PhD Forum Abstract: Understanding and Controlling the Sensing Coverage in WiFi Sensing System

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ABSTRACT

In the last decade, the employment of ubiquitous WiFi/4G/5G signals for wireless sensing has seen remarkable advancements, opening new vistas in the realm of wireless sensing. Despite these technological strides, the exploration into the fundamental theoretical aspects of wireless sensing, particularly concerning the sensing coverage and the mechanisms for its control, remains relatively uncharted. Addressing this critical gap, this paper introduces an innovative conceptual framework centered around the sensing signal-to-noise ratio and the application of diffraction theory to ubiquitous wireless sensing. This framework not only provides a quantitative characterization of the sensing coverage but also offers theoretical insights into controlling the sensing coverage. Understanding and adjusting sensing coverage paves the way for future innovations in sophisticated wireless signal-based sensing applications.

KEYWORDS

WiFi sensing, sensing signal-to-noise-ratio, sensing coverage, diffraction model

1 INTRODUCTION

In the rapidly evolving landscape of wireless technology, WiFi-based contactless sensing has emerged as a groundbreaking success, revolutionizing a multitude of applications from smart homes to healthcare monitoring. Despite its widespread adoption and the significant achievements made, the exploration of sensing coverage—both its definition and controllability—remains conspicuously under-researched. This gap not only highlights a critical oversight but also signals an opportunity for deep theoretical inquiry into the mechanics of wireless sensing.

The initial understanding of wireless sensing limits and coverage was based on empirical measurements, without quantitative theory. Research has focused on linking changes in Channel State Information (CSI) with target movements to create effective sensing models. Researchers introduce Fresnel zone concepts to wireless sensing, developing models that quantify the relationship between target movements, CSI fluctuations, and even allow accurate object size measurements [3].

In our study, we aim to define the sensing signal-to-noise ratio (SSNR), offering a quantitative exploration of sensing coverage in WiFi systems [2]. Delving into the principles of diffraction theory, we establish a mathematical model that delineates the relationship between the diffraction effect and object size. This investigation reveals how variations in object size influence the amplitude and phase of received signals, laying the groundwork for innovative approaches to designing object shapes that effectively control sensing coverage. Through this comprehensive analysis, our work seeks to bridge theoretical gaps and enhance the application of wireless signals for more nuanced and precise sensing capabilities.

2 PRELIMINARY: THE WIRELESS SENSING MODEL

In a typical WiFi sensing system as shown in Fig. 1, besides the LoS direct path signal between the transmitter and receiver, the WiFi signals also bounce off objects in the environment such as the sofa and the human body. These signal propagation paths can be divided into two categories: *static path* and *dynamic path*. The static paths (green lines in Fig. 1) include the LoS path and the reflection paths from static objects in the environment. The target movement, on the other hand, induces dynamic signal paths (yellow line in Fig. 1). At the WiFi receiver, channel state information (CSI) is leveraged to characterize the signal propagation through multiple paths. Given a WiFi channel with a central frequency f, the CSI ($H(f,t)$) of this channel at time t can be expressed as $H(f,t) = Y(f,t)/X(f,t)$, where $X(f,t)$ and $Y(f,t)$ are the frequency domain representations of the transmitted and received signals, respectively [1]. The CSI can be represented as a linear superposition of all the paths including the dynamic path ($H_d(f,t)$), static path ($H_s(f,t)$) and noise ($H_n(f,t)$):

$$\begin{aligned} H(f,t) &= H_s(f,t) + H_d(f,t) + H_n(f,t) \\ &= |H_s(f,t)|e^{-j\theta_s} + |H_d(f,t)|e^{-j\cdot 2\pi\frac{d(t)}{\lambda}} + |H_n(f,t)|e^{-j\theta_n}, \end{aligned} \tag{1}$$

$|H_s(f,t)|$, $|H_d(f,t)|$, and $|H_n(f,t)|$ are the amplitude of each CSI component. θ_s and θ_n represent the phases of the static path signal and noise, respectively. $e^{-j\cdot 2\pi\frac{d(t)}{\lambda}}$ represents the phase of the dynamic path with a changing path length of $d(t)$. The three signal components (H_d, H_s and H_n) are also illustrated in the I-Q space in Fig. 2.

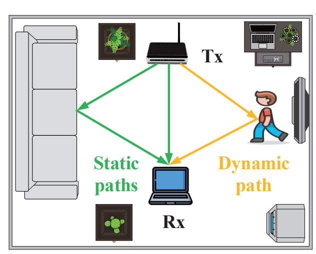

Figure 1: WiFi signal propagation can be grouped into two categories: static path signal and dynamic path signal.

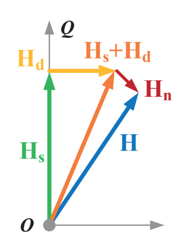

Figure 2: The vector representation of CSI components in the I-Q space.

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3 MODELING THE SENSING COVERAGE IN WIFI SYSTEMS

In WiFi systems, the paradigm of sensing diverges significantly from that of traditional wireless communication. While communication systems leverage both static and dynamic signals for transmitting information, in wireless sensing, it is the dynamic signal, reflecting target movements, that becomes crucial for sensing activities. Static signals, though present, fail to offer sensing information.

This distinction necessitates a redefinition of the conventional Signal to Noise Ratio (SNR) for the context of wireless sensing. Thus, we introduce the Sensing Signal-to-Noise Ratio (SSNR), specifically formulated to quantify a system's sensing capabilities. The SSNR is defined as follows:

$$SSNR = \frac{P_d}{P_i} = \frac{|H_d(f,t)|^2}{|f(H_s(f,t)) + H_n(f,t)|^2}, \tag{2}$$

where P_d denotes the power of the dynamic signal, which is reflected off moving targets, capturing their motion. Conversely, P_i comprises the thermal noise $H_n(f,t)$ and interference induced by the static signal $H_s(f,t)$, denoted as $g(H_s(f,t))$. This equation effectively distinguishes between the beneficial dynamic signals and the 'noise' constituted by static signals and thermal noise, accurately mirroring the system's motion-sensing capabilities.

The minimal value of SSNR marks the sensing boundary—the threshold below which the system's sensing capability diminishes markedly. By leveraging the SSNR equation, one can map out the sensing coverage for different distances between the transmitter and receiver shown in Fig. 3. Notably, as the distance between these components widens, the coverage area bifurcates into two distinct ovals surrounding each transceiver, thereby illustrating the dynamic and spatially dependent nature of sensing coverage in WiFi systems. This model provides critical insights for the strategic deployment of wireless sensing.

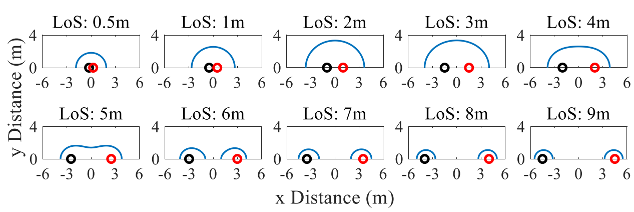

Figure 3: The sensing coverage boundary under different LoS path lengths.

4 CONTROLLING THE SENSING COVERAGE IN WIFI SYSTEMS

Manipulating WiFi sensing coverage centers on using the diffraction zone, especially the first Fresnel zone, where most signal energy transmits. Objects within this zone change signal energy distribution, with their size affecting coverage alterations.

4.1 Modeling Diffraction Effect for object size measurement

Building on the understanding that the diffraction zone is pivotal in determining sensing coverage, we explore the relationship between the diffraction effect and object size. This relationship is not just theoretical but has practical applications in measuring object size through WiFi signals. The diffraction of WiFi signals by an object introduces singularities in the WiFi Channel State Information (CSI), which vary based on the object's dimensions. By correlating the number of these singularities with the size of the object, we can measure the object's size with remarkable accuracy, achieving a median error as low as 2.6 mm using commodity WiFi cards. This method stands as a significant advancement in WiFi-based sensing, offering a novel approach to object size measurement that is both precise and practical.

4.2 Design the object in diffraction zone with Generative AI

The correlation between diffraction effects and object size serves as a foundation for further manipulating the sensing coverage. By designing objects with specific shapes and sizes to be placed within the diffraction zone, we can control the distribution of energy and, consequently, the sensing coverage. We introduce the application of Generative AI (AIGC) for this purpose. Generative AI allows us to design objects that, when positioned in the diffraction zone, create the desired alterations in energy distribution. This capability enables us to tailor the sensing coverage to specific needs, enhancing the flexibility and applicability of WiFi-based sensing systems. Through this innovative approach, we not only address the challenge of controlling sensing coverage but also expand the potential uses of WiFi-based sensing technology in various scenarios.

5 BIOGRAPHY

Xuanzhi Wang, currently in their fourth year of the Ph.D. program, is on track to graduate next year. Under the guidance of Prof. Dr. Daqing Zhang, Peking University.

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