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Daqing Zhang

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How Target's Location and Orientation Affect Velocity Extraction Accuracy in WiFi Sensing Systems

Kai Niu
Peking University, Beijing Xiaomi
Mobile Software Company Ltd.

Xuanzhi Wang
Peking University

Zhiyun Yao
Peking University

Fusang Zhang
Institute of Software, Chinese
Academy of Sciences

Si Cheng
Beijing Xiaomi Mobile Software
Company Ltd.

Yalan jiang
Beijing Xiaomi Mobile Software
Company Ltd.

Daqing Zhang*
Peking University, Telecom SudParis,
Institut Polytechnique de Paris

ABSTRACT

WiFi sensing has emerged as a promising technology for smart services, including gesture recognition and trajectory tracking. One of the key challenges in these applications is accurately extracting velocity from WiFi signals. In this paper, we report our latest development to investigate the impact of location and orientation on velocity extraction in WiFi sensing systems. The proposed theory demonstrates that the velocity extraction significantly depends on the target's location and orientation. Thus careful consideration of the target's location and orientation is necessary for WiFi sensing system design. Specifically, two real-world applications (gesture recognition and trajectory tracking) are presented to illustrate how to eliminate the impact of location and orientation independent in velocity extraction.

KEYWORDS

WiFi sensing, contactless sensing, human tracking, gesture recognition, location and orientation

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1 INTRODUCTION

WiFi signals are pervasive in indoor environments along with billions of end-user devices such as smartphones and IoT devices. Besides the traditional communication function, researchers also reuse these devices to enable various sensing applications, including gesture recognition, human tracking. The basic assumption is that

*Daqing Zhang is the corresponding author.

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there exists a fixed mapping between human activity and WiFi signal patterns induced by target's movement, i.e., the corresponding WiFi signal pattern is consistent for the same activity, yet different for different activities. One of the most important relationships is the relation between the target's velocity (i.e., speed and motion direction) and the Doppler frequency shift due to the Doppler effect. However, our latest development indicates the Doppler frequency shift not only varies with the velocity, but also depends on target's location and orientation.

In this paper, we theoretically investigate the impact of location and orientation on the relation between Doppler frequency shift and the target's velocity, demonstrating the importance of target's location and orientation when we design a WiFi sensing system. In addition, we also give two application examples (i.e., gesture recognition and human trajectory tracking) to illustrate how to eliminate the impact of target's location and orientation when we employ velocity patterns in WiFi sensing system.

2 THE VELOCITY MODEL IN WIFI SENSING SYSTEM

The principle of velocity estimation in WiFi sensing system is that the moving target reflects the WiFi signals and introduces frequency shift (called Doppler frequency shift, DFS) due to the Doppler effect. Consider the transmitter and receiver in WiFi sensing system are physically separated, our latest work [1, 2] demonstrates the relationship between Doppler frequency shift (f_D) and target's velocity (speed of v and movement direction of θ) can be denoted as

$$f_D = -\frac{f}{c} \cdot \underbrace{v \cos(\theta - \frac{\alpha_R + \alpha_T}{2})}_{\textcircled{1}} \cdot \underbrace{2 \cos(\frac{\alpha_R - \alpha_T}{2})}_{\textcircled{2}}, \quad (1)$$

where f is the carrier frequency of WiFi signal, and c is the light speed and is a constant, α_R is AoA (Angle of Arrival) of the WiFi signal at receiver (Rx), α_T is the AoD (Angle of Departure) of the signal at transmitter (Tx), as illustrated in Figure 1. The sign of f_D indicates the target approaches (positive) or moves away from (negative) the transceivers.

To deeply understand the effect of location and orientation on the velocity estimation from Eq. (1), let us consider an ellipse with

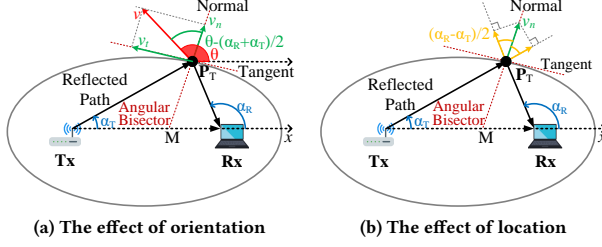


Figure 1: The meanings of DFS-velocity model.

the two foci at Tx and Rx and the target locates at the ellipse by P_T (Figure 1). $P_T M$ is the angular bisector of $\angle T x P_T R x$ and is also the normal line of the ellipse. Then we analyze the effect of orientation and location on velocity estimation as below:

- *The effect of orientation.* Consider the target's orientation is the same as the motion direction during walking, term ① in Eq. 1 indicates whatever the orientation is, only the component projected in normal line of ellipse (i.e., $v_n = v \cos(\theta - \frac{\alpha_R + \alpha_T}{2})$) induces the Doppler frequency shift and the component projected in tangential line (v_t) introduces zero Doppler frequency shift. For a same target speed v , the Doppler shift is maximum when the target moves along the normal line, while the Doppler shift is 0 when the target moves along the tangent line, demonstrating the significant effect of orientation on the Doppler frequency shift.
- *The effect of location.* Since the AoA and DoA is determined by the target's location, term ② in Eq. 1 illustrates the effect of location on the Doppler frequency shift. When the target keeps away from the transceiver, both AoA and DoA approach to 90 degrees. Thus the term ② in Eq. 1 approaches to 2 from 0. In other words, for the same speed and motion direction, the Doppler frequency shift may change from zero to the maximum (i.e., $\frac{2vf}{c}$).

In summary, the location and orientation of target do matter for the Doppler frequency shift, so is that leverages DFS to estimate the velocity.

3 APPLICATIONS

3.1 Gesture Recognition

Gesture recognition is a widely used human-computer interaction method. However, the velocity obtained from Doppler frequency shift in WiFi sensing system significantly depends on the target's location and orientation. To achieve location and orientation independent gesture recognition, we have identified two features in gestures: the number of segments and motion direction change. The number of segments in a gesture is an intrinsic feature that is resistant to location and orientation changes, while the relative motion direction change between adjacent fragments is a robust feature to location and orientation. Figure 2 gives the two features for "Zigzag" gesture. Extensive experiments demonstrate the features can be leveraged to achieve an average accuracy of 96.8% for eight gestures without training, outperforming previous work.

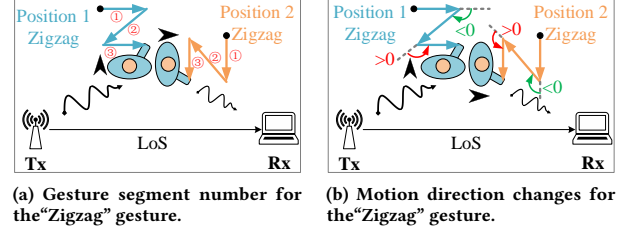


Figure 2: The location and orientation independent features in gesture recognition.

3.2 Human Trajectory Tracking

Trajectory tracking is crucial for various smart home applications. To achieve location and orientation independent trajectory tracking, we propose a device selection algorithm to automatically identify the best set of transmitter-receiver pairs among multiple randomly placed WiFi devices. Then only the selected optimal transceiver pairs are employed to estimate target's velocity and reconstruct the moving trajectory. Figure 3a show the trajectories estimated by our system named PITrack (red) match very well with the ground truth (blue). Figure 3b illustrate the median localization errors of PITrack is 31.08cm, significantly outperforming state of the art IndoTrack and WiDar2.0.

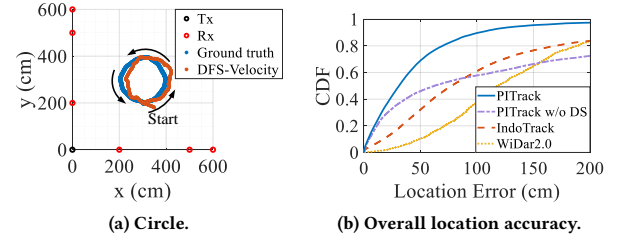


Figure 3: Estimated trajectories and tracking performance.

4 CONCLUSION

In this paper, we have discussed the latest developments of velocity extraction in WiFi sensing systems, indicating the importance of target's location and orientation for the velocity extraction in real-world applications. It is crucial to fully account for the impact of these factors to develop robust practical applications that can perform effectively in real-world scenarios.

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