}_B(v)
\end{aligned} \tag{10}$$

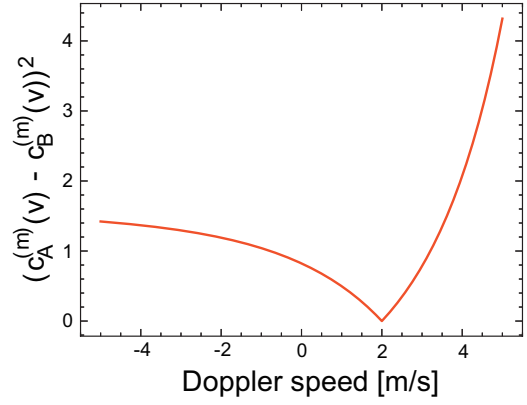


Fig. 2: Doppler shift magnitude (speed) estimation using complex amplitudes ($v = 2$ m/s, $M = 4$, $m = 1$)

At this point, the complex amplitudes $\mathbf{c}_A^{(m)}(v)$ and $\mathbf{c}_B^{(m)}(v)$ at each frequency f_m are physical quantities that depend only on the amplitude and phase of the transmitted signal and are inherently independent of the Doppler effect. Although they are computed using two different sets of reference frequencies ($F^{(A)}$ and $F^{(B)}$), they are both derived from the same received signal. Therefore, when the Doppler compensation is applied correctly at $v = v_{\text{mic}}$, the reconstructed complex amplitudes should coincide regardless of the choice of reference frequency groups. This principle allows us to estimate the true Doppler velocity v_{mic} by identifying the velocity at which $\mathbf{c}_A^{(m)}(v)$ and $\mathbf{c}_B^{(m)}(v)$ match (Fig. 2).

$$\mathbf{c}_A^{(m)}(v) = \mathbf{c}_B^{(m)}(v) \quad (v = v_{\text{mic}}) \tag{11}$$

Thus, the estimated Doppler speed $v_{\text{est}}^{(m)}$ at frequency f_m can be determined as follows:

$$v_{\text{est}}^{(m)} = \arg \min_v \left(\mathbf{c}_A^{(m)}(v) - \mathbf{c}_B^{(m)}(v) \right)^2 \tag{12}$$

In our method, we discretely search for the optimal v in the above equation within a predefined range using a grid search. Hereafter, the mean of these values is defined as the estimated Doppler speed v_{est} .

D. Comparison of Time Complexity with Reference Signal Search Methods

We describe the method of searching for reference signals based on maximum likelihood estimation (hereafter referred to as the MLE method), and compare its time complexity with that of the proposed method. When the noise of each sample is independent and follows a Gaussian distribution, the maximum likelihood estimator is given by:

$$\begin{aligned}
&\arg \min_v P(v) \\
P(v) &= ((I - BB^+)g_a(t))^2
\end{aligned} \tag{13}$$

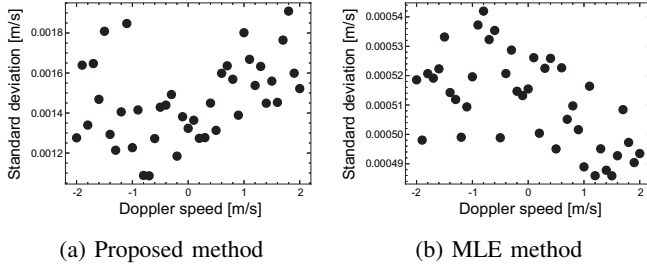


Fig. 3: Doppler speed estimation error simulation

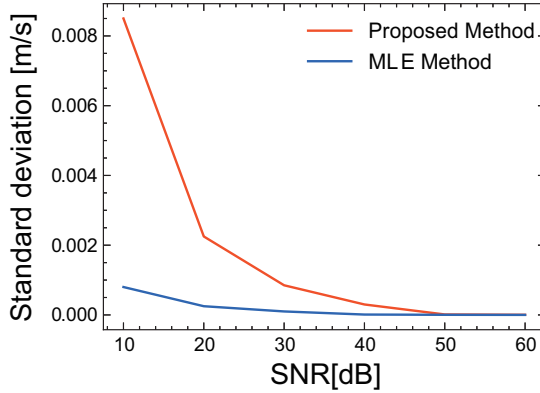


Fig. 4: Relationship between SNR and Doppler speed estimation precision

$$B = \begin{pmatrix} \exp(j(\omega'_1 t[0])) & \cdots & \exp(j(\omega'_M t[0])) \\ \vdots & \ddots & \vdots \\ \exp(j(\omega'_1 t[N-1])) & \cdots & \exp(j(\omega'_M t[N-1])) \end{pmatrix} \quad (14)$$

where B^+ is the Moore-Penrose pseudoinverse of B , defined as $(B^T B)^{-1} B^T$ (T is the conjugate transpose), and I is the $N \times N$ identity matrix. Expanding and simplifying Eq. (13), and using the relationship $(BB^+)^T (BB^+) = BB^+$, it follows that:

$$g_a(t)^T g_a(t) - g_a(t)^T (BB^+)^T (BB^+) g_a(t) \quad (15)$$

Therefore, the value of v that maximizes $g_a(t)^T (BB^+) g_a(t)$ should be determined. From the above, assuming that BB^+ is precomputed, the number of multiplication operations required per Doppler speed candidate is $N^2 + N$.

On the other hand, in the proposed method, assuming that D_A^{-1} and D_B^{-1} are precomputed, the number of multiplication operations required per Doppler speed candidate is $2M^2 + M$, as derived from Eq. (12). Therefore, the computational complexity can be reduced by a factor of $(2M^2 + M)/(N^2 + N)$. For example, in the subsequent experiments where $N = 96$ and $M = 4$, the computational complexity is reduced to approximately 0.004 times that of the MLE method.

IV. SIMULATION EXPERIMENT

TABLE I: Carrier frequencies and reference frequency groups

Carrier frequencies f_m [Hz]	16000, 17000, 18000, 19000
Reference frequency groups $F^{(A)}$ [Hz]	15500, 16500, 17500, 18500
Reference frequency groups $F^{(B)}$ [Hz]	16500, 17500, 18500, 19500

A. Overview

In this section, we conduct simulations to evaluate the performance of Doppler shift estimation and the time complexity of the methods, including the effect of noise. We set the sampling frequency to 96,000 Hz. Noise was added to the received signal to achieve a signal-to-noise ratio (SNR) of 40 dB. The Doppler speed was varied from -2 m/s to 2 m/s in increments of 0.1 m/s, assuming the movement speed of humans or robots. Additionally, in all simulations, the Doppler speed is divided into 1,000 points within the range of -3 to 3 m/s, and a grid search is performed. We then compared the performance of the proposed method with that of existing methods.

B. Doppler Shift Estimation Performance for 4-Carrier Setting

We evaluate the performance of the proposed method for the case of 4 carriers and compare it with the performance of the maximum likelihood estimation method. We set the number of carriers to $M = 4$, and configured the carrier frequencies and reference frequencies as shown in Table I. And 1,000 trials were conducted for each speed.

The standard deviation of Doppler speed estimation errors is shown in Fig. 3, and the standard deviation of errors when varying the SNR is shown in Fig. 4. From Fig. 3, the proposed method estimates velocities in the range of -2 to 2 m/s with a precision within ± 0.002 m/s. This indicates that the proposed method can achieve highly precise Doppler speed estimation. Furthermore, as shown in Fig. 4, while the proposed method exhibits a greater decline in estimation precision compared to MLE method as the SNR decreases, the standard deviation remains below 0.01 m/s at an SNR of 10 dB. This level of performance suggests that the proposed method remains practically effective even in relatively noisy environments, demonstrating its robustness for real-world applications.

C. Comparison of Time Complexity with MLE Method

We compare the time complexity of the proposed method with that of MLE method. We set the number of carriers to $M = 4$, and configured the carrier frequencies and reference frequencies as shown in Table I. We used an 11th Gen Intel® Core™ i9-11900K CPU with 94 GB RAM. Our operating system was Ubuntu 20.04, and we implemented the program in Python 3.8.10. For each true Doppler speed, the grid search is conducted 10 times, and the average processing time is calculated.

The average processing time for each true Doppler speed in each method is shown in Fig. 5. From Fig. 5, the proposed method significantly reduces computation time compared to the MLE method, consistently completing the grid search in

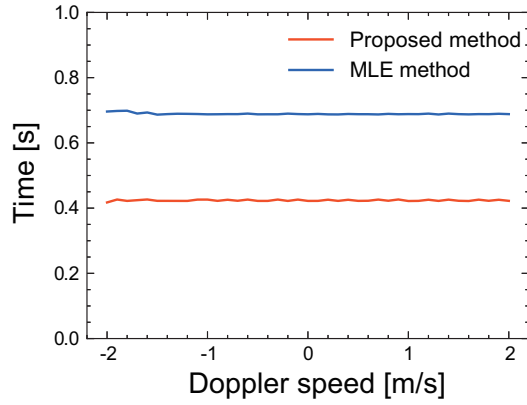


Fig. 5: Average processing time for each true Doppler speed

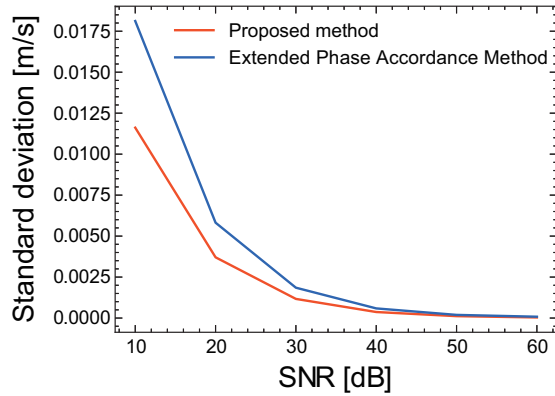


Fig. 6: The standard deviation of errors when varying the SNR

less than 60 % of the time required by MLE. These results demonstrate the high computational efficiency of the proposed method. Note that the term “Doppler Speed” in Fig. 5 refers to the radial component of the true relative speed (m/s) between the transmitter and receiver, which was used as a simulation parameter.

D. Comparison of Doppler Shift Estimation Performance with the Extended Phase Accordance Method

We compare the Doppler shift estimation performance of the proposed method with that of the extended phase Accordance method [5]. We set the number of carriers to $M = 2$, as the extended phase accordance method supports up to 2 carriers. We set the carrier frequencies to $(f_1, f_2) = (16000, 17000)$ [Hz], the reference frequencies of the proposed method to $F^{(A)} = (15500, 16500)$, $F^{(B)} = (16500, 17500)$ [Hz], and the reference frequencies of the extended phase accordance method to $(F_A, F_B) = (15500, 17500)$ [Hz]. We set the amplitude ratio of the two carriers to 1 : 1 for estimation, as the extended phase accordance method requires the amplitude ratio to be known. And 1,000 trials were conducted for each speed.

The standard deviation of errors when varying the SNR, assuming a received amplitude ratio of 1 : 1, is shown in Fig. 6. From Fig. 6, the proposed method consistently achieves lower standard deviation across all SNR levels compared

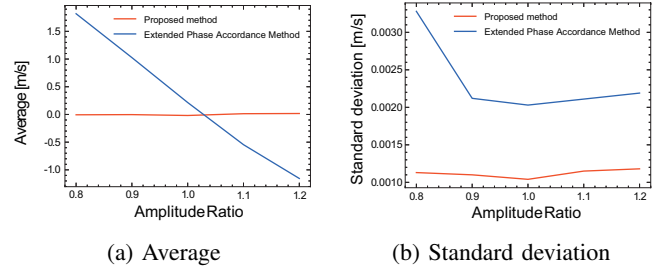


Fig. 7: The mean and standard deviation of errors when the received amplitude ratio is varied

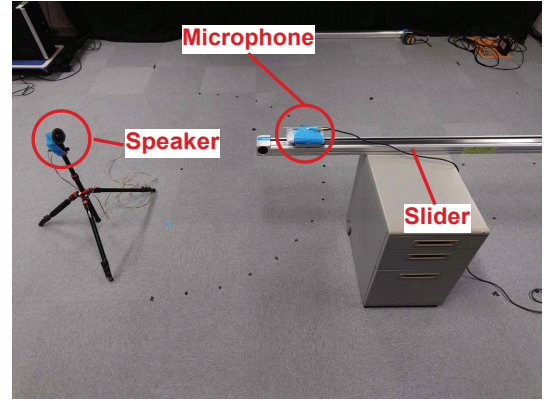


Fig. 8: Experimental environment

to the extended phase accordance method. In particular, for SNR values above 10 dB, the proposed method exhibits a significantly higher estimation accuracy, demonstrating its superior ability to suppress noise effects more effectively than the extended phase accordance method.

Next, the mean and standard deviation of errors when the SNR is fixed at 40 dB and the received amplitude ratio is varied from 1 : 0.8 to 1 : 1.2 is shown in Fig. 7. Doppler velocities were set from $-2 \sim 2$ m/s with a step size of 0.1 m/s, and 1000 measurements were performed at each Doppler velocity. From Fig. 7, the extended phase accordance method exhibits noticeable systematic errors that increase or decrease depending on the received amplitude ratio, indicating a strong dependency on signal amplitude imbalance. In contrast, the proposed method demonstrates stable performance, with both the mean and standard deviation of the errors remaining virtually unchanged across all amplitude ratios. This result explicitly confirms that the proposed method is highly robust to variations in received signal amplitude.

These results suggest that the proposed method achieves higher estimation accuracy compared to the extended phase accordance method and maintains stable performance regardless of variations in the received amplitude ratio of each carrier.

V. REAL-WORLD EXPERIMENT

A. Overview

In this section, we evaluate the performance of Doppler shift estimation for a moving microphone through experiments conducted in a real-world environment. The experimental setup included the following equipment: Fostex FT200D and

TABLE II: SNR for each speaker and Doppler speed

Doppler Speed v [m/s]	-2.0	-1.5	-1.0	-0.5	0	0.5	1.0	1.5	2.0
SNR(FT28D) [dB]	17.3	17.7	21.5	27.6	31.4	29.8	24.0	19.0	17.4
SNR(FT200D) [dB]	22.6	22.9	26.9	32.6	35.9	34.4	29.0	23.5	21.2

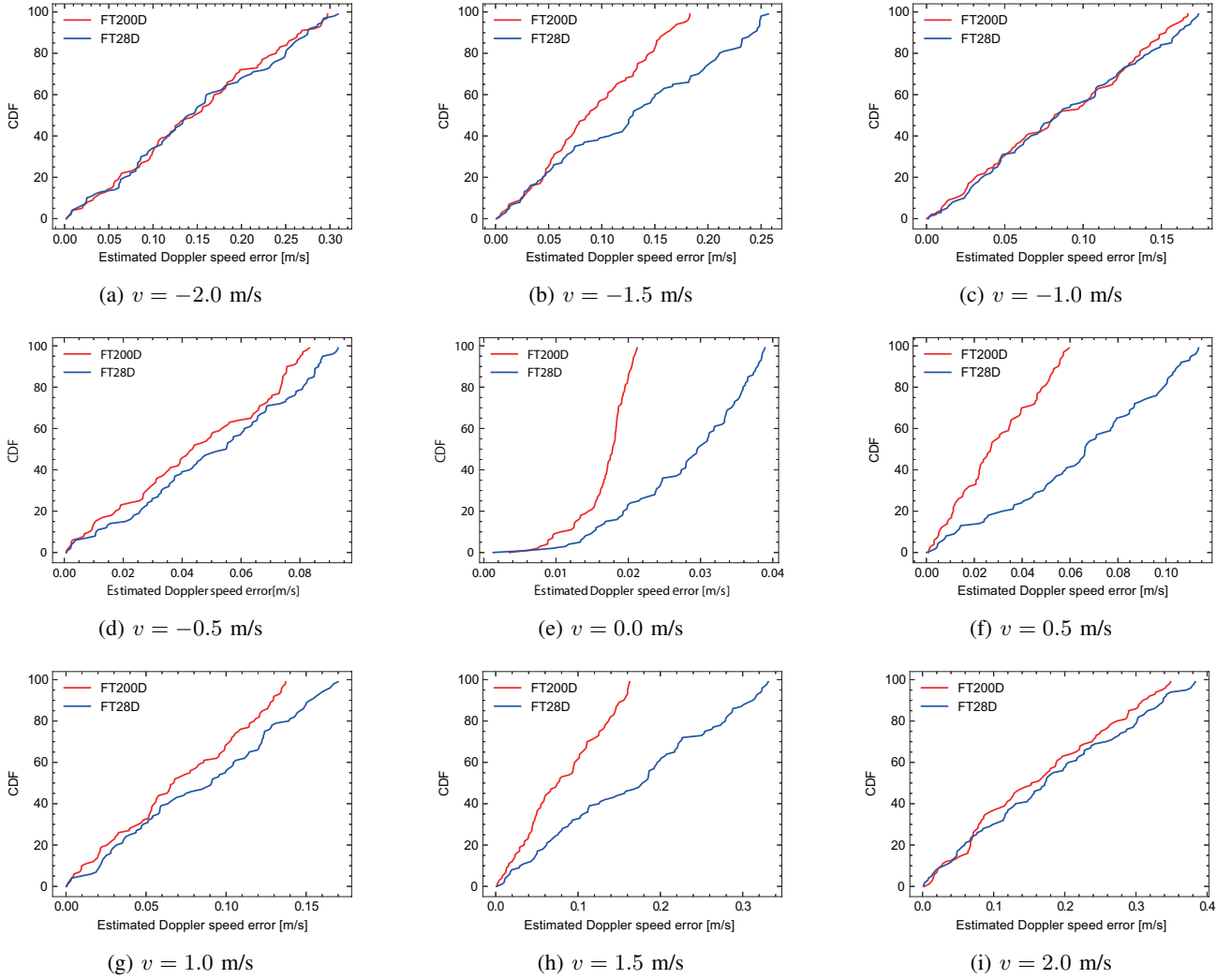


Fig. 9: Cumulative Distribution Function (CDF) of Doppler speed estimation errors for each microphone speed and speaker

FT28D as transmitting speakers, a Fostex AP20d as the speaker amplifier, a Rion UC-29 as the microphone, a Rion NH-05A as the preamplifier, a Rion UN-14 as the amplifier, and a ROLAND Rubix24 as the data logger. Additionally, an Oriental Motor AZM911AC as the motor for the electric slider controlling the microphone's motion, an Oriental Motor AZD-A as the driver for that and a Festo EGC-TB-KF as the belt-driven actuator for that. We set the sampling rate to 96,000 Hz.

The experimental room setup is shown in Fig. 8. The ceiling height was 2.5 m, the height of the speakers and microphone was 0.73 m, and the distance between the electric slider and the speakers was set to 1 m. The speakers were mounted on tripods and positioned to face directly toward the microphone.

The evaluation experiment involved varying the microphone's speed from -2 m/s to 2 m/s in increments of 0.5 m/s, with 100 Doppler speed estimations performed at each speed.

The measured SNR for each speed is shown in Table II. The SNR is defined as follows:

$$\text{SNR} = 10 \log_{10} \left(\frac{P_{\text{signal}} - P_{\text{noise}}}{P_{\text{noise}}} \right) \quad (16)$$

where P_{signal} is the power of the measured signal at $v = 0$, and P_{noise} is the power of the noise. It should be noted that the SNR differed for each speed, primarily due to variations in the driving noise of the electric slider.

We set the number of carriers to $M = 4$, and the carrier frequencies and reference frequencies were configured as shown in Table I, consistent with the simulation experiment.

B. Experimental Results

The cumulative distribution function (CDF) of Doppler speed estimation errors for each speed and speaker type

TABLE III: Mean Doppler speed estimation error for each Microphone speed and speaker

Doppler Speed v [m/s]	-2.0	-1.5	-1.0	-0.5	0	0.5	1.0	1.5	2.0
Average(FT28D)[dB]	-0.0290	-0.0050	0.0042	0.0099	0.0050	-0.0015	0.0214	-0.0191	0.0113
Average(FT200D)[dB]	-0.0213	0.0123	-0.0193	-0.0142	0.0017	0.0040	0.0113	-0.0173	-0.0302

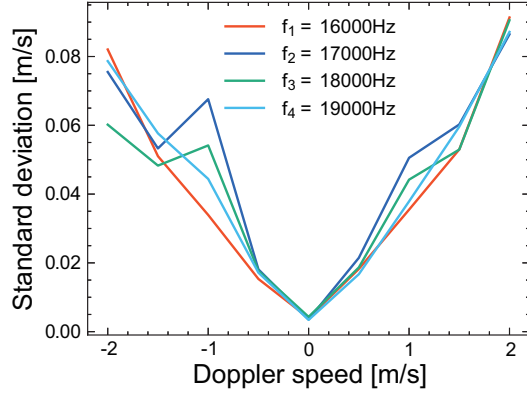


Fig. 10: Doppler speed estimation precision for each carrier

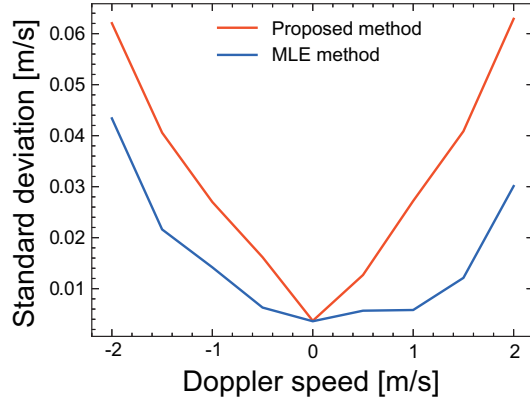
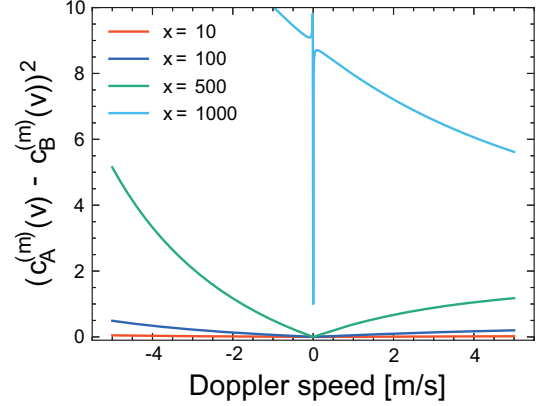
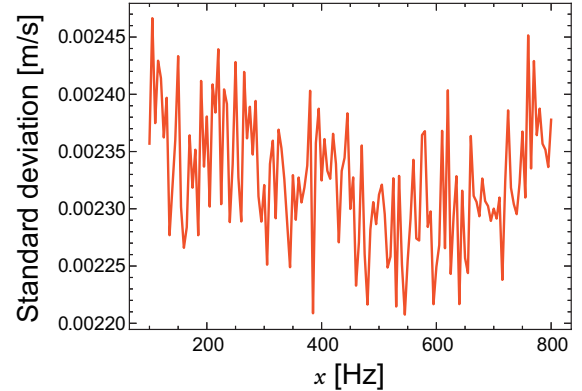


Fig. 11: Doppler speed estimation precision of the proposed method and MLE method

is shown in Fig. 9. Additionally, the mean Doppler speed estimation errors for each speed and speaker type are presented in Table III. For all microphone velocities, the Doppler speed estimation error is smaller when using the FT200D speaker compared to the FT28D speaker. This can be attributed to the higher SNR of the FT200D, as shown in Table II. Furthermore, the standard deviation for each carrier in the case of the FT200D speaker is shown in Fig. 10.

The standard deviations of the proposed method and MLE method for the FT200D speaker are shown in Fig. 11. The proposed method demonstrated the capability to estimate Doppler speed with a maximum standard deviation of 0.064 m/s in an environment where the minimum SNR was 21.2 dB. Additionally, as the microphone's speed decreases, the SNR improves, resulting in better estimation precision for MLE method compared to the proposed method, except at 0 m/s.

VI. DISCUSSION

Fig. 12: $c_A^{(m)}(v) - c_B^{(m)}(v)$ when $x = 10, 100, 500, 1000$ ($M = 4, m = 1$)Fig. 13: Doppler speed estimation precision for each value of x

A. Reference Frequencies

In the proposed method, the complex amplitude values are obtained using $2M$ reference frequencies, and the choice of reference frequencies may influence the estimation performance. Therefore, this section examines the combinations of reference frequencies for the case of $M = 4$ to enhance estimation precision.

In this paper, the reference frequencies are defined as shown in Eq. (17) and (18).

$$F_m^{(A)} = f_m - x \quad (17)$$

$$F_m^{(B)} = f_m + x \quad (18)$$

The influence of the value of x on estimation precision is investigated through simulation experiments. When $x \rightarrow$

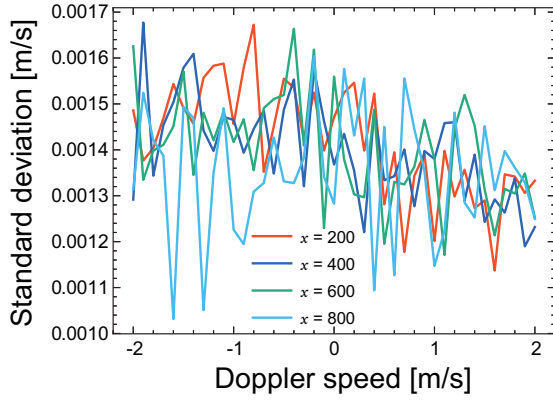


Fig. 14: Comparison of Doppler speed estimation precision for different values of x

0, as shown in Fig. 12, the value of $c_A^{(m)}(v) - c_B^{(m)}(v)$ decreases, it becomes more susceptible to the influence of noise when using the least squares method. Conversely, when $x \rightarrow 1000$, the carrier frequencies and reference frequencies become nearly orthogonal, which significantly degrades the estimation accuracy and leads to incorrect results (Fig. 12). Consequently, simulations were conducted for the interval $100 \leq x \leq 800$. The carrier frequencies were set to $f_m = [16000, 17000, 18000, 19000]$ Hz, and the Doppler speed was set to $v = 0$. Each value of x was tested over 1000 trials. The results are shown in Fig. 13. The standard deviation ranged between 0.0022~0.0025 m/s, confirming that there is no significant difference in estimation precision within the interval $100 \leq x \leq 800$ when $v = 0$. The apparent fluctuations in the estimation results stem from the nature of the numerical computations employed in this analysis. The y-axes in the figure represent standard deviations, all of which are sufficiently small, indicating statistical stability across the range of x . While theoretical derivation of these values would be ideal for deeper understanding, it remains a topic for future investigation.

Next, we verify whether there are differences in estimation precision when Doppler speed is present. Simulations were conducted for $x = 200, 400, 600, 800$ over a Doppler speed range of $-2 \sim 2$ m/s. The carrier frequencies were set to $f_m = [16000, 17000, 18000, 19000]$ Hz, and 1000 trials were performed for each x and Doppler speed. The results are shown in Fig. 14. No significant differences in estimation precision were observed due to the value of x . Similar to Fig. 13, the fluctuations observed in Fig. 14 are due to the numerical estimation process. The y-axes represent standard deviations and remain small throughout the tested range, confirming that the results are statistically consistent. A theoretical interpretation of these values is an important direction for future work. Therefore, even when the Doppler shift induces phase shifts in the carriers of the received signal within the Doppler speed range of $-2 \sim 2$ m/s, the value of x does not significantly affect estimation precision within the range of $200 \leq x \leq 800$. Based on these findings, this paper sets $x = 500$.

B. Differences in estimation performance among carriers

In this method, the estimated Doppler speed can be calculated for each carrier (Eq. (12)). While this paper used the average of the estimated values for all carriers as the estimated Doppler speed v_{est} , we examine whether there are differences in estimation performance among carriers. As shown in Fig. 10, there are no significant differences in estimation precision among the carriers, and no particular carrier stands out as superior. Therefore, under the current configuration, averaging the estimated values of all carriers to determine the estimated Doppler speed v_{est} is considered appropriate.

C. Systematic Errors

As shown in Table III, systematic errors were negligible in the present real-world experiments. While this study conducted experiments within a Doppler speed range of $-2 \sim 2$ m/s, a further increase in Doppler speed could lead to a decline in the precision of reception time estimation, potentially resulting in systematic errors. Additionally, the nonlinearity of the speakers and microphones could also serve as a contributing factor to systematic errors.

VII. CONCLUSION

In this paper, we proposed a method for estimating the Doppler shift magnitude of multicarrier acoustic signals composed of multiple sinusoidal waves. The proposed method eliminates the need for prior measurement of the transmission amplitudes and achieves lower computational complexity compared to MLE method. Evaluation experiments demonstrated that when the microphone was moved at velocities ranging from -2.0 to 2.0 m/s and the SNR exceeded 21.2 dB, the proposed method achieved Doppler shift estimation with a standard deviation of less than 0.064 m/s.

In this paper, the reference frequencies were defined as shown in Eq. (17) and (18); however, future work will involve exploring whether there are alternative, more effective definitions. Additionally, since the proposed method estimates complex amplitudes, further investigation is warranted to determine whether the estimated complex amplitudes can be utilized for communication or positioning purposes. Analytical evaluation of the impact of noise is also identified as an important topic for future work, as it is essential for enhancing the generality and applicability of the proposed method. Furthermore, we plan to investigate the application of the proposed Doppler speed estimation method to other modulation schemes [21]–[23].

ACKNOWLEDGMENTS

This research was supported by JSPS KAKENHI Grant Number JP21K17797.

REFERENCES

- [1] C. Peng, G. Shen, Y. Zhang, Y. Li, and K. Tan. Beepbeep: a high accuracy acoustic ranging system using cots mobile devices. In *Proceedings of the 5th International Conference on Embedded Networked Sensor Systems*, pages 1–14, 2007.

- [2] E. Novak, Z. Tang, and Q. Li. Ultrasound proximity networking on smart mobile devices for iot applications. *IEEE Internet of Things Journal*, 6(1):399–409, 2019.
- [3] X Cai, L Hu, W Xu, and L Wang. Design of an ofdm-based differential cyclic-shifted dcsk system for underwater acoustic communications. In *2021 26th IEEE Asia-Pacific Conference on Communications (APCC)*, pages 304–309, 2021.
- [4] X Cai, W Xu, L Wang, and G Kaddoum. Joint energy and correlation detection assisted non-coherent ofdm-dcsk system for underwater acoustic communications. *IEEE Transactions on Communications*, 70(6):3742–3759, 2022.
- [5] T. Sato, S. Nakamura, M. Sugimoto, and H. Hashizume. Extended phase accordance method: A real-time and accurate technique for estimating position and velocity of moving objects using ultrasonic communication. *Sensors & Transducers, suppl.Special Issue*, 9:56–70, 12 2010.
- [6] W.T. Kuang and A.S. Morris. Ultrasonic doppler distance measurement technique for robot tracking system. *Electronics Letters*, 35:942–943, 1999.
- [7] W.T. Kuang and A.S. Morris. Combined time-of-flight and doppler ultrasonic tracking system for better performance in robot tracking. *IEE Proceedings - Science, Measurement and Technology*, 147:213–218, 2000.
- [8] W.T. Kuang and A.S. Morris. Using short-time fourier transform and wavelet packet filter banks for improved frequency measurement in a doppler robot tracking system. *IEEE Transactions on Instrumentation and Measurement*, 51(3):440–444, 2002.
- [9] S. Widodo, T. Shiigi, N. Hayashi, H. Kikuchi, K. Yanagida, Y. Nakatsuchi, Y. Ogawa, and N. Kondo. Moving object localization using sound-based positioning system with doppler shift compensation. *Robotics*, 2(2):36–53, 2013.
- [10] M.O. Khyam, S.S. Ge, X. Li, and M. Pickering. Mobile ultrasonic transducer positioning. *The Journal of Engineering*, 2017(4):119–122, 2017.
- [11] T. Aguilera, F. J. Álvarez, J. A. Paredes, and J. A. Moreno. Doppler compensation algorithm for chirp-based acoustic local positioning systems. *Digital Signal Processing*, 100:102704, 2020.
- [12] F.J. Álvarez, Á. Hernández, J.A. Moreno, M.C. Pérez, J. Ureña, and C.D. Marziani. Doppler-tolerant receiver for an ultrasonic lps based on kasami sequences. *Sensors and Actuators A: Physical*, 189:238–253, 2013.
- [13] M. McCarthy and H. Muller. Positioning with independent ultrasonic beacons. *Sveučilište u Bristolu, Bristol*, 2005.
- [14] H. L. Muller, M. McCarthy, and C. Randell. Particle filters for position sensing with asynchronous ultrasonic beacons. In *Location- and Context-Awareness*, pages 1–13, Berlin, Heidelberg, 2006. Springer Berlin Heidelberg.
- [15] M. McCarthy, H.L. Muller, A. Calway, and R.E. Wilson. Position and velocity recovery from independent ultrasonic beacons. In *14th European Signal Processing Conference*, pages 1–5, 2006.
- [16] P. Misra, N. Kottege, B. Kusy, D. Ostry, and S. Jha. Acoustical ranging techniques in embedded wireless sensor networked devices. *ACM Transactions on Sensor Networks*, 10(1), 2013.
- [17] K. Ashhar, M. O. Khyam, C. B. Soh, and K. H. Kong. A doppler-tolerant ultrasonic multiple access localization system for human gait analysis. *Sensors*, 18(8), 2018.
- [18] K. Ashhar, Md. Noor-A-Rahim, M. O. Khyam, and C.B. Soh. A narrowband ultrasonic ranging method for multiple moving sensor nodes. *IEEE Sensors Journal*, 19(15):6289–6297, 2019.
- [19] K. Ashhar, M.O. Khyam, Md. Noor-A-Rahim, A. Jayasuriya, and C.B. Soh. Doppler correction in moving narrowband ultrasonic ranging sensors for small-scale motion tracking. *IEEE Sensors Letters*, 4(9):1–4, 2020.
- [20] M. Nakamura, T. Akiyama, M. Sugimoto, and H. Hashizume. 3d fdm-pam: rapid and precise indoor 3d localization using acoustic signal for smartphone. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication, UbiComp '14 Adjunct*, page 123–126, New York, NY, USA, 2014. Association for Computing Machinery.
- [21] X. Cai, C. Huang, P. Chen, E. Basar, and C. Yuen. Design of non-coherent ris-empowered dcsk with two-level nested index modulation. *IEEE Transactions on Wireless Communications*, 24(4):3044–3058, 2025.
- [22] X. Cai, C. Yuen, C. Huang, W. Xu, and L. Wang. Toward chaotic secure communications: An ris enabled m-ary differential chaos shift keying system with block interleaving. *IEEE Transactions on Communications*, 71(6):3541–3558, 2023.
- [23] X. Cai, D. Wang, W. Xu, L. Wang, and F. C. M. Lau. Design of carrier index keying-aided m-ary differential chaos cyclic shift keying for d2d communications. *IEEE Transactions on Communications*, 71(6):3233–3250, 2023.