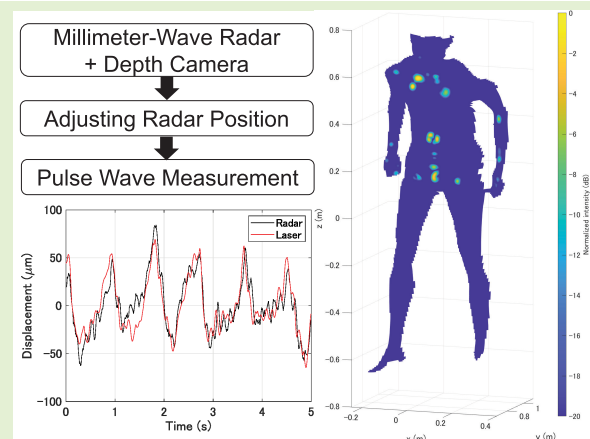


Radar-Based Pulse Wave Sensing at Multiple Sites Using a 3-D Human Model

Takehito Koshisaka and Takuya Sakamoto^{ib}, Senior Member, IEEE

Abstract—This study proposes a sensing method using a millimeter-wave array radar and a depth camera to measure pulse waves at multiple sites on the human body. Using a 3-D shape model of the target human body measured by the depth camera, the method identifies reflection sites on the body through electromagnetic scattering simulation. On the basis of the simulation, the radar system can be positioned at a suitable location for measuring pulse waves depending on the posture of the target person. Through measurements using radar and depth camera systems, we demonstrate that the proposed method can estimate the body displacement waveform caused by pulse waves accurately, improving the accuracy by 14% compared with a conventional approach without a depth camera. The proposed method can be a key to realizing an accurate and noncontact sensor for monitoring blood pressure.

Index Terms—Depth camera, electromagnetic scattering, millimeter-wave radar, pulse wave sensing.



I. INTRODUCTION

HYPERTENSION increases the risk of cardiovascular diseases [1], and the percentage of hypertensive patients age 30–79 years was 33.1% in 2019 [2]. Because regular blood pressure measurement is necessary to keep blood pressure within an appropriate range [3], it is necessary to have a sensing system for constant monitoring of blood pressure.

Blood pressure is related to pulse transit time, which is calculated from the arrival time of pulse waves measured at multiple sites on the human body [4]. This has been achieved mostly using contact sensors [5], [6], [7]. Research on noncontact pulse wave measurement has been conducted intensively to make the system unobtrusive and easy to set up;

the use of millimeter-wave radar systems has been reported for such purposes [8], [9], [10], [11], [12], [13], [14], [15]. For example, Oyamada et al. [15] measured the body displacement waveform at the back and thigh simultaneously using a 79-GHz frequency-modulated continuous-wave (FMCW) radar system, and the accuracy was evaluated through simultaneous measurements with laser displacement sensors. To apply this technique in practice, however, it is necessary to adjust the position of either the radar system or the target person and then record the echoes from multiple target sites on the body; the position adjustment process requires empirical intuition and knowledge because no systematic sensor-based approach has been established to date, and this represents the key technical challenge faced in this study. This technical challenge compromises the practicality of array-radar-based blood pressure sensing because the repeatability of such systems cannot be ensured when it depends on the operating personnel.

In this study, we propose a new approach for determining the position of the radar system depending on the target person's position and posture using electromagnetic scattering simulation to estimate the part of the body from which the reflected waves are received. This approach allows accurate pulse wave measurements to be acquired at multiple sites on the target human body, regardless of the target person's positioning and posture, and can thus resolve the key technical challenge discussed above. We reduce the computational complexity using a simplified approximation instead of full-wave electromagnetic simulation. Some studies on electromagnetic

Received 14 November 2024; revised 13 December 2024; accepted 15 December 2024. Date of publication 24 December 2024; date of current version 31 January 2025. This work was supported in part by Japan Science and Technology Agency (JST) under Grant JPMJCE1307, Grant JPMJMI22J2, and Grant JPMJMS2296; in part by the SECOM Science and Technology Foundation; and in part by Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant 19H02155, Grant 21H03427, Grant 23H01420, and Grant 23K26115. The associate editor coordinating the review of this article and approving it for publication was Dr. Yuyong Xiong. (Corresponding author: Takuya Sakamoto.)

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the Graduate School of Engineering, Kyoto University, under Application No. 201916.

The authors are with the Department of Electrical Engineering, Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan (e-mail: sakamoto.takuya.8n@kyoto-u.ac.jp).

Digital Object Identifier 10.1109/JSEN.2024.3519571

simulations with a human body are also based on the physical optics (PO) approximation because of its simplicity and practicality [17], [18], [19], [20], [21], [22]. Some studies use geometrically simplified human models [23], [24], while other studies use precise human models obtained from a 3-D laser scanner [25], [26], [27].

Konishi and Sakamoto [28] and Sakamoto et al. [29] reported electromagnetic wave scattering analysis with a human model obtained by a depth camera, assuming a radar frequency of 60 GHz, and visualized the reflection sites on the human body. Although the method proposed by Konishi et al. [28] enables estimation of reflection sites on the human body surface, the method has not been applied to pulse wave measurement. In this study, we propose a method to achieve accurate pulse wave measurement without prior adjustment of the participant's body posture by estimating the reflection sites on the target human body using electromagnetic wave scattering analysis to determine an appropriate radar position.

To obtain 3-D human body shape data, Vahidpour and Sarabandi [27] used a 3-D laser scanner to obtain a precise human model, which requires several cameras and a sufficiently large space. In this study, we use a depth camera to acquire a human model following the approach of Konishi and Sakamoto [28] and Sakamoto et al. [29]. Although some studies have used both a depth camera and a radar system [30], [31], they used the depth data only to estimate the position of the target person, whereas we consider the shape of the human body for radar measurement.

In this study, we propose a system to measure pulse waves at multiple locations with high accuracy by combining a depth camera and millimeter-wave radar. In Section II, we investigate the characteristics of millimeter-wave scattering from the human body surface by performing electromagnetic wave scattering analysis based on PO approximation using a precise human model. In Section III, we propose a measurement system that integrates a depth camera and a millimeter-wave radar system and evaluate its performance through experiments with two participants in the supine and prone positions. A preprint of this article has been posted online [34].

The main contributions of this work are summarized as follows.

- 1) A method to visualize the reflection points in radar-based human body measurements acquired using a depth camera is introduced.
- 2) Software to optimize radar positioning is developed based on visualization of the reflection points on the human body surface.
- 3) The ability to measure multiple parts of the human body simultaneously using a radar system through visualization of the surface reflections is demonstrated.

II. ELECTROMAGNETIC SCATTERING ANALYSIS AND ESTIMATION OF REFLECTION SITES

A. Electromagnetic Scattering Analysis With PO Approximation

PO approximation is used for electromagnetic wave scattering analysis. This approximation calculates the current

TABLE I
PARAMETERS OF THE DEPTH CAMERA

Resolution	1280 × 720
Frame rate	30 fps
Horizontal field of view	87° ± 3°
Vertical field of view	58° ± 1°
Diagonal field of view	95° ± 1°

distribution on the target surface caused by the incident magnetic field and the normal vector of the surface. If the target material is modeled as a perfect electric conductor, the current density $\mathbf{J}(\mathbf{r}')$ at position $\mathbf{r}'$ on the target surface is approximated as

$$\mathbf{J}(\mathbf{r}') = 2\hat{\mathbf{n}}(\mathbf{r}') \times \mathbf{H}^{\text{inc}}(\mathbf{r}') \quad (1)$$

where $\hat{\mathbf{n}}(\mathbf{r}')$ is a unit normal vector, and $\mathbf{H}^{\text{inc}}(\mathbf{r}')$ is an incident magnetic field.

Assuming that the polarization directions of the transmitting and receiving elements are both in the z -direction and the current density $\mathbf{J}(\mathbf{r}')$ at each position $\mathbf{r}'$ is approximated by an infinitesimal dipole, the z -component of the radiated electric field $E_z(\mathbf{r}; \mathbf{r}')$ at antenna position $\mathbf{r}$ is approximated as

$$E_z(\mathbf{r}; \mathbf{r}') = j \frac{k Z_0 \ell}{4\pi |\mathbf{r} - \mathbf{r}'|} \hat{\mathbf{z}} \cdot \mathbf{J}(\mathbf{r}') e^{-jk|\mathbf{r} - \mathbf{r}'|} \quad (2)$$

where $\hat{\mathbf{z}}$ is a unit z vector, j is an imaginary unit, ℓ is the length of the dipole, Z_0 is the impedance of free space, and k is the wavenumber. Here, we assume $|\mathbf{r} - \mathbf{r}'|$ is sufficiently large compared with the reflection area.

Shijo et al. [32] proposed a PO-based method for visualizing high-frequency diffraction using a weighting function, called the eye function, defined as

$$w(\mathbf{r}; \mathbf{r}') = \begin{cases} \frac{1}{2} \left\{ \cos \left(\frac{\pi |\mathbf{r} - \mathbf{r}'|}{a_0} \right) + 1 \right\}, & (|\mathbf{r} - \mathbf{r}'| \leq a_0) \\ 0, & (\text{otherwise}) \end{cases} \quad (3)$$

where a_0 is the radius of the eye function and should be sufficiently larger than the wavelength [32]. Using (3), we can approximate the intensity of the electric field received from the vicinity of the scattering point $\mathbf{r}'$ as

$$E_{\text{scat}}(\mathbf{r}') = \left| \iint_{\Omega} w(\mathbf{r}; \mathbf{r}') E_z(\mathbf{r}; \mathbf{r}') dS \right|^2 \quad (4)$$

where Ω is the entire target boundary surface.

In this work, we use an Intel RealSense D435 depth camera (Intel Corporation, Santa Clara, CA, USA); the camera's parameters are listed in Table I. Fig. 1 shows $E_{\text{scat}}(\mathbf{r}')$ for the human model in a supine position, where we set $a_0 = 5\lambda$ and λ is the wavelength. In the figure, we see that reflection occurs mainly at several spots around the chest and abdomen. In addition, each area contributing reflection is small compared with the size of the human body.

B. Simplified Method for Estimation of Reflection Spots

Because the calculation of E_{scat} using the PO approximation according to (4) contains a double integral over an area much larger than the wavelength, the computational cost

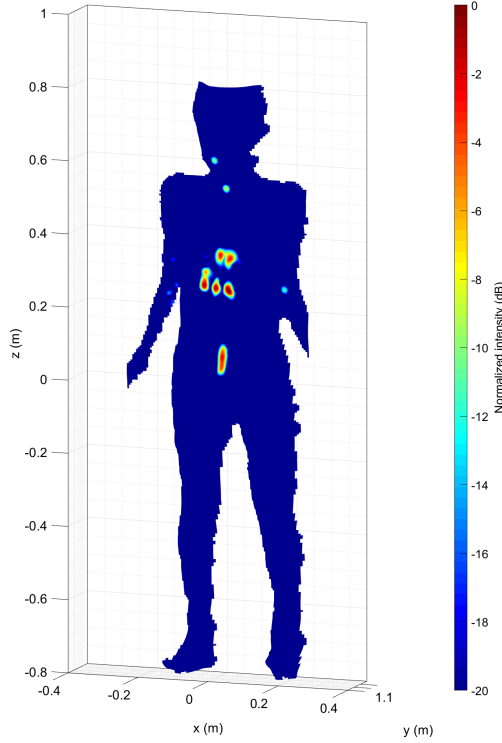


Fig. 1. Intensity of the reflected electric field distribution for a human model in a supine position calculated with PO for 79 GHz.

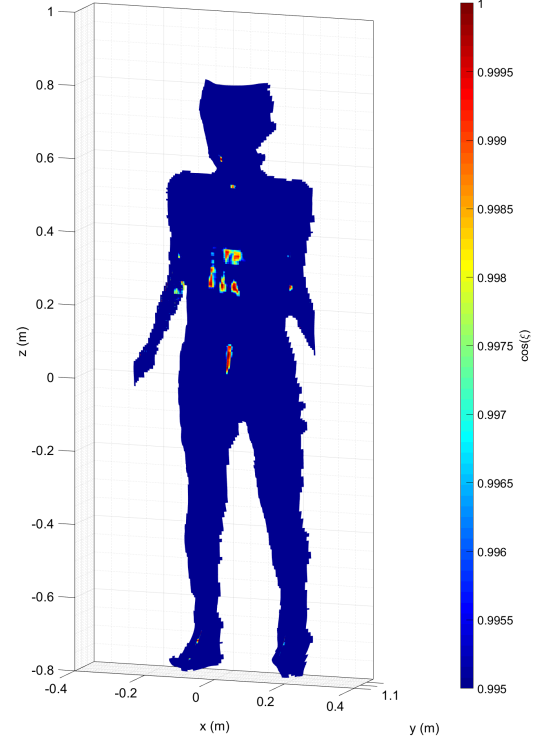


Fig. 2. Cosine of the angle between the radar line-of-sight vector and the normal vector.

can be unacceptably large in practice. To address this issue, we introduce an even simpler method as follows: Let $\mathbf{r}$ be a radar antenna position and $\mathbf{r}'$ be a position on the target surface. We define

$$\xi(\mathbf{r}; \mathbf{r}') = \cos^{-1} \left(\frac{\hat{\mathbf{n}}(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \right) \quad (5)$$

where ξ is the angle between the radar line-of-sight direction and the normal vector $\hat{\mathbf{n}}$. Note that ξ satisfies $0 \leq \xi \leq \pi$.

If a point located at $\mathbf{r}'$ on the target surface has a large $|\xi|$, the electric field scattered from the point is unlikely to contribute to the radar signal. Fig. 2 shows $\cos \xi$ for a human model in a supine position with the same condition as in Fig. 1. Comparing this with Fig. 1, we see that $\cos \xi$ is large close to the reflection area on the target surface, which indicates that $\cos \xi$ can be used approximately to estimate the reflection areas instead of PO approximation, and the computational cost in calculating ξ is much smaller than that of PO-based calculation.

III. PROPOSED MEASUREMENT SYSTEM AND PERFORMANCE EVALUATION

A. Experimental Setup

In this study, we propose a method to determine an appropriate location of the radar system to obtain echoes from target sites on the human body. The method assumes a system with a millimeter-wave radar and depth camera installed over a target person lying in a prone position on a bed.

Fig. 3 shows a diagram of the proposed measurement system with a coordinate system with the x -axis in the direction

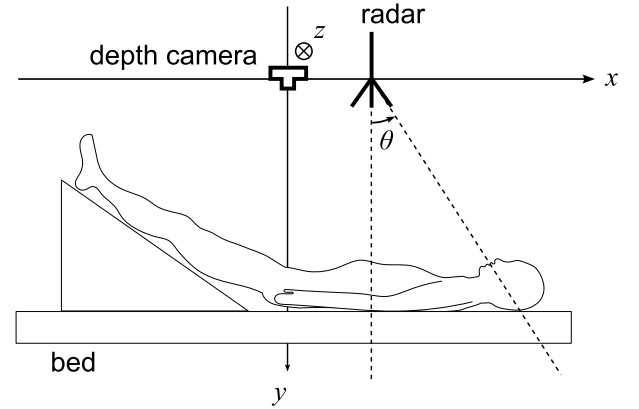


Fig. 3. Schematics of the proposed measurement system with a depth camera located at the origin and a radar system on the x -axis.

of the body axis and the y -axis vertical to the floor. The depth camera is fixed at the top of the bed and set as the origin of the coordinate system. The millimeter-wave radar can scan along the x -axis, where the x -axis is 1.1 m from the bed top.

The measurement procedure using the proposed method is as follows.

- 1) Obtain a human 3-D model using a depth camera.
- 2) Visualize the radiated power distribution using software developed based on (5).
- 3) Adjust the radar position manually such that the power radiated from the desired sites becomes greater than -20 dB of the maximum power radiated from the target person.

TABLE II
PARAMETERS OF THE MILLIMETER-WAVE RADAR

Type of radar	FMCW radar
Center frequency	79.0 GHz
Bandwidth	3.4 GHz
Number of transmit antennas	3
Number of receive antennas	4
Spacing of transmit antennas	7.6 mm (2λ)
Spacing of receive antennas	1.9 mm ($\lambda/2$)
Beamwidth in the E-planes	$\pm 4^\circ$
Beamwidth in the H-planes	$\pm 35^\circ$
Range resolution	44 mm
Sampling frequency (slow-time)	145.6 Hz

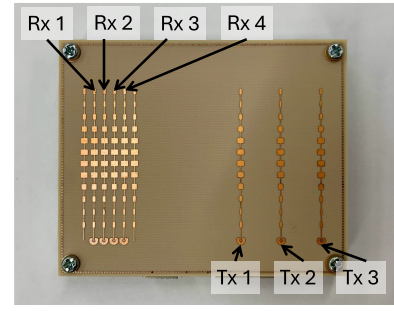
TABLE III
PARAMETERS OF THE LASER SENSOR

Measurement principle	triangulation
Wavelength of the light source	655 nm
Diameter of the spot size	120 μm
Repeatability	0.2 μm
Sampling frequency	200 Hz

- 4) Measure a body displacement waveform using the radar system.

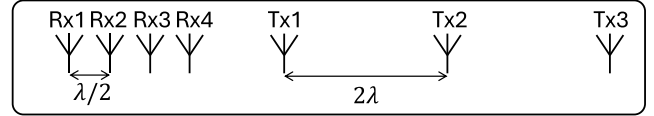
In this study, we used a radar module (T14_01120112_2D, S-Takaya Electronics Industry, Okayama, Japan) that comprises a single-chip millimeter-wave sensor (IWR1443, Texas Instruments Inc., Dallas, TX, USA). The parameters of the radar module are given in Table II. We used a multiple-input and multiple-output (MIMO) array radar. If the distance to a target from the radar antennas is sufficiently greater than the antenna aperture size, the array can be approximated as a virtual array with $M = M_T M_R = 12$ elements, where $M_T = 3$ and $M_R = 4$ are the numbers of transmitting and receiving elements, respectively.

Fig. 4(a) shows a photograph of the radar module used in this study, in which three transmitting elements (Tx) and four receiving elements (Rx) are shown in addition to two dummy elements, and these elements form an MIMO antenna array. Fig. 4(b) shows a schematic of the configuration of the MIMO array elements and the corresponding virtual array composed of 12 elements, where adjacent elements are spaced half a wavelength apart. Fig. 5 shows the array factor of the 12-element virtual array with the half-wavelength spacings, where the angular resolution in the H -plane is approximately $\pm 4.3^\circ$. Because each element comprises 12 rectangular patches that are aligned linearly in the E -plane direction, as shown in Fig. 4(a), the beamwidths for each element's radiation pattern in the E - and H -planes are $\pm 4^\circ$ and $\pm 35^\circ$, respectively, as shown in Table III. Therefore, when using array beamforming, the MIMO array antenna beamwidths in the E - and H -planes become approximately 8° and 8.5° with resulting beam spot sizes of 0.15 and 0.16 m in the E - and H -planes, respectively, at a distance of 1.1 m; the beam spot size is small enough to enable separation of echoes from multiple sites, e.g., the chest and thigh. We used laser displacement sensors (CDX-150, OPTEX FA Company Ltd., Kyoto, Japan) as a reference for body displacement measurement. The parameters of the laser displacement sensors are shown in Table III.

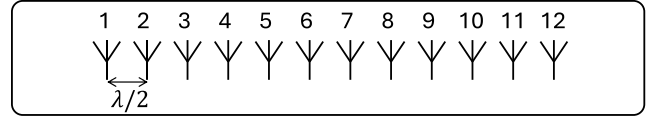


(a)

Multiple-Input and Multiple-Output Array



Virtual Array



(b)

Fig. 4. (a) Photograph of an MIMO antenna array of the T14_01120112_2D radar module and (b) schematics of the MIMO array and the corresponding virtual array.

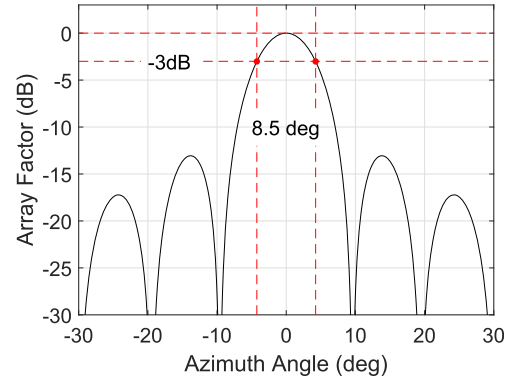


Fig. 5. H -plane array factor of the 12-element virtual array with half-wavelength spacing, which is displayed with a beamwidth of 8.5° .

In this study, we developed software that displays an image of the human body with $\cos \xi$ and indicates the intensity of the reflected electric field. With this software, the reflection sites on the body can be confirmed immediately when the radar position changes. The software runs on MATLAB as shown in Fig. 6, in which the image corresponds to $\cos \xi(\mathbf{r})$ calculated using the simplified method in Section II-B. The x -coordinate of the radar position can be changed with the slider at the bottom of the screen. The radar position is expected to be optimized automatically if an appropriate objective function is defined. Despite this, the implementation of the optimization process is outside the scope of this study and will be an important topic to study in the future. In this study, we selected the radar position manually using this software.

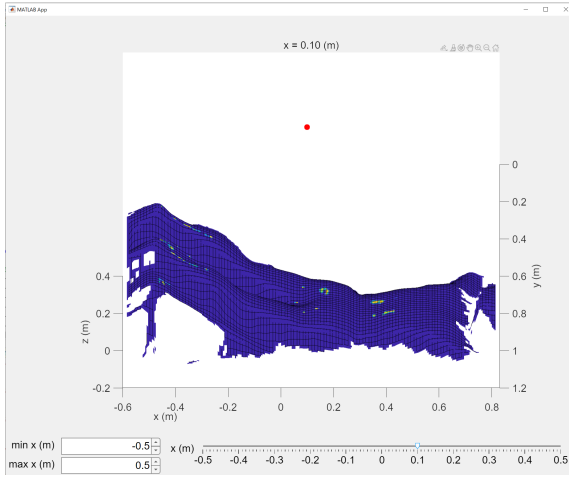


Fig. 6. Software for visualizing $\cos\xi$ that indicates the intensity of the reflected electric field, where the red dot represents the position of a radar. Its x-coordinate can be changed with the slider.

B. Array Radar Measurement of Pulse Waves

We propose a method for measuring a displacement waveform at multiple sites on the human body using a millimeter-wave radar system. Let us assume N reflection points on the target human body, and let θ_n be the direction of arrival of the n th echo with the corresponding displacement $d_n(t)$ for $n = 1, 2, \dots, N$. The n th echo is phase-modulated by the body motion as $s_n(t) \propto e^{j2kd_n(t)}$. For simplicity, we assume $s_n(t) = e^{j2kd_n(t)}$ hereafter.

For a radar system with a virtual array comprising M elements with an element spacing of $\lambda/2$, the signal received from the m th element $x_m(r, t)$ ($m = 1, 2, \dots, M$) is expressed as a function of range $r = c\tau/2$ and slow time t , where τ is a fast time. The received signal x_m is then modeled as

$$x_m(r, t) = \sum_{n=1}^N a_{m,n}(r) s_n(t) \quad (6)$$

where $a_{m,n}(r)$ is a complex constant corresponding to the propagation path between the n th target and the m th antenna element. Then, we define signal vector $\mathbf{x}(r, t) = [x_1(r, t), \dots, x_M(r, t)]^T$, which is used to estimate the n th echo $x_n(r, t)$ as $\hat{x}_n(r, t) = \mathbf{w}_n^H \mathbf{x}(r, t)$ using an appropriate weight vector $\mathbf{w}_n = [w_{1,n}, \dots, w_{M,n}]^T$ for the n th echo, where superscripted T and H represent a transpose operator and a complex-conjugate transpose operator, respectively. By selecting range r_n for the n th echo, we can estimate the displacement $d_n(t)$ as $\hat{d}_n(t) = (1/2k) \angle \hat{x}_n(r_n, t)$.

To determine weight vector $\mathbf{w}$, we use a minimum variance distortionless response (MVDR) method, which is also called directionally constrained minimization of power (DCMP) [33]. Let $\mathbf{a}(\theta)$ be a steering vector for direction of arrival θ expressed as $\mathbf{a}(\theta) = [a_1(\theta), \dots, a_M(\theta)]^T$, where $a_m(\theta) = e^{jm\pi \sin \theta}$ for an array with antenna spacing $\lambda/2$.

The MVDR (DCMP) weight vector is determined by

$$\mathbf{w}(\theta) = (\mathbf{a}^H(\theta) R_{xx}^{-1} \mathbf{a}(\theta))^{-1} R_{xx}^{-1} \mathbf{a}(\theta) \quad (7)$$

where R_{xx} is a correlation matrix of $\mathbf{x}$ formulated as $R_{xx} = E[\mathbf{x}(r_n, t) \mathbf{x}^H(r_n, t)] \simeq (1/T) \int_0^T \mathbf{x}(r_n, t) \mathbf{x}^H(r_n, t) dt$ with the measurement time length T .

For example, when measuring the displacements at two sites $(r, \theta) = (r_1, \theta_1)$ and (r_2, θ_2) on the target body, we used the MVDR weight vectors $\mathbf{w}(\theta_1)$ and $\mathbf{w}(\theta_2)$ to estimate the displacements $\hat{d}_1(t) = (1/2k) \angle \{\mathbf{w}^H(\theta_1) \mathbf{x}(r_1, t)\}$ and $\hat{d}_2(t) = (1/2k) \angle \{\mathbf{w}^H(\theta_2) \mathbf{x}(r_2, t)\}$.

C. Experimental Evaluation of the Proposed Method

We performed experiments using a depth camera, a millimeter-wave radar system, and a pair of laser displacement sensors with two participants lying on a bed in supine and prone positions. The measurement was performed six times for each participant. For three out of the six times, the position of the radar system was adjusted using the proposed method (case A), and for the other three times, the position was not adjusted (case B). The radar position in case B was shifted by 0.3 m from the position in case A. The target sites on the body were selected to be the chest and the front of the thigh when the participants were in supine positions and were selected to be the back and the back of the thigh when the participants were in prone positions. The radar and laser measurements were performed simultaneously for 30 s while the participants were holding their breaths to prevent respiratory effects.

The accuracy of the proposed method is evaluated in terms of the correlation coefficient ρ_n of the estimated and reference displacement waveforms $\hat{d}_n(t)$ and $d_n(t)$ defined as

$$\rho_n = \frac{1}{\hat{D}_n D_n} \int_0^T \hat{d}_n(t) d_n(t) dt \quad (8)$$

where $\hat{D}_n^2 = \int_0^T \hat{d}_n^2(t) dt$ and $D_n^2 = \int_0^T d_n^2(t) dt$ assuming $\int_0^T \hat{d}_n(t) dt = \int_0^T d_n(t) dt = 0$ for $T = 5.0$ s.

We also evaluate the root-mean-square (rms) error ε_n between $\hat{d}_n(t)$ and $d_n(t)$ defined as

$$\varepsilon_n^2 = \frac{1}{T} \int_0^T |\hat{d}_n(t) - \alpha d_n(t)|^2 dt \quad (9)$$

where α is adjusted properly to compensate for the inclination of the laser displacement sensors. The range r_n for the measurement and definition of slow time $t = 0$ are also adjusted to compensate for the imperfect synchronization of the radar and laser data.

Figs. 7 and 8 show the estimated displacements when the radar position was adjusted using the proposed method for participant A in supine and prone positions, respectively. Here, the black and red lines represent the estimated and reference displacements, respectively. Figs. 9 and 10 show the estimated displacements when the radar position was shifted by 0.3 m from the case in Figs. 7 and 8.

First, Table IV summarizes ρ_n and ε_n for six measurements of participant A in a supine position, where $i = 1$ and 2 correspond to the chest and front of the thigh, respectively. The average correlation coefficients were 0.66 and 0.85 for the conventional and proposed methods, respectively. The average rms errors were 26.3 and 30.5 μm for the conventional and

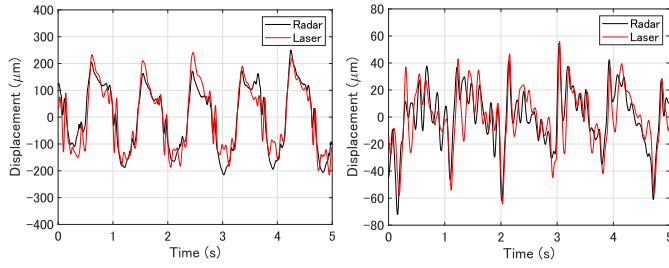


Fig. 7. Estimated and reference waveforms of the chest (left) and thigh (right) measured with a radar (black line) and a laser sensor (red line) for participant A in a supine position when the radar position is optimized.

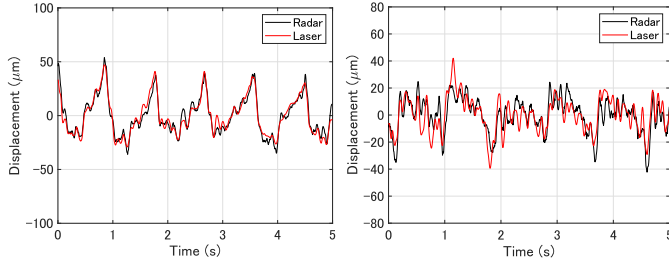


Fig. 8. Estimated and reference waveforms of the back (left) and thigh (right) measured with a radar (black line) and a laser sensor (red line) for participant A in a prone position when the radar position is optimized.

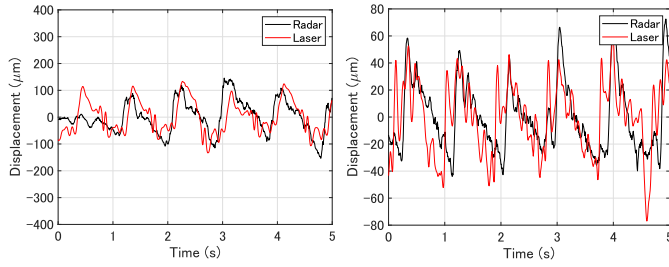


Fig. 9. Estimated and reference waveforms of the chest (left) and thigh (right) measured with a radar (black line) and a laser sensor (red line) for participant A in a supine position when the radar position is not optimized.

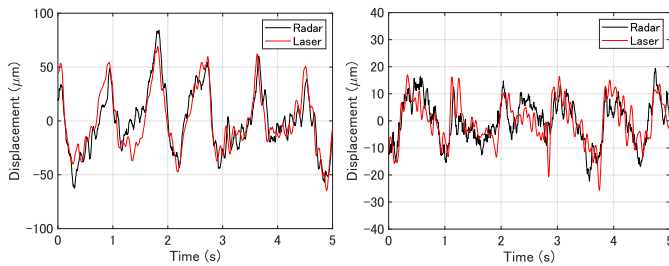


Fig. 10. Estimated and reference waveforms of the back (left) and thigh (right) measured with a radar (black line) and a laser sensor (red line) for participant A in a prone position when the radar position is not optimized.

proposed methods, respectively. Although the rms error of the proposed method was 16% larger than that of the conventional method, the correlation coefficient of the proposed method was improved by 19% compared with that of the conventional method.

Next, Table V summarizes the results for participant B in a supine position. The average correlation coefficients were 0.56 and 0.87 for the conventional and proposed methods,

TABLE IV

PERFORMANCE EVALUATION OF THE PROPOSED METHOD FOR PARTICIPANT A IN A SUPINE POSITION

Method	ρ_1	ρ_2	ε_1 (μm)	ε_2 (μm)
Conventional	0.58	0.57	56.0	24.5
	0.82	0.69	16.9	20.1
	0.51	0.80	21.4	18.8
Proposed	0.93	0.79	46.8	14.0
	0.82	0.71	77.3	16.3
	0.91	0.93	21.9	6.9

TABLE V

PERFORMANCE EVALUATION OF THE PROPOSED METHOD FOR PARTICIPANT B IN A SUPINE POSITION

Method	r_1	r_2	e_1 (μm)	e_2 (μm)
Conventional	0.74	0.42	51.3	23.7
	0.63	0.44	76.1	83.4
	0.61	0.54	54.9	24.2
Proposed	0.87	0.85	38.9	9.2
	0.97	0.80	16.1	13.9
	0.91	0.82	25.5	8.4

TABLE VI

PERFORMANCE EVALUATION OF THE PROPOSED METHOD FOR PARTICIPANT A IN A PRONE POSITION

Method	ρ_1	ρ_2	ε_1 (μm)	ε_2 (μm)
Conventional	0.88	0.70	14.2	6.2
	0.87	0.70	22.6	14.1
	0.88	0.63	13.8	14.7
Proposed	0.96	0.76	4.9	8.9
	0.97	0.80	4.1	8.8
	0.93	0.86	4.3	6.1

TABLE VII

PERFORMANCE EVALUATION OF THE PROPOSED METHOD FOR PARTICIPANT B IN A PRONE POSITION

Method	ρ_1	ρ_2	ε_1 (μm)	ε_2 (μm)
Conventional	0.94	0.52	11.9	10.0
	0.88	0.80	30.1	12.9
	0.93	0.67	8.8	17.8
Proposed	0.97	0.91	7.0	6.1
	0.96	0.87	7.2	10.7
	0.44	0.36	69.1	17.2

respectively. The average rms errors were 52.3 and 18.6 μm for the conventional and proposed methods, respectively. The proposed method improved the correlation coefficient and rms error by factors of 1.6 and 2.8, respectively.

Then, Table VI summarizes the results for participant A in a prone position. The average correlation coefficients were 0.78 and 0.88 for the conventional and proposed methods, respectively. The average rms errors were 14.2 and 6.2 μm for the conventional and proposed methods, respectively. The proposed method improved the correlation coefficient and rms error by factors of 1.1 and 2.3, respectively.

Finally, Table VII summarizes the results for participant B in a prone position. The average correlation coefficients were 0.79 and 0.75 for the conventional and proposed methods, respectively. The average rms errors were 15.3 and 19.5 μm for the conventional and proposed methods, respectively. In this case, the rms error of the proposed method was worse than that of the conventional method by a factor of 1.3, whereas the correlation coefficient was improved by a

factor of 1.1 using the proposed method. In this case, the estimation accuracy was degraded with the proposed method, partly owing to the significantly low accuracy in one of the six measurement datasets. If we exclude the last measurement, the average correlation coefficient and rms error for the proposed method were 0.93 and 7.8 μm , respectively.

IV. CONCLUSION

In this study, we proposed a radar sensing system and method for measuring heart pulse waves at multiple sites on the human body using a depth camera and electromagnetic wave scattering analysis. First, we verified that the PO-based electromagnetic scattering simulation could be replaced with a simplified method that uses the angle between the radar line-of-sight direction and the normal vector when applied to the 3-D human body model. Next, we developed software to visualize the radiated power distribution on the human body surface when using the simplified method. Then, we proposed a procedure in which the radar position was adjusted manually to ensure that strong echoes were received from the desired sites on the target person's body. Finally, the MVDR method was applied to separate the echoes as they arrived from the desired sites on the body. In the experiments, we selected two body positions (supine and prone), and then set the desired sites to be the chest and thigh in the supine position, and the back and thigh in the prone position.

To evaluate the performance of the proposed method, we conducted measurements involving two participants in supine and prone positions using both the proposed and conventional methods. The performances of the methods were evaluated in terms of the correlation coefficient and rms error in estimating displacement waveforms using reference data taken with laser displacement sensors. The key technical challenge involved in array-radar-based sensing of pulse waves at multiple sites on the human body is that the radar position cannot be determined in a systematic manner; our proposed method overcomes this challenge by providing a procedure based on a combination of use of the depth camera and visualization of the radiated power distribution that does not require either empirical intuition or knowledge.

Compared with the conventional method, the proposed method improved the estimation accuracy of the body displacement at two positions by 14% and 19% on average with respect to the correlation coefficient and rms error, respectively. These results indicate that the proposed method can achieve accurate measurement of pulse waves at multiple sites. Although the proposed method enables accurate measurement of pulse waves at multiple desired sites on the target person's body, the radar position was determined manually based on the developed software; therefore, there is still some room for improvement by making the entire process automatic and removing any requirement for manual operation. It will be important to study and develop a method for automatic optimization of the radar position using the proposed approach.

REFERENCES

- [1] R. S. Vasan et al., "Impact of high-normal blood pressure on the risk of cardiovascular disease," *New England J. Med.*, vol. 345, no. 18, pp. 1291–1297, Nov. 2001.
- [2] World Health Organization. *World Health Statistics 2023: Monitoring Health for the SDGs, Sustainable Development Goals*. Accessed: May 8, 2024. [Online]. Available: <https://www.who.int/data/gho/publications/world-health-statistics>
- [3] K. B. Bryant et al., "Impact of self-monitoring of blood pressure on processes of hypertension care and long-term blood pressure control," *J. Am. Heart Assoc.*, vol. 9, no. 15, Jul. 2020, Art. no. e016174, doi: [10.1161/JAHA.120.016174](https://doi.org/10.1161/JAHA.120.016174).
- [4] R. Mukkamala et al., "Toward ubiquitous blood pressure monitoring via pulse transit time: Theory and practice," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 8, pp. 1879–1901, Aug. 2015, doi: [10.1109/TBME.2015.2441951](https://doi.org/10.1109/TBME.2015.2441951).
- [5] P. C.-P. Chao, C.-C. Wu, D. H. Nguyen, B.-S. Nguyen, P.-C. Huang, and V.-H. Le, "The machine learnings leading the cuffless PPG blood pressure sensors into the next stage," *IEEE Sensors J.*, vol. 21, no. 11, pp. 12498–12510, Jun. 2021, doi: [10.1109/JSEN.2021.3073850](https://doi.org/10.1109/JSEN.2021.3073850).
- [6] X. He, R. A. Goubran, and X. P. Liu, "Secondary peak detection of PPG signal for continuous cuffless arterial blood pressure measurement," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 6, pp. 1431–1439, Jun. 2014, doi: [10.1109/TIM.2014.2299524](https://doi.org/10.1109/TIM.2014.2299524).
- [7] M. S. Roy, R. Gupta, and K. D. Sharma, "BePCon: A photoplethysmography-based quality-aware continuous beat-to-beat blood pressure measurement technique using deep learning," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–9, 2022, doi: [10.1109/TIM.2022.3212750](https://doi.org/10.1109/TIM.2022.3212750).
- [8] F. Michler et al., "A radar-based vital sign sensing system for in-bed monitoring in clinical applications," in *Proc. German Microw. Conf. (GeMiC)*, Cottbus, Germany, Mar. 2020, pp. 188–191.
- [9] D. Buxi, J. Redouté, and M. R. Yüce, "Blood pressure estimation using pulse transit time from bioimpedance and continuous wave radar," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 4, pp. 917–927, Apr. 2017, doi: [10.1109/TBME.2016.2582472](https://doi.org/10.1109/TBME.2016.2582472).
- [10] M. Pour Ebrahim et al., "Blood pressure estimation using on-body continuous wave radar and photoplethysmogram in various posture and exercise conditions," *Sci. Rep.*, vol. 9, no. 1, Nov. 2019, Art. no. 16346, doi: [10.1038/s41598-019-52710-8](https://doi.org/10.1038/s41598-019-52710-8).
- [11] H. Zhao, X. Gu, H. Hong, Y. Li, X. Zhu, and C. Li, "Non-contact beat-to-beat blood pressure measurement using continuous wave Doppler radar," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Philadelphia, PA, USA, Jun. 2018, pp. 1413–1415.
- [12] J. E. Johnson, O. Shay, C. Kim, and C. Liao, "Wearable millimeter-wave device for contactless measurement of arterial pulses," *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 6, pp. 1525–1534, Dec. 2019, doi: [10.1109/TBCAS.2019.2948581](https://doi.org/10.1109/TBCAS.2019.2948581).
- [13] L. Lu, C. Li, and D. Y. C. Lie, "Experimental demonstration of noncontact pulse wave velocity monitoring using multiple Doppler radar sensors," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol.*, Buenos Aires, Argentina, Aug. 2010, pp. 5010–5013.
- [14] F. Michler et al., "Pulse wave velocity detection using a 24 GHz six-port based Doppler radar," in *Proc. IEEE Radio Wireless Symp. (RWS)*, Orlando, FL, USA, Jan. 2019, pp. 1–3.
- [15] Y. Oyamada, T. Koshisaka, and T. Sakamoto, "Experimental demonstration of accurate noncontact measurement of arterial pulse wave displacements using 79-GHz array radar," *IEEE Sensors J.*, vol. 21, no. 7, pp. 9128–9137, Apr. 2021, doi: [10.1109/JSEN.2021.3052602](https://doi.org/10.1109/JSEN.2021.3052602).
- [16] Y. Oyamada et al., "Laser-based noncontact blood pressure estimation using human body displacement waveforms," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Denver, CO, USA, Jun. 2022, pp. 1020–1022.
- [17] E. R. Ranjbar and M. Dehmollaian, "Scattering of an object with impedance surfaces using IPO and MLFMM," in *Proc. 22nd Iranian Conf. Electr. Eng. (ICEE)*, Tehran, Iran, May 2014, pp. 1610–1613.
- [18] E. Rashidi-Ranjbar and M. Dehmollaian, "Target above random rough surface scattering using a parallelized IPO accelerated by MLFMM," *IEEE Geosci. Remote Sens. Lett.*, vol. 12, no. 7, pp. 1481–1485, Jul. 2015, doi: [10.1109/LGRS.2015.2409555](https://doi.org/10.1109/LGRS.2015.2409555).
- [19] A. Mazzinghi, L. Facheris, F. Cuccoli, and A. Freni, "2.5D physical optics based algorithm for vehicles classification through a FM-CW radar," in *Proc. 15th Eur. Radar Conf. (EuRAD)*, Madrid, Spain, Sep. 2018, pp. 257–260.
- [20] W. Zhang, H. Gomez-Sousa, J. Heredia-Jueas, and J. A. Martinez-Lorenzo, "Single-frequency imaging and material characterization using reconfigurable reflectarrays," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 7, pp. 3360–3371, Jul. 2021, doi: [10.1109/TMTT.2021.3061597](https://doi.org/10.1109/TMTT.2021.3061597).
- [21] M. Arias et al., "A physical optics simulator for dielectric bodies characterization using a multistatic radar," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Mtg.*, Atlanta, GA, USA, vol. 25, Jul. 2019, pp. 819–820.

- [22] L. Corucci, E. Giusti, M. Martorella, and F. Berizzi, "Near field physical optics modelling for concealed weapon detection," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 6052–6057, Dec. 2012, doi: [10.1109/TAP.2012.2210017](https://doi.org/10.1109/TAP.2012.2210017).
- [23] G. Manfredi, J.-P. Ovarlez, and L. Thirion-Lefevre, "Features extraction of the Doppler frequency signature of a human walking at 1 GHz," in *Proc. IEEE Int. Geosci. Remote Sens. Symp.*, Yokohama, Japan, Jul. 2019, pp. 2260–2263.
- [24] N. Keerativoranan, P. Hanpinitak, K. Saito, and J.-I. Takada, "Analysis of non-intrusive hand trajectory tracking by utilizing micro-Doppler signature obtained from Wi-Fi channel state information," *IEEE Access*, vol. 8, pp. 176430–176444, 2020, doi: [10.1109/ACCESS.2020.3026743](https://doi.org/10.1109/ACCESS.2020.3026743).
- [25] L. Perez-Eijo et al., "A physical optics simulator for multireflector THz imaging systems," *IEEE Trans. Terahertz Sci. Technol.*, vol. 9, no. 5, pp. 476–483, Sep. 2019, doi: [10.1109/TTHZ.2019.2930918](https://doi.org/10.1109/TTHZ.2019.2930918).
- [26] F. Mokhtari-Koushyar and A. A. Shishegar, "Scattering analysis of human body modeled by NURBS surfaces in MM-wave band," in *Proc. 3rd Conf. Millimeter-Wave Terahertz Technol. (MMWATT)*, Tehran, Iran, Dec. 2014, pp. 1–4.
- [27] M. Vahidpour and K. Sarabandi, "Millimeter-wave Doppler spectrum and polarimetric response of walking bodies," *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 7, pp. 2866–2879, Jul. 2012, doi: [10.1109/TGRS.2011.2176342](https://doi.org/10.1109/TGRS.2011.2176342).
- [28] K. Konishi and T. Sakamoto, "Automatic tracking of human body using millimeter-wave adaptive array radar for noncontact heart rate measurement," in *Proc. Asia-Pacific Microw. Conf. (APMC)*, Kyoto, Japan, Nov. 2018, pp. 836–838.
- [29] T. Sakamoto, K. Konishi, K. Yamashita, M. Muragaki, S. Okumura, and T. Sato, "Adaptive array radar imaging of a human body for vital sign measurement," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Boston, MA, USA, Jul. 2018, pp. 617–618.
- [30] A. Shokouhmand, S. Eckstrom, B. Gholami, and N. Tavassolian, "Camera-augmented non-contact vital sign monitoring in real time," *IEEE Sensors J.*, vol. 22, no. 12, pp. 11965–11978, Jun. 2022, doi: [10.1109/JSEN.2022.3172559](https://doi.org/10.1109/JSEN.2022.3172559).
- [31] I. V. Mikhelson, P. Lee, S. Bakhtiari, T. W. Elmer, A. K. Katsaggelos, and A. V. Sahakian, "Noncontact millimeter-wave real-time detection and tracking of heart rate on an ambulatory subject," *IEEE Trans. Inf. Technol. Biomed.*, vol. 16, no. 5, pp. 927–934, Sep. 2012, doi: [10.1109/TITB.2012.2204760](https://doi.org/10.1109/TITB.2012.2204760).
- [32] T. Shijo, T. Itoh, and M. Ando, "Visualization of high frequency diffraction based on physical optics," *IEICE Trans. Electron.*, vol. 87, no. 9, pp. 1607–1614, Sep. 2004.
- [33] K. Takao, M. Fujita, and T. Nishi, "An adaptive antenna array under directional constraint," *IEEE Trans. Antennas Propag.*, vol. AP-24, no. 5, pp. 662–669, Sep. 1976, doi: [10.1109/TAP.1976.1141411](https://doi.org/10.1109/TAP.1976.1141411).
- [34] T. Koshisaka and T. Sakamoto, "Radar positioning for accurate sensing of pulse waves at multiple sites using a 3D human model," 2024, *arXiv:2405.10540*.



Takehito Koshisaka received the B.E. degree in electrical and electronic engineering from Kyoto University, Kyoto, Japan, in 2021, and the M.E. degree in electrical engineering from the Graduate School of Engineering, Kyoto University, in 2023.



Takuya Sakamoto (Senior Member, IEEE) received the B.E. degree in electrical and electronic engineering from Kyoto University, Kyoto, Japan, in 2000, and the M.I. and Ph.D. degrees in communications and computer engineering from the Graduate School of Informatics, Kyoto University, in 2002 and 2005, respectively.

From 2006 to 2015, he was an Assistant Professor at the Graduate School of Informatics, Kyoto University. From 2011 to 2013, he was also a Visiting Researcher at Delft University of Technology, Delft, The Netherlands. From 2015 to 2019, he was an Associate Professor at the Graduate School of Engineering, University of Hyogo, Himeji, Japan. In 2017, he was also a Visiting Scholar at the University of Hawaii at Manoa, Honolulu, HI, USA. From 2019 to 2022, he was an Associate Professor at the Graduate School of Engineering, Kyoto University. From 2018 to 2022, he was also a PRESTO Researcher of the Japan Science and Technology Agency, Japan. Since 2022, he has been a Professor at the Graduate School of Engineering, Kyoto University. His current research interests lie in wireless human sensing, radar signal processing, and radar measurement of physiological signals.

Prof. Sakamoto was a recipient of the Best Paper Award from the International Symposium on Antennas and Propagation (ISAP) in 2004; the Young Researcher's Award from the Information and Communication Engineers of Japan (IEICE) in 2007; the Best Presentation Award from the Institute of Electrical Engineers of Japan in 2007; the Best Paper Award from the ISAP in 2012; the Achievement Award from the IEICE Communications Society in 2015, 2018, and 2023; the Achievement Award from the IEICE Electronics Society in 2019; the Masao Horiba Award in 2016; the Best Presentation Award from the IEICE Technical Committee on Electronics Simulation Technology in 2022; the Telecom System Technology Award from the Telecommunications Advancement Foundation in 2022; and the Best Paper Award from the IEICE Communication Society in 2007 and 2023.