

Geometry-Based Reliability Mapping for Device Placement Analysis in Multi-Link Wi-Fi CSI Gait Quantification

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Abstract—Wi-Fi channel state information (CSI)-based gait sensing provides a device-free approach for indoor walking velocity estimation, but sensing reliability depends strongly on link geometry and walking direction. This study proposes a geometry-based reliability mapping method for device placement analysis in multi-link Wi-Fi CSI gait sensing. The proposed map identifies low-reliability regions by considering walking heading, local Fresnel ellipse direction, and bistatic path-length sensitivity. The method was used to search for a second transmitter position in a 5.6×5.6 m experimental area with a fixed TX_1 – RX link, resulting in a selected TX_2 position of $[5.60, 1.73]$ m. Preliminary CSI validation using $+45^\circ$ and -45° walking paths showed that the path with greater predicted low-reliability overlap produced higher single-link velocity mean absolute percentage error (MAPE). In contrast, merged multi-link velocity estimation substantially reduced MAPE across all validation trials. These results suggest that geometry-based reliability mapping may provide a useful pre-collection reference for device placement, weak-path prediction, and multi-link gait sensing analysis.

Index Terms—Wi-Fi CSI, gait sensing, velocity estimation, device placement, reliability map, multi-link sensing.

I. INTRODUCTION

Quantitative gait analysis is important for evaluating human mobility, functional decline, fall risk, and neurological health conditions. Long-term gait monitoring can provide information that may not be captured by single clinical measurements. However, conventional gait assessment methods, including wearable sensors, cameras, and motion-capture systems, are often limited by user discomfort, privacy concerns, restricted field of view, or high deployment cost.

Wi-Fi channel state information (CSI) provides a promising device-free approach for indoor gait monitoring [1], [2], [4], [5]. Human walking perturbs the propagation paths between transmitters (TX s) and receivers (RX s), enabling the estimation of clinically relevant gait parameters, including walking velocity.

Wi-Fi-based velocity estimation commonly relies on Doppler shift or bistatic path-length variation. The Doppler response depends on the relative geometry among the TX , RX , target, and walking heading. When walking approaches the tangent direction of the Fresnel ellipse, the Doppler response

weakens and velocity accuracy may degrade [3]. Although existing studies mainly improve post-collection signal processing, transmitter placement before data collection remains less explored.

For at-home gait monitoring, walking paths and headings are not always fixed, and Wi-Fi devices may be placed differently depending on the room layout. A single Wi-Fi link (TX_i – RX) may therefore contain geometry-dependent low-reliability sensing regions. To reduce these heading-dependent blind spots, multi-link CSI sensing can be used to improve spatial coverage.

To improve CSI-based walking velocity estimation before data collection, this study proposes a geometry-based reliability map that identifies low-reliability regions according to walking heading, local Fresnel ellipse direction, and bistatic path-length sensitivity. The map is used to select a second transmitter position that minimizes the overlap of low-reliability regions. The selected placement is preliminarily validated by comparing predicted path-level reliability with real CSI velocity MAPE and by evaluating multi-link velocity fusion.

II. METHOD

The proposed framework first uses geometry-based reliability mapping to select the transmitter placement and then processes the collected CSI to estimate walking velocity.

A. Geometry-Based Reliability Mapping Device Placement Analysis

The reliability map provides a pre-collection estimate of regions with weak walking-induced Doppler response under different headings, allowing candidate device placements to be compared under practical deployment constraints.

The bistatic propagation path length is defined as

$$d_i(\mathbf{P}) = \|\mathbf{P} - \mathbf{P}_{TX_i}\| + \|\mathbf{P} - \mathbf{P}_{RX}\|. \quad (1)$$

where $\mathbf{P}_{TX_i}$ and $\mathbf{P}_{RX}$ denote the device coordinates of the i -th TX and RX , respectively. The vector $\mathbf{P} = [x, y]^T$ denotes the target position.

Since Doppler frequency depends on the rate of change of the bistatic path length, the local sensing geometry is represented by a constant-path-length ellipse passing through $\mathbf{P}$, with the TX and RX as its foci. Here, the Fresnel ellipse characterizes bistatic Doppler sensitivity rather than diffraction. Its center is

$$\mathbf{o}_i = \frac{\mathbf{P}_{TX_i} + \mathbf{P}_{RX}}{2}. \quad (2)$$

The semi-major axis is calculated as

$$a_i(\mathbf{P}) = \frac{\|\mathbf{P} - \mathbf{P}_{TX_i}\| + \|\mathbf{P} - \mathbf{P}_{RX}\|}{2}, \quad (3)$$

and the focal distance is

$$c_i = \frac{\|\mathbf{P}_{TX_i} - \mathbf{P}_{RX}\|}{2}. \quad (4)$$

The semi-minor axis is then obtained by

$$b_i^2(\mathbf{P}) = a_i^2(\mathbf{P}) - c_i^2. \quad (5)$$

Following the normal direction calculation used in the implementation, the local normal direction of the Fresnel ellipse is estimated by

$$m_i(\mathbf{P}) = \tan^{-1} \left(\frac{a_i^2(\mathbf{P})(y - o_{i,y})}{b_i^2(\mathbf{P})(x - o_{i,x})} \right), \quad (6)$$

where $\mathbf{o}_i = [o_{i,x}, o_{i,y}]^T$.

For a walking heading angle θ , the angle difference used for reliability classification is defined as

$$\Delta_i(\mathbf{P}, \theta) = -\theta - m_i(\mathbf{P}), \quad (7)$$

where θ is the walking heading angle defined with respect to the LOS direction of Link 1, which corresponds to the $TX_1 - RX$ link. The case $\theta = 0^\circ$ represents walking parallel to the Link 1 LOS direction, while $\theta = 90^\circ$ represents walking perpendicular to this LOS direction.

When the walking direction is close to the tangential direction of the Fresnel ellipse, the bistatic path-length variation becomes weak and the Doppler response approaches zero [3]. Therefore, the tangent-direction low-reliability indicator is defined as

$$\mathcal{U}_{i,\tan}(\mathbf{P}, \theta) = \begin{cases} 1, & 60^\circ < |\Delta_i(\mathbf{P}, \theta)| < 120^\circ, \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

In addition, the LoS-related low-reliability condition is evaluated using the bistatic path-length sensitivity. The gradient of the bistatic path length is given by

$$\nabla d_i(\mathbf{P}) = \frac{\mathbf{P} - \mathbf{P}_{TX_i}}{\|\mathbf{P} - \mathbf{P}_{TX_i}\|} + \frac{\mathbf{P} - \mathbf{P}_{RX}}{\|\mathbf{P} - \mathbf{P}_{RX}\|}. \quad (9)$$

The magnitude of this gradient is defined as

$$r_i(\mathbf{P}) = \|\nabla d_i(\mathbf{P})\|. \quad (10)$$

A smaller $r_i(\mathbf{P})$ means that the bistatic path length is less sensitive to target movement at location $\mathbf{P}$. Thus, the LoS-related low-reliability indicator is defined as

$$\mathcal{U}_{i,\text{LoS}}(\mathbf{P}) = \begin{cases} 1, & r_i(\mathbf{P}) < \tau_r, \\ 0, & r_i(\mathbf{P}) \geq \tau_r, \end{cases} \quad (11)$$

where τ_r is the LoS-related sensitivity threshold. In this implementation, τ_r is empirically set to 0.3.

The final low-reliability indicator of the i -th link is obtained by combining the tangent-direction and LoS-related conditions:

$$\mathcal{U}_i(\mathbf{P}, \theta) = \mathcal{U}_{i,\tan}(\mathbf{P}, \theta) \vee \mathcal{U}_{i,\text{LoS}}(\mathbf{P}). \quad (12)$$

If $\mathcal{U}_i(\mathbf{P}, \theta) = 1$, the grid point is classified as a low-reliability sensing region for the i -th link.

For the two-link system, the combined low-reliability sensing region is defined as the region where both links are simultaneously unreliable:

$$\mathcal{U}_{\text{combined}}(\mathbf{P}, \theta) = \mathcal{U}_1(\mathbf{P}, \theta) \cdot \mathcal{U}_2(\mathbf{P}, \theta). \quad (13)$$

For each walking direction, the combined low-reliability percentage is then calculated as

$$\eta_{\text{combined}}(\theta) = \frac{\sum_{\mathbf{P} \in \Omega} \mathcal{U}_{\text{combined}}(\mathbf{P}, \theta)}{|\Omega|} \times 100\%, \quad (14)$$

where Ω is the monitored area and $|\Omega|$ is the total number of grid points. A lower $\eta_{\text{combined}}(\theta)$ indicates that fewer grid points are classified as unreliable by both links under the same walking direction.

The tested walking directions are defined as

$$\Theta = \{0^\circ, \pm 15^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ, \pm 75^\circ, 90^\circ\}. \quad (15)$$

The candidate search space of the TX_2 is defined as a circular region around the RX :

$$\mathcal{S} = \left\{ \mathbf{P}_{RX} + R_s \begin{bmatrix} \cos \phi \\ \sin \phi \end{bmatrix} \middle| \phi \in [0, 2\pi) \right\}, \quad (16)$$

where R_s is the search radius. In this study, R_s is 2 m, and ϕ is sampled every 2° .

For each candidate coordinate $\mathbf{P}_{TX_2} \in \mathcal{S}$, the objective function is defined as

$$J(\mathbf{P}_{TX_2}) = \frac{1}{|\Theta|} \sum_{\theta \in \Theta} \eta_{\text{combined}}(\theta). \quad (17)$$

Finally, the optimal TX_2 coordinate is obtained by

$$\mathbf{P}_{TX_2}^* = \arg \min_{\mathbf{P}_{TX_2} \in \mathcal{S}} J(\mathbf{P}_{TX_2}). \quad (18)$$

This optimization selects the TX placement that minimizes the region where both sensing links have weak Doppler sensitivity. As a result, the second link can compensate for the low-reliability sensing regions of the first link, improving the robustness of multi-link Wi-Fi CSI gait sensing.

B. CSI-Based Gait Quantification

The overall CSI processing pipeline is shown in Fig. 1. The system consists of one RX and two TX s. CSI packets are separated by TX MAC address, and each link is processed as an independent link.

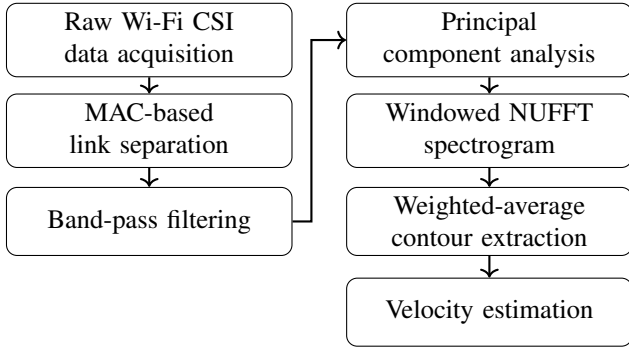


Fig. 1: Flowchart of CSI-based gait quantification using MAC-based link separation and NUFFT-based time-frequency analysis.

For each packet, the complex CSI of the n -th subcarrier at timestamp t is expressed as

$$H(t, n) = A(t, n)e^{j\phi(t, n)}, \quad (19)$$

where $A(t, n)$ and $\phi(t, n)$ are the CSI amplitude and phase, respectively. This work uses CSI amplitude because it is more robust to random phase offsets and contains walking-induced variations.

The CSI amplitude is filtered and processed by Principal Component Analysis (PCA) to obtain a motion-sensitive signal $z(t)$. Since AX210 packet timestamps may be non-uniform due to packet loss and timestamp jitter, a windowed Nonuniform Fast Fourier Transform (NUFFT) is used. For a window centered at t_c , the local timestamp is

$$\tilde{t}_m = t_m - t_c. \quad (20)$$

The spectrum is then calculated as

$$Z(f_k, t_c) = \sum_{m=1}^M w_m z(t_m) e^{-j2\pi f_k \tilde{t}_m}, \quad (21)$$

where w_m is the Kaiser window and M is the number of packets in the window.

The dominant walking-induced Doppler contour is extracted from the normalized spectrogram using an energy-weighted average. For the i -th link, the resulting contour frequency $c_{w,i}(t_c)$ is converted into raw Doppler velocity as

$$v_{i,\text{raw}}(t_c) = \left| \frac{\lambda c_{w,i}(t_c)}{2} \right|, \quad (22)$$

where λ is the carrier wavelength. The geometry-corrected velocity is then

$$v_{i,\text{corr}}(t_c) = \frac{v_{i,\text{raw}}(t_c)}{M_{i,\text{eff}}}, \quad (23)$$

where $M_{i,\text{eff}}$ is the effective bistatic projection factor defined in Section II-A. The corrected velocities from both links are fused to estimate the final walking velocity.

III. EXPERIMENTAL SETUP AND DATA COLLECTION

A. Second Link Placement Search Using the Reliability Map

The first experiment was conducted to evaluate whether the proposed reliability map can be used to determine a suitable location for the TX_2 . In this stage, a fixed placement of TX_1 and RX was tested. TX_2 was searched around RX with a predefined search radius.

For each candidate position of TX_2 , reliability maps were generated under multiple walking directions. The combined low-reliability percentage was then calculated to evaluate whether the two sensing links would become unreliable at the same target location and walking direction. The candidate position with the lowest average combined low-reliability percentage was selected as the best TX_2 location for that fixed TX_1 - RX placement.

This experiment was used to examine whether the reliability map can guide the placement of the TX_2 and reduce the regions where both sensing links are simultaneously unreliable.

B. Validation Experiment

After the reliability map placement search, the selected TX_2 position was used for practical CSI data collection. CSI data were collected using Intel AX210 devices with PicoScenes to record CSI, packet timestamps, TX MAC addresses, and subcarrier information [6]. As shown in Fig. 2, TX_2 was obtained from the placement search, while the TX_1 - RX link was fixed.

Two straight walking paths, $+45^\circ$ and -45° , were selected according to the reliability map and defined with respect to a common center point. During each trial, CSI packets from the two TX devices were separated by MAC address and processed as independent Wi-Fi sensing links. A camera recorded the walking motion, and the videos were analyzed using Kinovea to obtain the ground-truth walking velocity for evaluating the CSI-based velocity estimation error.

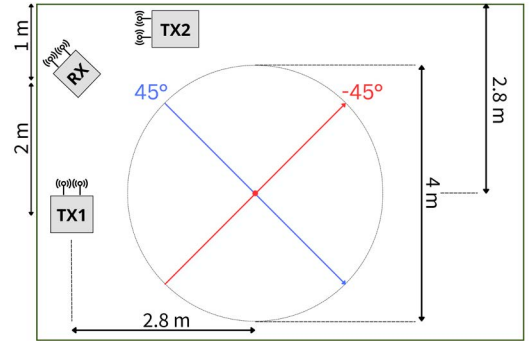


Fig. 2: Real CSI validation setup.

IV. RESULTS

A. Reliability Map Devices Placement Evaluation

Fig. 3 shows the combined reliability maps obtained using the selected global best TX_2 placement at $[5.60, 1.73]$ m in the 5.6×5.6 m experimental area. The RX and TX_1 positions were fixed, whereas TX_2 was selected by minimizing the average

combined low-reliability area ratio across all tested walking headings. In the maps, green regions indicate reliable sensing areas, whereas red regions indicate low-reliability areas for velocity estimation.

The reliability maps showed clear heading-dependent sensing characteristics. The combined low-reliability area ratio varied across walking headings, indicating that the sensing reliability of the two-link configuration depends on the walking direction relative to the link geometry. These results suggest that the proposed reliability map can be used to compare candidate device placements before CSI data collection.

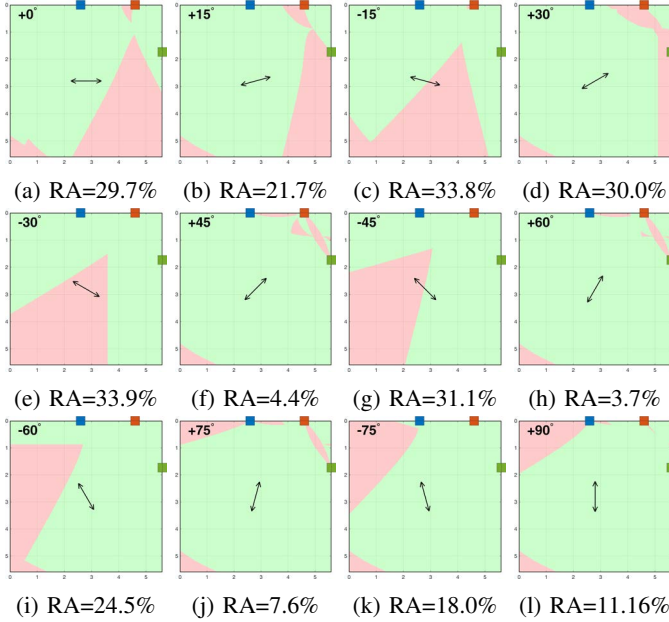


Fig. 3: Combined reliability maps for all tested walking headings under the global best TX_2 placement. The value of RA represents the percentage of low-reliability area in each map. The blue, green, and orange squares represent TX_1 , the selected global best TX_2 , and RX , respectively. The black arrow indicates the walking direction.

B. Real CSI Validation Experiment

The path-level reliability-map results are summarized in Table I. The -45° path had a substantially larger low-reliability path overlap than the $+45^\circ$ path. Specifically, the combined path-level low-reliability overlap was 37.33% for the -45° path and 0.00% for the $+45^\circ$ path. This result indicates that the reliability map predicted the -45° path to be less favorable for CSI-based velocity estimation under the selected device placement.

The corresponding real CSI validation results are summarized in Table II. The single-link velocity MAPE values were higher for the -45° trials than for the $+45^\circ$ trials. For the -45° path, Link 1 and Link 2 produced MAPE values greater than 40% in both trials. In contrast, the $+45^\circ$ path produced lower single-link MAPE values, mostly in the range of 20–30%. This trend is consistent with the predicted path-level low-reliability overlap.

Despite the higher single-link errors in the -45° trials, the merged velocity estimate substantially reduced MAPE across all validation trials. The merged MAPE values were 4.60% and 0.34% for the -45° trials and 1.15% and 1.43% for the $+45^\circ$ trials. These results suggest that multi-link velocity fusion can compensate for weak single-link sensing conditions and improve the robustness of Wi-Fi CSI-based gait velocity estimation.

TABLE I: Path-level low-reliability region percentages from reliability map

Heading	Link 1 Path unreliable (%)	Link 2 Path unreliable (%)	Combined Path unreliable (%)
$+45^\circ$	2.33	0.00	0.00
-45°	49.00	86.00	37.33

TABLE II: Real CSI validation results velocity MAPE.

Trial	Heading	TX_1 MAPE (%)	TX_2 MAPE (%)	Merged MAPE (%)
1	-45°	55.34	42.88	4.60
2	-45°	55.47	47.36	0.34
3	$+45^\circ$	23.92	22.51	1.15
4	$+45^\circ$	21.81	31.85	1.43

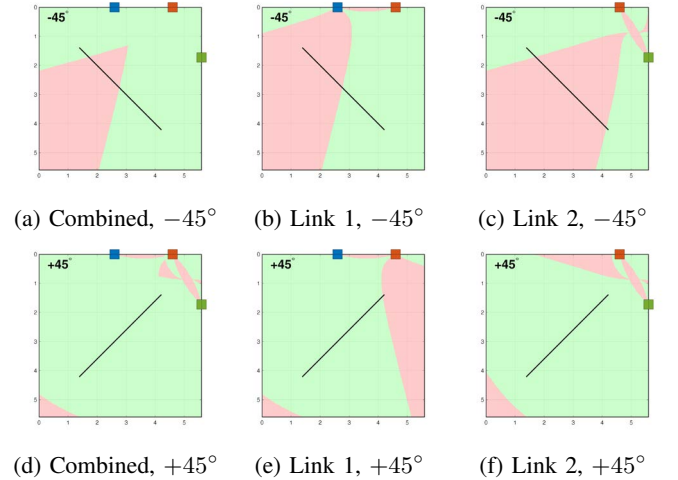


Fig. 4: Reliability maps and path-overlap results for the $+45^\circ$ and -45° validation paths under the selected device placement.

V. DISCUSSION

The real CSI validation results show that Wi-Fi-based velocity estimation is strongly affected by walking heading at the single-link level. Although the same global best TX_2 placement was used, the two walking headings produced clearly different velocity estimation errors for the individual links. For the -45° trials, both TX_1 and TX_2 showed relatively high MAPE values, with errors larger than 40% in most cases. In contrast, the $+45^\circ$ trials produced lower single-link MAPE values, mostly around 20–30%. This result indicates that the sensing quality of each Wi-Fi link is highly dependent on

the walking direction and the corresponding bistatic Doppler geometry.

This heading-dependent behavior can be explained by the geometric Doppler sensitivity. When the walking direction is close to the tangential direction of the Fresnel ellipse, the reflected path length changes only slightly during walking. As a result, the Doppler component observed by that link becomes weak, which leads to larger velocity estimation error. Therefore, walking paths that pass through low-sensitivity regions in the reliability map are expected to produce less reliable single-link velocity estimation.

The two validation paths, $+45^\circ$ and -45° , were selected because they are symmetric walking directions, but the reliability map predicted different sensing conditions under the selected device placement. The $+45^\circ$ path mainly passed through reliable sensing regions, whereas the -45° path overlapped more with predicted low-reliability regions. The experimental results are consistent with this prediction at the single-link level, since the -45° trials produced much higher raw MAPE values than the $+45^\circ$ trials.

The merged velocity results show a substantial improvement compared with the individual links. Even when both single links showed high MAPE values in the -45° trials, the merged velocity MAPE was reduced to 4.60% and 0.34%. For the $+45^\circ$ trials, the merged MAPE was also low, with values of 1.15% and 1.43%. These results suggest that multi-link fusion can compensate for weak single-link sensing conditions and improve the robustness of CSI-based velocity estimation.

Nevertheless, the current reliability map represents link-level geometric sensitivity rather than the full signal-level fusion process. A region classified as low reliability for one link may still provide useful information when combined with another link, depending on the spectral response strength, noise level, and fusion strategy. This may explain why the merged velocity estimation remained accurate even when the single-link errors were high. Therefore, the proposed reliability map should be interpreted as a preliminary geometric reference for weak-path prediction and device placement, rather than as a complete predictor of final fused velocity accuracy.

Although the proposed reliability map was consistent with the observed single-link velocity errors in the preliminary CSI validation, the present study was limited to two walking headings and four validation trials under one selected device placement. Therefore, the reported results should be interpreted as initial feasibility evidence rather than as general performance estimates across different participants, walking paths, room layouts, or device configurations. Future work should incorporate signal-level fusion behavior into the reliability map and validate the proposed framework across more walking headings, repeated trials, device placements, participants, and indoor environments.

VI. CONCLUSION

This study proposed a geometry-based reliability mapping method for device placement analysis in multi-link Wi-Fi CSI gait sensing. By considering walking heading, local Fresnel

ellipse direction, and bistatic path-length sensitivity, the proposed map identifies low-reliability sensing regions before CSI data collection. In the tested 5.6×5.6 m area, the map was used to select a second transmitter position of $[5.60, 1.73]$ m for a fixed TX_1 - RX link.

Preliminary CSI validation showed that the -45° path, which had greater predicted low-reliability path overlap, produced higher single-link velocity MAPE than the $+45^\circ$ path. In contrast, merged multi-link velocity estimation substantially reduced MAPE across all validation trials, suggesting that multi-link fusion can compensate for weak single-link sensing conditions under the tested setup.

Future work should incorporate signal-level fusion behavior into the reliability map and validate the proposed framework across more walking headings, repeated trials, device placements, participants, and indoor environments.

REFERENCES

- [1] C.-L. Lin, W.-J. Chang, and G.-H. Tu, "Wi-Fi-based tracking of human walking for home health monitoring," *IEEE Internet of Things Journal*, vol. 9, no. 11, pp. 8935–8942, Jun. 1, 2022.
- [2] C. Y. Hsu, A. Ahuja, S. Yue, R. Hristov, Z. Kabelac, and D. Katabi, "Extracting gait velocity and stride length from surrounding radio signals," in *Proc. CHI Conf. Human Factors Comput. Syst.*, 2017, pp. 2116–2126.
- [3] K. Niu, X. Wang, F. Zhang, R. Zheng, Z. Yao, and D. Zhang, "Rethinking Doppler effect for accurate velocity estimation with commodity Wi-Fi devices," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 7, pp. 2164–2178, Jul. 2022.
- [4] F. Zhang, C. Chen, B. Wang, and K. J. R. Liu, "WiSpeed: A statistical electromagnetic approach for device-free indoor speed estimation," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 2163–2177, Jun. 2018.
- [5] C. Li, L. Liu, Z. Cao, and M. Zhang, "WiVelo: Fine-grained walking velocity estimation for Wi-Fi signals," in *Proc. IEEE Int. Conf. Sensing, Communication, and Networking (SECON)*, 2022.
- [6] Z. Jiang *et al.*, "Eliminating the barriers: Demystifying Wi-Fi baseband design and introducing the PicoScenes Wi-Fi sensing platform," *IEEE Internet of Things Journal*, vol. 9, no. 6, pp. 4476–4496, Mar. 2022.