ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Sensing your heartbeat (and others)

Team #32

XIN CHEN
(xin13@illinois.edu)
YUKAI HAN
(yukaih3@illinois.edu)
XUANQI WANG
(xuanqiw3@illinois.edu)
QIYANG WU
(qiyangw2@illinois.edu)

Sponsor: Howard Yang

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1 Introduction

1.1 Problem

Nowadays, most monitoring systems rely on specialized hardware like wearable sensors or cameras. These subjects, however, could be costly and inconvenient for people to use. In that case, WiFi signal, as a ubiquitous object around our lives, is a good choice to provide non-contact sensing which cannot be achieved by traditional monitoring systems. Despite the convenience that WiFi signals convey, it is still a problem that extracting and interpreting Channel State Information (CSI) accurately and making use of them to detect subtle human activities such as breathing and heartbeats with the interference from the outside environment.

To be specific, two main problems appear in the traditional systems. One is unavoidable physical contact like the chest straps it contains. Although the existing medical technology has minimized the discomfort caused by such contact, they are unsuitable for some certain applications and people. Another issue that conventional methods have is the cost and limited accessibility. Some wearable health monitoring devices are often expensive and even if they can afford it. Taking a burden on the body always affects and restricts their normal activities. Then for WiFi-based sensing method, the major problem is concentrated on the environmental interference. The signal might be influenced by noise and dynamic surroundings easily, making it hard to extract exact physiological signals.

1.2 Solution

The solution we choose is utilizing WiFi signals as our non-contact sensing tool to detect human behaviors using CSI. The approach will extract fine-grained CSI data from a WiFi transmitter-receiver setup. The signal will reflect subtle physiological activities like breathing and heartbeats. By analyzing the amplitude and phase variations of signals when they interact with the human body, we can infer the breath or heartbeat rates. To make it visually intuitive, we will map the data to some LED indicators lying on a chest model and these lights could flash in sync with the measured activities frequency. Moreover, we add a ground truth measurement system to make comparison. This system will use a respiration or heartbeat belt to provide accurate physiological data for validation with another group of LED indicators.

To implement our system, a WiFi sensing network is needed. We will equip this network with AX200 cards for both transmitter and receiver to achieve CSI extraction. During the experiment process, the receiver will take the CSI data by Ubuntu 22.04 LTS and PicoScenes software and then apply filtering and signal processing algorithms to reduce environmental noise. The processed activity frequency will then be used to modulate LED flashing frequency, making the experiment visually. In addition, a ground truth which is behaved as a control group will exist and it will use the belt data to ensure reliability.

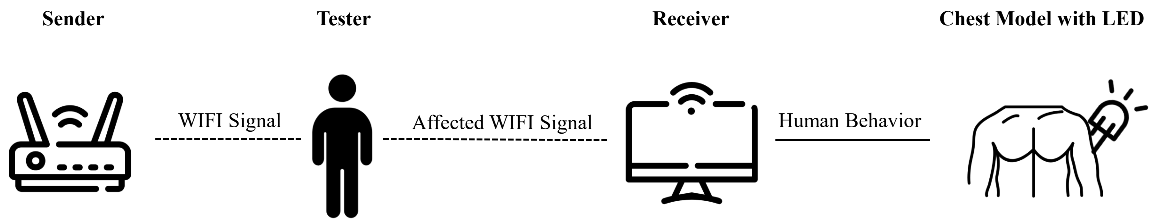

Figure 1: Visual aid

1.3 Visual aid

The whole process without ground truth is shown in Figure 1. A WiFi transmitter (Sender) will emit signals and then these signals will be affected by tester's movements before being accepted by a WiFi receiver (Receiver). The receiver will then process the CSI to analyze tester's behavior patterns. Finally this extracted data will be mapped onto a chest model with some LED indicators, making the behavior rate visually.

1.4 High-level requirements list

- The system should accurately detect human behavior patterns using WiFi CSI data, with a minimum correlation of **70%** compared to the behavior ground truth measurements.
- The system must be able to visualize behavior data in real-time with a maximum delay of **750 milliseconds** between data acquisition and LED output to ensure immediate feedback for health monitoring
- The system must maintain consistent behavior detection with sufficient environmental noise such as background movement and multipath effects and give an accuracy that does not drop below **70%** in different indoor conditions.

2 Design

2.1 Block Diagram

See Figure 2

2.2 Subsystem Overview

2.2.1 WIFI Signal Transmission Subsystem

The WiFi Signal Transmission Subsystem establishes a robust wireless communication channel to ensure stable and high-quality signal transmission, which is essential for acquiring accurate Channel State Information (CSI). The subsystem acts as the foundation of the system by delivering raw WiFi signals to the subsequent CSI Extraction Subsystem for further processing.

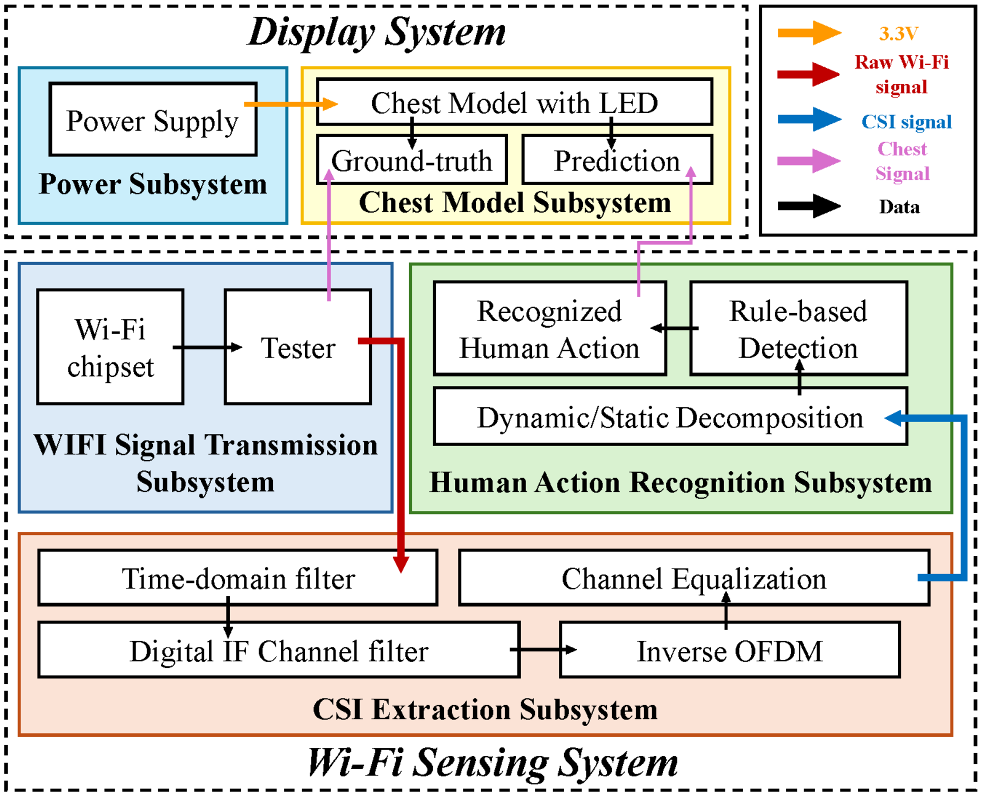

Figure 2: Block Diagram

2.2.2 CSI Extraction Subsystem

The CSI Extraction Subsystem processes the raw wireless signals received from the WiFi Signal Transmission Subsystem. It extracts detailed CSI data in real time, capturing fine-grained variations in the wireless channel. This critical intermediate stage transforms the raw signal into structured data that is subsequently relayed to the Human Action Recognition System for activity analysis.

2.2.3 Human Action Recognition Subsystem

The Human Action Recognition System leverages the refined CSI data provided to detect and interpret human movements. It analyzes both amplitude and phase variations in the signal to accurately recognize various human actions. This subsystem converts processed signal information into actionable insights on human behavior and then transmitted to display subsystems for visualization.

2.2.4 Power Subsystem

The Power Subsystem provides the necessary electrical energy to drive the components of the Display System, including the Chest Model Subsystem. It ensures stable and efficient power distribution to maintain reliable operation of all hardware elements. The subsystem must support continuous operation without voltage fluctuations that could impact LED performance in the chest model.

2.2.5 Chest Model Subsystem

The Chest Model Subsystem comprises an LED array installed on a physical chest cavity model to visually represent human action. This subsystem translates the strength of the detected signals into varying LED brightness, thereby reflecting the predicted human action patterns. By comparing these LED brightness levels with the actual measured activity (ground-truth), the subsystem enables real-time validation of the Human Action Recognition System's performance.

2.3 Subsystem Requirements

2.3.1 WiFi Sensing System

WiFi Signal Transmission Subsystem

The WiFi Signal Transmission Subsystem provides the critical foundation for the overall design by establishing a robust wireless communication channel. To ensure high-quality signal delivery, it should support dual-band operation (2.4GHz and 5GHz) so that signals are transmitted with a minimum signal-to-noise ratio of **25dB**. Besides, in order to support real-time CSI capture, signal transmission latency must remain under **10ms**. Furthermore, it is essential that the signal transmission and reception environment is free from interference by other signals to maintain data integrity. To ensure that the CSI data accurately represents the movements of the intended subject, only **one subject** should be present during signal transmission.

CSI Extraction Subsystem

The CSI Extraction Subsystem is integral to the design as it transforms the raw WiFi signals into precise, actionable CSI data. Running on Ubuntu with CSI extraction software, it is expected to continuously extract CSI at a rate of at least **1000 samples per second** while maintaining a processing latency below **50ms**. These stringent quantitative requirements ensure that even fine-grained variations in the wireless channel are captured accurately and in a timely manner, which is vital for subsequent analysis. The extracted CSI data is then forwarded to the Human Action Recognition System; any deviation from these performance benchmarks would result in degraded data quality, ultimately impairing the system's ability to recognize human movements accurately.

Human Action Recognition Subsystem

At the heart of the overall design, the Human Action Recognition System converts the refined CSI data into meaningful insights about human behaviors. It separates CSI into static and dynamic components, with the dynamic portion being highly sensitive to even slight displacements of the subject. Implemented using MATLAB, Python, and specialized CSI analysis toolboxes, the system quantitatively tracks both movement magnitude and direction in a rule-based manner, with an inference latency under **100ms per cycle**. It continuously handles data at a minimum rate of **1000 samples per second** to ensure real-time performance.

2.3.2 Display System

Power Subsystem

The Power Subsystem supplies stable and efficient electrical power to all components of the Display System, particularly the Chest Model Subsystem, and must operate reliably over extended periods without voltage or current drops that might disrupt LED performance. It is required to maintain a stable **3.3V** supply with a maximum fluctuation of ±5% to ensure consistent LED brightness while providing at least **500mA** of current to accommodate peak loads from the LED array and associated control circuitry. In addition, the subsystem should achieve a power efficiency of at least 85% to minimize energy waste and heat generation, and it must support continuous operation for at least 8 hours to meet typical experimental durations.

Chest Model Subsystem

The Chest Model Subsystem visually represents human action through an LED array installed on a chest cavity model, providing a tangible demonstration of both ground-truth (i.e., the tester's actual actions) and predicted (i.e., the monitored system's recognized) signals for real-time validation of the Human Action Recognition Subsystem. The LED array is arranged to simulate human action, with each LED individually addressable to control brightness based on the strength of the detected signals. This design enables direct comparison between the monitored signal intensity and the actual measured activity. The system must update the LED brightness levels within **50ms** for timely synchronization, and the LEDs should be sufficiently bright for clear observation under typical indoor and outdoor lighting conditions.

2.4 Tolerance Analysis

A major risk in the design is whether Wi-Fi CSI can reliably detect subtle human behaviors—such as the small chest displacements during breathing—given the inherent noise and multipath interference in indoor environments. Based on Fresnel zone theory[1], our analysis shows that detection sensitivity strongly depends on the subject's position within the Fresnel zones.

For example, at a Wi-Fi frequency of 5.24GHz, the wavelength λ is approximately 57mm. A typical chest displacement during normal breathing is about 5mm. According to the Fresnel zone model, the phase change $\Delta\phi$ induced by this displacement is given by:

$$\Delta\phi = \frac{2\pi\,\Delta d}{\lambda}, \tag{1}$$

where Δd is the displacement. Substituting the values:

$$\Delta\phi \approx \frac{2\pi \times 5mm}{57mm} \approx 0.55 \text{ radians} \quad (\approx 31.6^\circ). \tag{2}$$

This phase shift, although small, is within detectable limits provided that the system's phase resolution is on the order of 0.1 radians. However, this detection is critically sensitive to the target's location:

- **Optimal Detection:** When the subject is centered within a Fresnel zone, the interference between the direct and reflected signals yields maximum phase sensitivity.
- **Degraded Detection:** When the subject is near the Fresnel zone boundaries, the phase contributions may partially cancel out, reducing the effective signal change and making detection more vulnerable to noise.

The analysis shows that, under controlled conditions with stable noise levels (phase noise less than 0.1 radians RMS), a phase shift of 0.55 radians is discernible. This confirms that the design can detect subtle human motions if the following tolerances are maintained:

- **Phase Measurement Accuracy:** The system must maintain a phase resolution better than 0.1 radians.
- **Positional Tolerance:** The subject should ideally remain within a specified range from the center of the Fresnel zone to ensure maximal sensitivity.
- **Noise and Interference Control:** The environment must be managed to minimize extraneous reflections and electronic noise that could obscure these subtle phase changes.

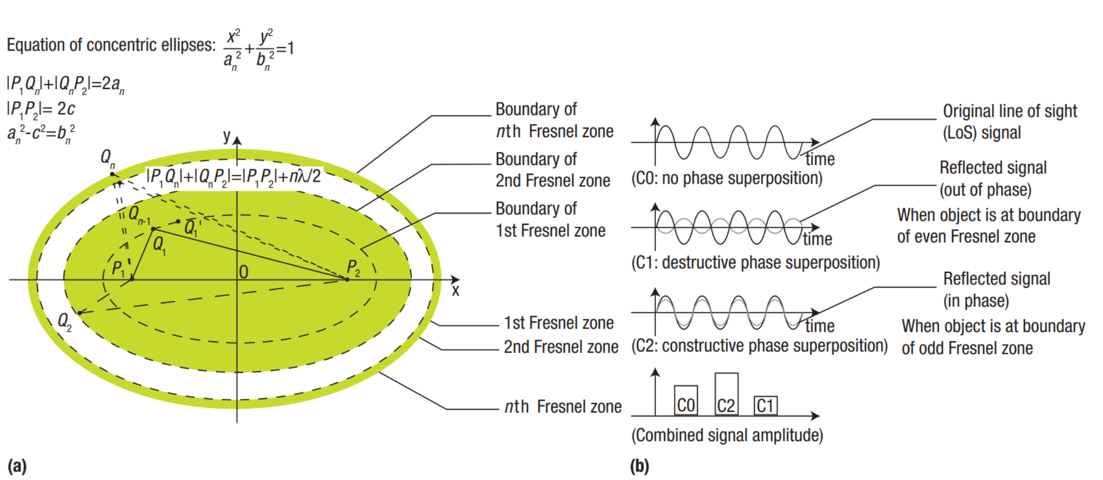

Figure 3: The Fresnel model.

3 Ethics and Safety

3.1 Ethics

Our project will strictly follow ethical standards by prioritizing public safety, privacy protection, and responsible technology use. To be specific, since we use WiFi signals to detect physiological activities, it will touch some privacy of testers so we must ensure that no personally identifiable information is collected, and all data remains anonymous to protect user privacy [2]. Additionally, we recognize some potential risks such as unauthorized tracking or surveillance, and we commit to implementing safeguards to prevent ethical violations. Following IEEE's principles, we are committed to ensuring that our project serves public welfare, minimizes harm, and operates safely within ethical and regulatory boundaries [3].

3.2 Safety

Our project strictly follows ECE 445 safety guidelines. Since our system involves wireless signal transmission, electronic components, and circuit board handling, we will comply with wireless communication regulations and operate all hardware within safe power limits. While working with circuit boards, including insulating connections and preventing short circuits, we will follow two-person rules to avoid damage. Any necessary soldering will be done in a well-ventilated area with heat-resistant tools [4].

References

[1] D. Zhang, H. Wang, and D. Wu, “Toward centimeter-scale human activity sensing with wi-fi signals,” *Computer*, vol. 50, no. 1, pp. 48–57, 2017.

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[4] University of lllinois at Urbana-champaign. “ECE 445 Safety Guidelines.” (n.d), [Online]. Available: https://courses.grainger.illinois.edu/ece445zjui/guidelines/safety.asp (visited on 03/14/2025).