Environmental sensing through millimeter wave radios

Human motion tracking and analysis via signal processing and deep learning imaging techniques to mm-wave radar data

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Motivation

Millimeter wave (mm Wave) communications are considered a key component of 5G-and-beyond ultra-dense wireless networks, offering new opportunities to perform environmental sensing. Compared with traditional sound waves, ultrasonic waves and Wi-Fi signals, mm Wave sensing has great advantages, such as fine-grained resolution and the ability to detect subtle movements.

Figure 1. penetration of mm waves through different materials and objects

Penetration, the unique sensing feature of mm Wave has attracted more and more attention.

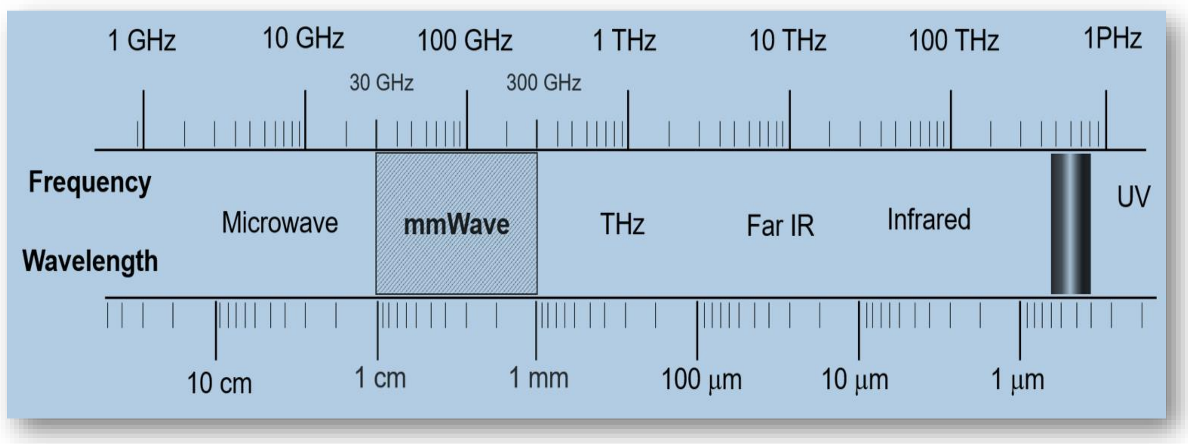

Figure 2. mm Wave occupies the area of spectrum between 30 GHz and 300 GHz.

Why sensing through mm waves

- To meet end-user privacy
- Large bandwidth and small component size
- Low interference and increased security
- Usage for motion analysis in the clinical field
- High spatial resolution and accurate velocity estimation of moving objects

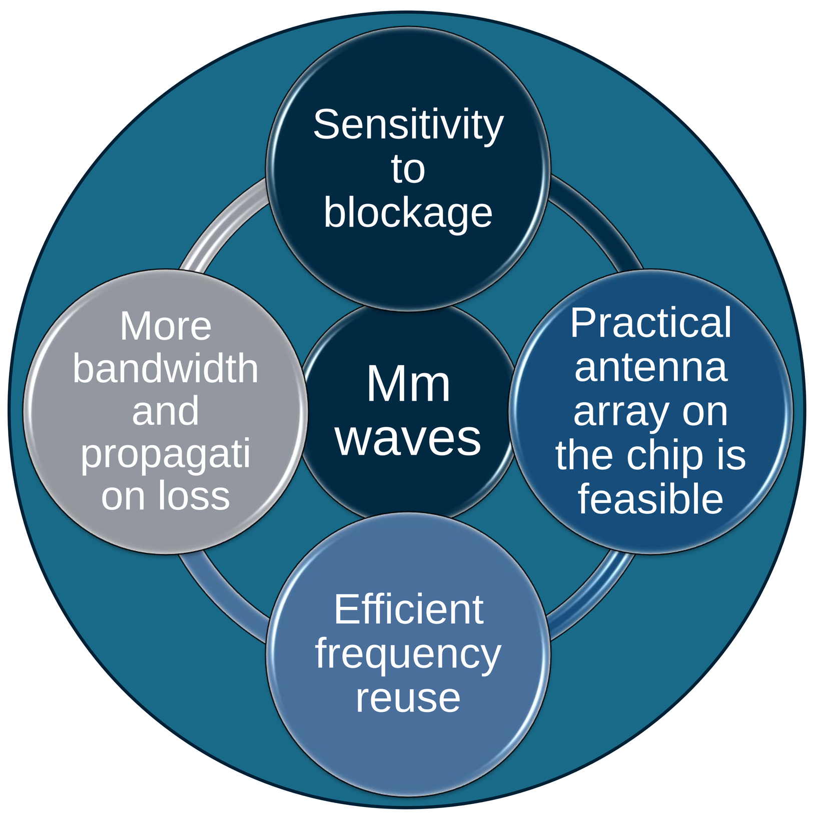

Figure 3. Benefits and challenges in mm wave

Problem statement: objectives

- Attain high spatial resolution
- Attain high accuracy
- Ensure robustness to occlusions (loss of LoS)
- Ensure high speed transmission and reception of data
- Extract fine-grained information from the channel data

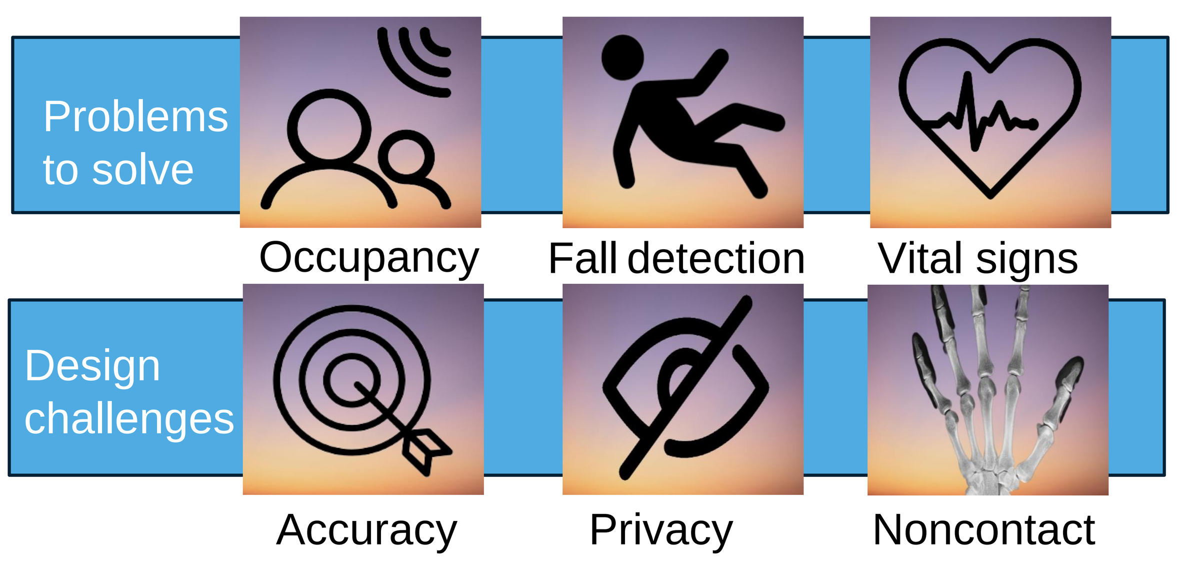

Figure 4. Challenges while designing the sensing system

Abstract

With the rapid development of 5G technology, more and more attention has been attracted to mm Wave sensing. As an emerging sensing medium, mm Wave has the advantages of both high spatial sensitivity and precision. Different from its networking applications, the core idea behind mm Wave sensing is to analyze the changes in the reflected radio signals, as they contain information on moving objects within the physical environment. In our work, we design a full-fledge system for mm Wave sensing and communication. We utilized micro doppler signature, the standard approach for the identification of human motion, behavior and gestures. We aim to apply some signal analysis techniques to the data collected to increase the spatial resolution of the sensing algorithm.

Methodologies and Results

- A widely adopted method to perform the identification is the extraction of the **micro-Doppler signature** of the targets, which is computationally demanding in case of co-existing multiple targets within the monitored physical space.
- A frequency-modulated continuous wave (FMCW) radar allows the joint estimation of the distance and the radial velocity of the target with respect to the radar device.

$$s(t) = exp[j2\pi\left(f_0 + \frac{\xi}{2}t\right)t] \qquad \leq t \leq T$$

- This is achieved by transmitting sequences of linear chirps

$$\varphi(m, l) = 2\pi\left[\frac{2f_0R}{c} + fdlTrep + (f_d + f_b)mT_f\right]$$

(m, l) respectively represent the Doppler frequency and the beat frequency of the reflected signal,

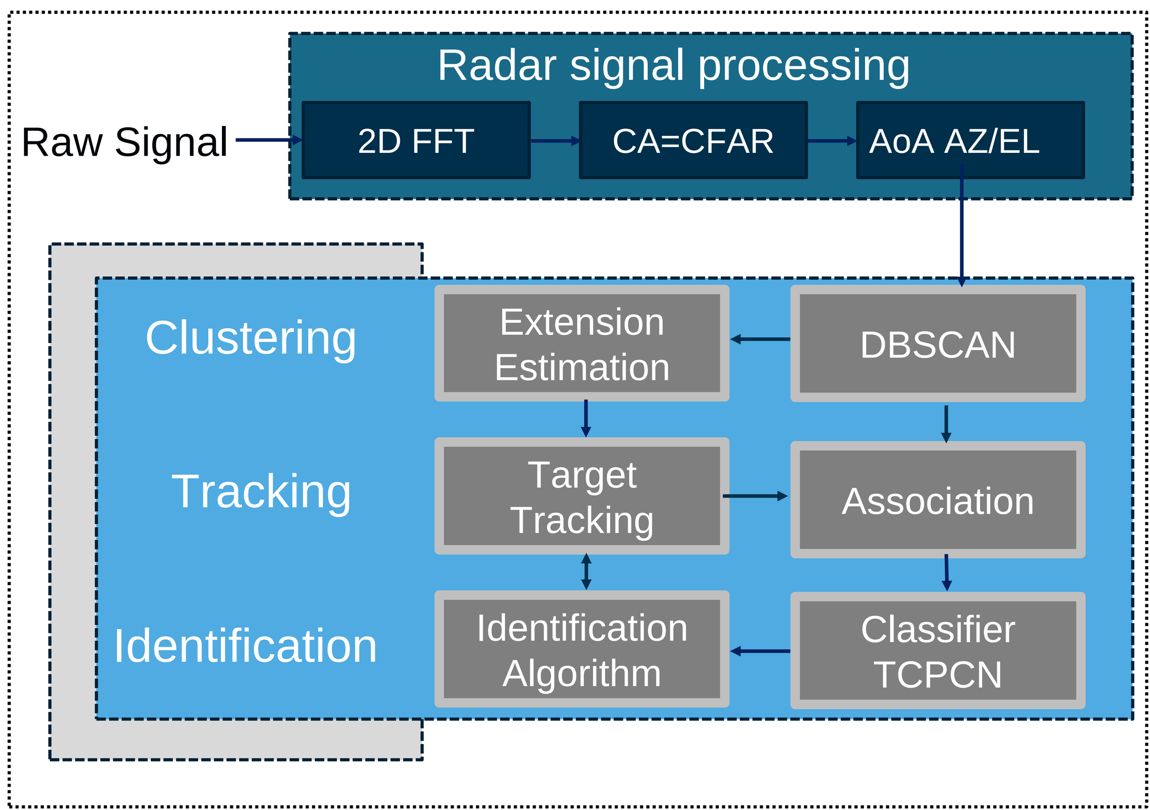

Figure 5. Block diagram of the proposed signal processing workflow: the raw radar data is processed on the radar device

Human gestures identification and classification

However, current millimeter-wave sensing approaches are mainly based on micro-Doppler feature identification or machine learning with lots of labeled data, resulting in poor robustness to changing environments or high dependency on data availability. In my design, a novel feature-driven recognition method is sought, where five feature metrics with physical meaning are constructed. The focus is on the features of the Range-Slow Time domain and Micro-Doppler features to study the recognition of human activity.

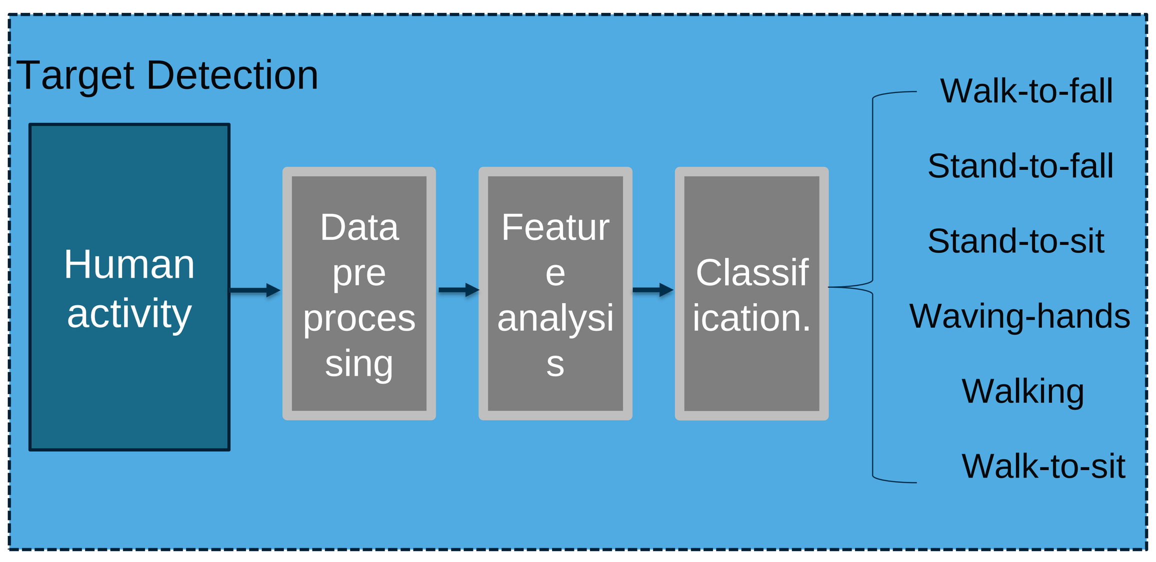

Figure 6. The framework of the human activity recognition system.

Detailed procedures for the proposed method:

- pre-processing
- feature extraction
- classification

FMCW radar is applied.

The transmitted signals can be written as

$$S_T(t) = A_T(t)\ exp\ [j(2\pi f_0 t + \pi K t^2 \pi + \varphi_0)]$$

The difference method can be used to calculate the gradient of energy which can be expressed as

Grad(j) = Re_ Energy(j) - Re_ Energy(j+k)

As aforementioned, the movement of the human body creates many reflection points with different spatial features, as shown in Figure. 7. So, we must treat the human body as a soft body instead of a rigid one (e.g., a wall). In order to obtain the position-scattering points, existing work utilizes FMCW, which can separate the reflection points with their spatial features, i.e.,

- Distance
- Velocity
- Angle

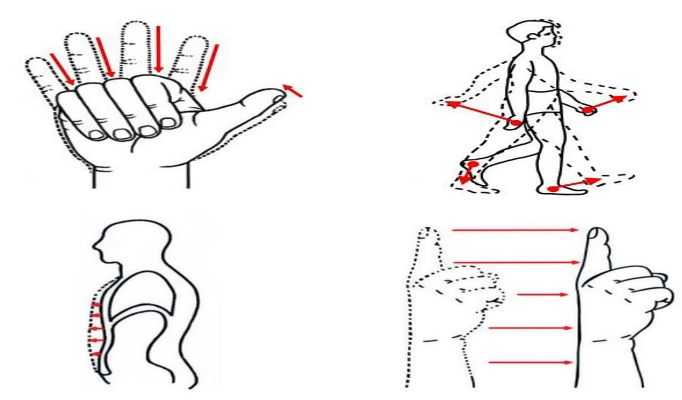

Figure 7. Detecting compound human movements

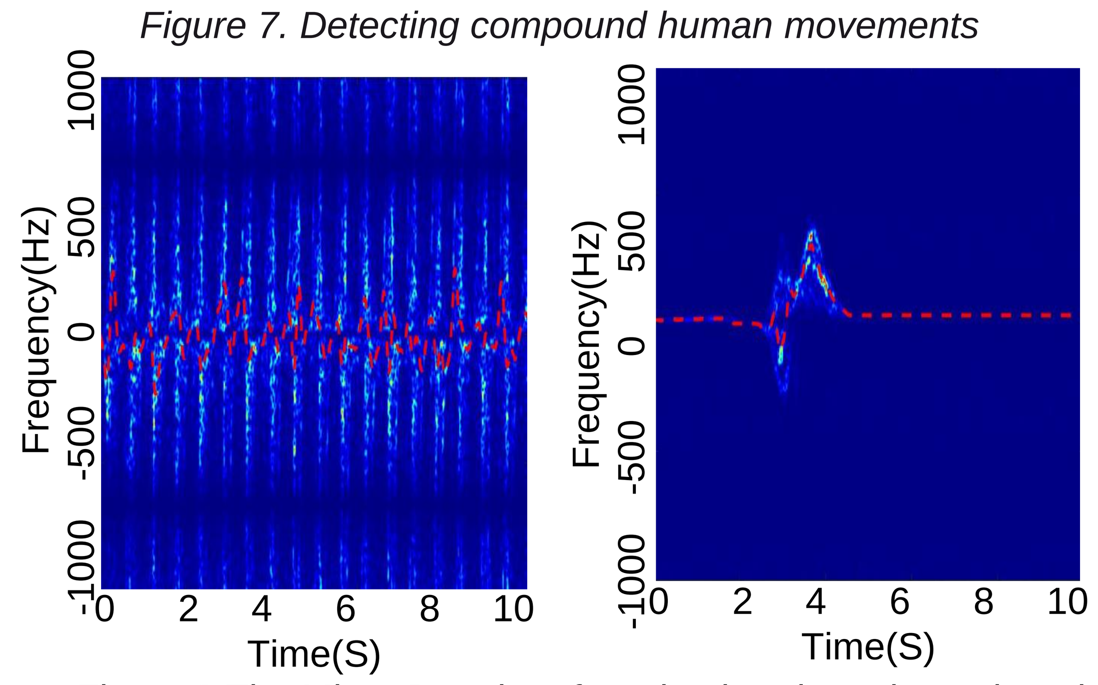

Figure 8.The Micro-Doppler of waving hands and stand-to-sit.

Future work

We are currently working along the following lines:

- Develop an experimental (FPGA-based) system for joint communication and sensing at mm-Waves
- Implement new channel estimation methods based on OFDM for next gen and multi-band 6G systems
- Implement Orthogonal Time Frequency Space (OTFS) modulation and test is experimentally
- Monitoring vital signs, in a dynamic environment
- Training efficient AI algorithms for feature extraction and classification

Conclusion

- Identifying the moment when a person's motion changes
- Discriminating motion type using mm-Wave radio channels
- Implementation of novel OTFS modulation
- Neural network model for the classification
- Apply processing techniques into an integrated FPGA-based system capable of performing sensing operations at runtime

References

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(2) Shen, Xiangtian, et al. "Indoor Human Activity Recognition using Millimeter-Wave Radio Signals." *2022 International Conference on Sensing, Measurement & Data Analytics in the era of Artificial Intelligence (ICSMD)*. IEEE, 2022.

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