SeRadar: Embracing Secondary Reflections for HumanSensing with mmWave Radar

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Background (Problems)

High-frequency (e.g., mmWave) RF sensing is of high resolution, but with the following prominent problems:

- Can be easily blocked.
- Performance of gesture recognition is highly dependent on orientation.
- When multiple sensing target exists.

SeRadar: Utilize Secondary Reflections

First reflections: Signals reflected directly from the target back to the radar

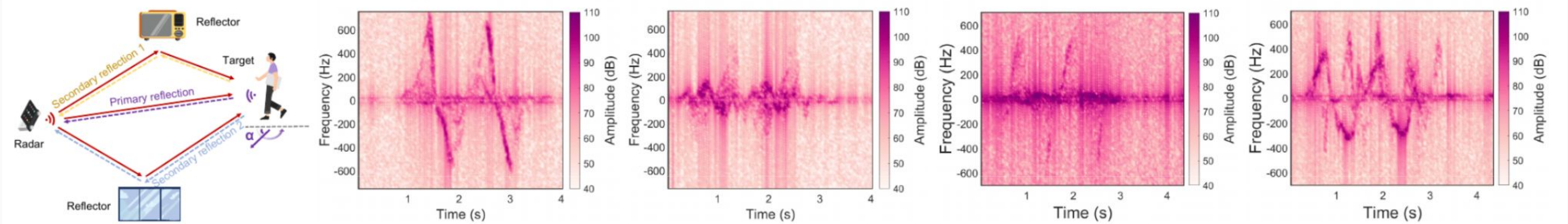
Secondary reflections: Radar → Reflector → Target → Radar; Radar → Target → Reflector → Radar

- Blockage of the first reflection: easily solved by the secondary reflection(s)
- Orientation dependency: multiple secondary paths create multiple views on different directions
- Multiple sensing targets: secondary paths increases diversity to help separate the signals

Challenges and Contributions

- Realize SeRadar (sensing using also secondary reflections) on commercial hardwares and testing the hand movement detections (macro gestures) and respiration rate detections (micro gestures) in various scenarios.
- A pipeline that addresses the following challenges:
  - Weak signals of secondary reflections
  - Path Recognition (e.g., how to determine the secondary reflections)
  - Multi-target interference

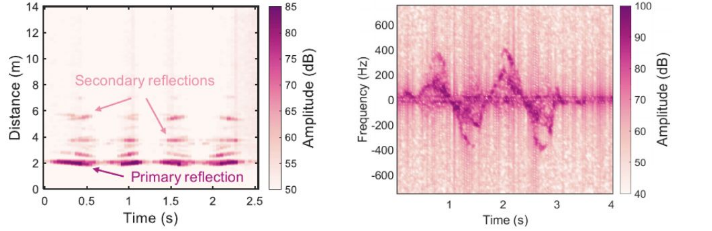
Illustrations (Motivations)



(a) Sensing settings. (b) Orientation: $\alpha = 0^\circ$. (c) Orientation: $\alpha = 90^\circ$. (d) Under Occlusion. (e) Under Interference.

Table 1: Degradation of breath monitoring reliability based on primary reflection

Case	Mean Absolute Error (bpm)
Ordinary condition	0.3
Orientation variation	4.7
Occlusion	5.1
Interference	8.6



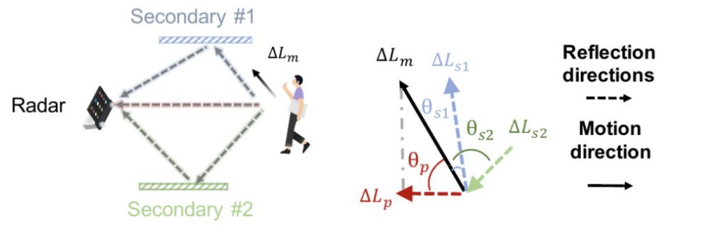
(a) Existence of multiple secondary reflections. (b) Features extracted via a secondary reflection ($\alpha = 90^\circ$).

More Detailed Theoretical Model

First reflections: M → T → M

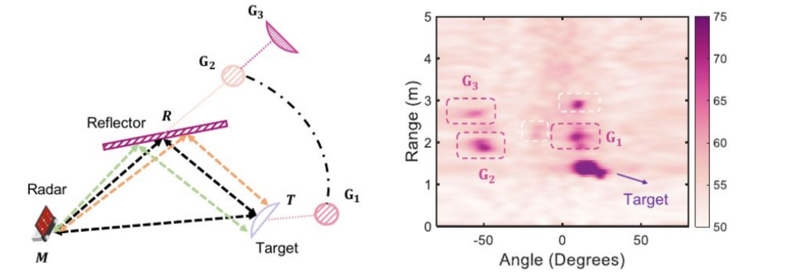
Secondary-order secondary reflections: M → R → T → M, or M → T → R → M

Third-order secondary reflections: M → R → T → R → M



(a) Multi-view observation. (b) Correlated paths.

Figure 6: Reflectors provide multi-view observation.



(a) Geometric model of secondary reflections. (b) Reflections reveal reflector and target directions.

Figure 5: The theoretical multi-reflection model.

SeRadar System Overview

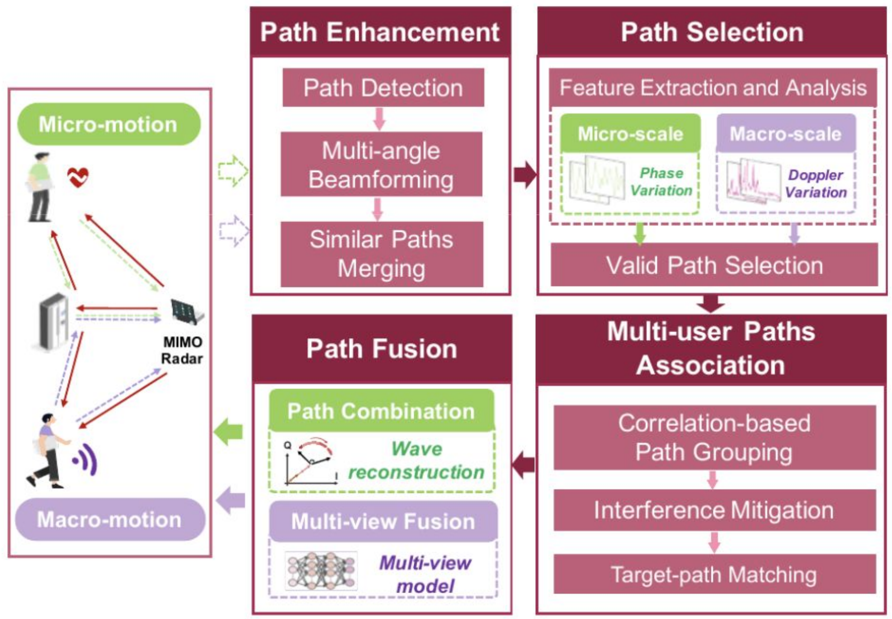
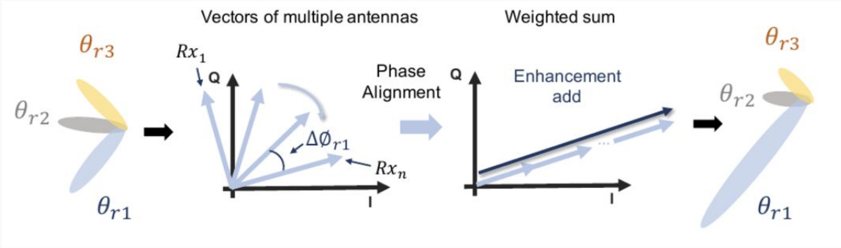


Figure 7: System overview of SeRadar.

- Path Enhancement: Amplify the raw signals
- Path Selections: What reflections should be used/ignored
- Multi-User Path Associations: grouping signals when multiple targets present
- Path Fusion: Detect the gestures

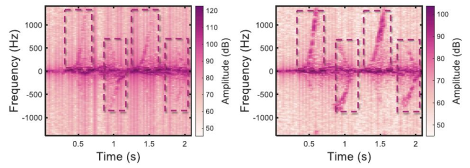
Path Enhancement

Multi-Angle Beamforming (RX): Simply beamforming to different angles by turn to amplify signals from different directions, thus having amplified received secondary reflections.



$$S_{BF_{\theta_{ri}}}(t) = \sum_{n=1}^{N} S_{IF,n}(t) \exp\left(-j(n-1)\Delta\phi_{ri}\right). \quad (4)$$

Similar Path Merging: Multiple secondary reflections from the same reflectors, and sharing high time-domain correlations. Merge them together.

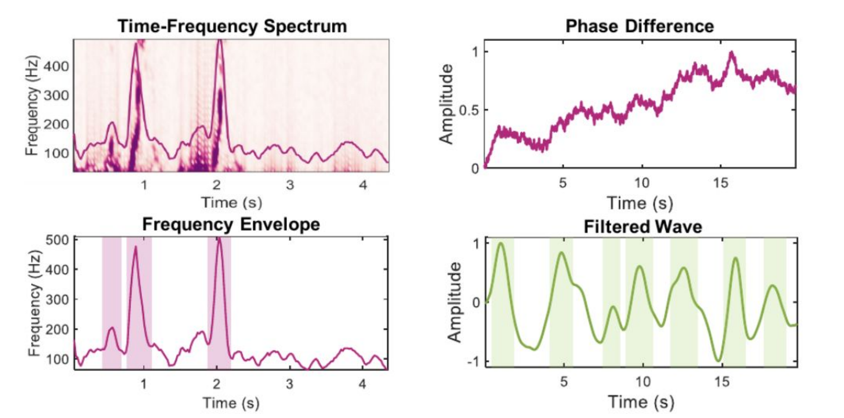


(a) Before path merging. (b) After path merging.

Figure 9: Time-frequency spectrums before and after merging similar signal paths from the same reflector.

Path Selection

First, do a feature extraction. For macro gesture, we check frequency patterns in a signal’s frequency-time spectrogram. For micro gesture, check phase patterns after a band-pass filter.



Path Selection

$$SVNR = 10\log_{10}(\frac{P_{dynamic}}{P_{noise}}), \quad (5)$$

Signal Variation Noise Ratio

For Macro Gestures:

P_dynamic: $\frac{1}{R_d}\sum_t \sum_{f\in\mathcal{F}_f} |S(t,f)|^2$

$$P_{noise} = \frac{1}{R_n}\sum_t \sum_{f\notin\mathcal{F}_f} |S(t,f)|^2$$

For Micro Gestures:

$$P_{dynamic} = \frac{1}{N_d}\sum_{f_d}^{f_u} |\Phi_m(f)|^2$$

$$P_{noise} = \frac{1}{N_n}\sum_{f\notin[f_u,f_d]} |\Phi_m(f)|^2$$

Those reflections with top 70% SVNR are selected

Multi-User Path Association

Correlation-Based Path Grouping

Core idea is that reflections from the same target share strong correlations (in phase for micro gestures/in frequency for macro gestures).

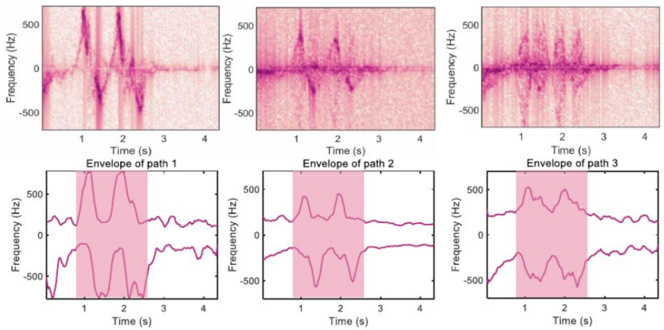
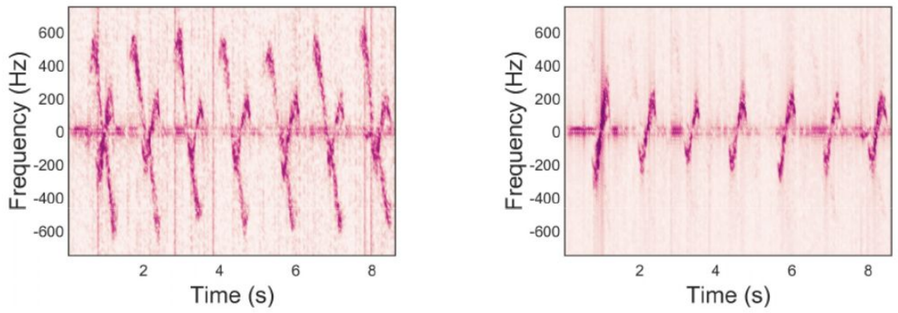


Figure 11: Examples of three paths within a correlation group, exhibiting synchronous variation.

- Use Mutual Information Correlation (MIC) as the metric
- Build n * n upper triangle matrix
- Connect nodes if their MIC > a threshold
- Find the connected components

Interference Mitigation

Apply null steering technique to suppress side lobe interference from other targets.



(a) Targets' features overlap. (b) Feature for Target 1.

Figure 13: The features (a) before and (b) after mitigating interference.

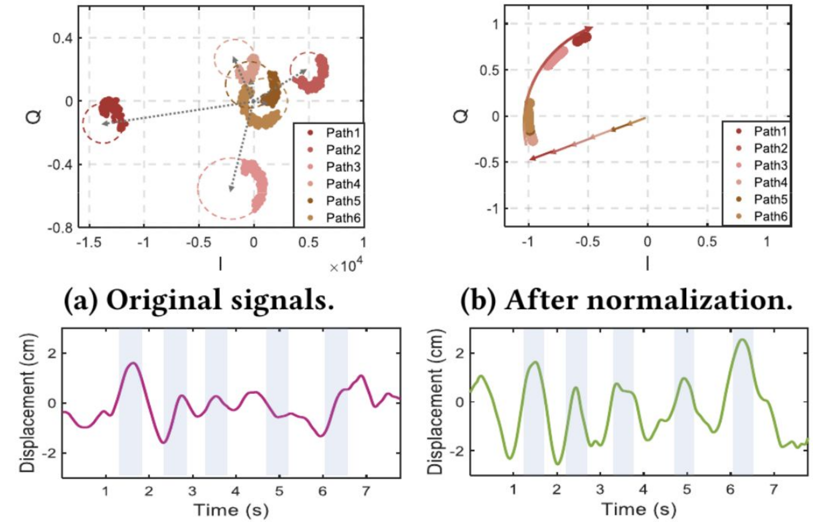
Path Fusion (Recognize Gestures)

For micro-motion sensing:

- Path Phase Alignments: align paths' initial phases with the reference signal's (first reflection) initial phase.
- Phase Normalizations: normalize phase changes of each reflection signal within a window T.
- Phase Weighting: prioritizing high-quality signals based on

$$w_i = SVNR_i \cdot \mathrm{Corr}\left[\phi_i(t), \bar{\phi}(t)\right]$$

Path Fusion



(c) Sample of signal for a single reflection.

(d) Sample of signal for paths combination.

Figure 14: Combination of multiple correlated paths.

Path Fusion

For macro-motion gesture, they deploy a deep-learning based model:

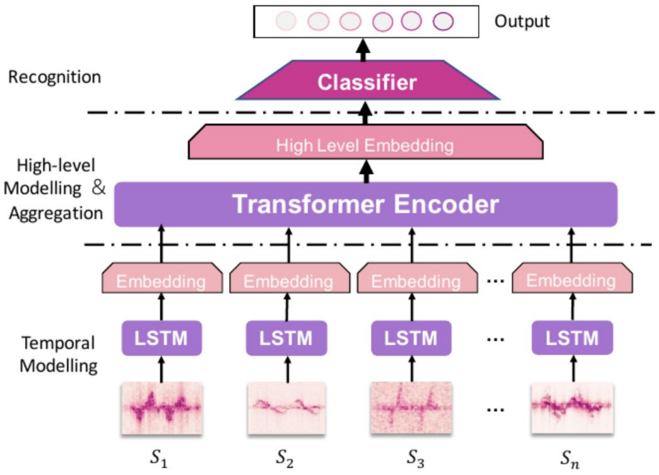


Figure 15: The architecture of multi-view model.

Evaluation (Macro-Motion Gestures)

Figure 16: Experiment settings.

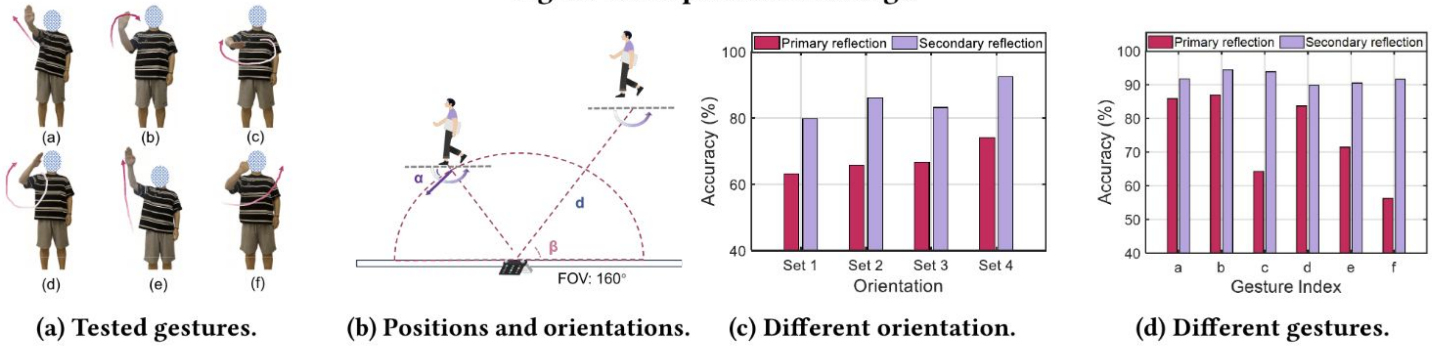
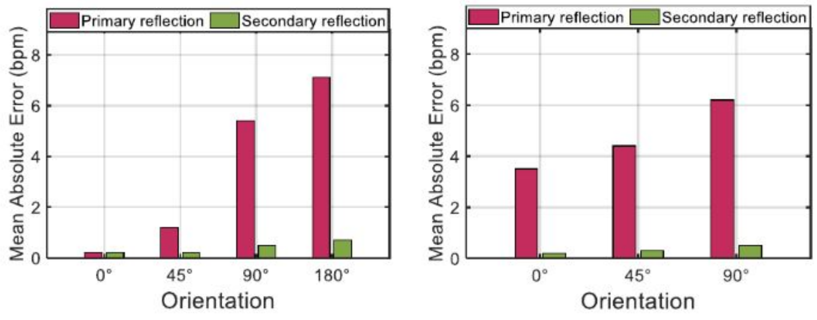


Figure 17: Experimental setting and performance of macro-motion sensing.

Evaluation (Micro & Path Selection Mini-Bench)



(a) In indoor scenarios. **(b) In vehicle cabins.**

Figure 18: Comparison for respiration sensing.

Table 2: Performance of path selection methods.

Method	Opt reflection	All reflections	SeRadar
Macro-motion	84.21%	87.57%	92.43%
Micro-motion	1.5 bpm	2.8 bpm	0.4 bpm

Evaluation (Multi-Targets)

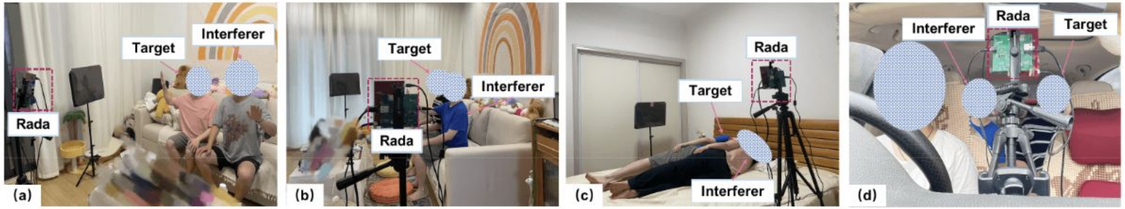
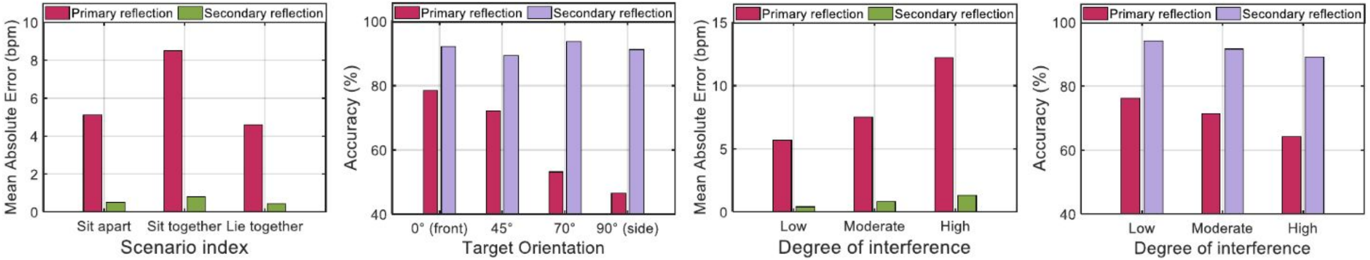


Figure 19: Experiment settings in multi-person scenarios. (a) and (b): sitting on the sofa; (c): lying on the bed; (d): sitting in the cabin.



(a) Performance of respiration monitoring.

(b) Performance of gesture recognition.

(c) Respiration monitoring performance under interference.

(d) Gesture recognition performance under interference.

Figure 20: Performance comparison in multi-person scenes.

Other Benchmarking

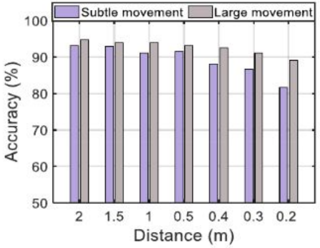


Figure 21: Impact of distance between targets.

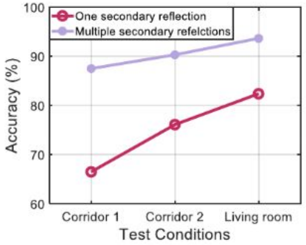
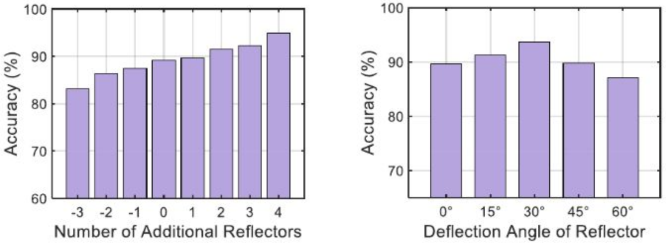
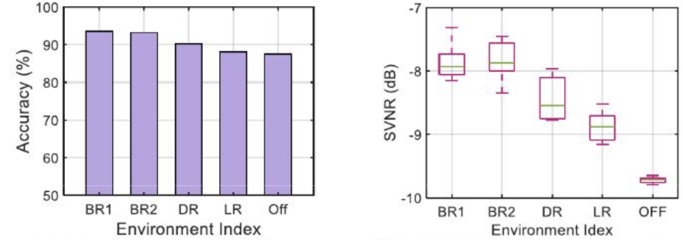


Figure 22: Performance for out-of-view targets.



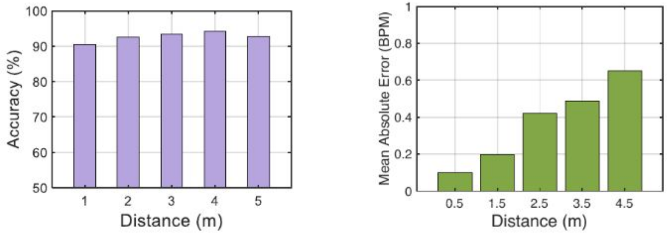
(a) Impact of number. (b) Impact of orientation.

Figure 24: The impact of reflectors.



(a) Gesture recognition. (b) SVNR in five scenarios.

Figure 23: The impact of environments.



(a) Gesture recognition. (b) Respiration monitoring.

Figure 25: Impact of distance from reflector and target.

Questions

Let’s look at Perusall.

My Opinions

- Limited gesture evaluations: only some simply hand gestures and respiration detections.
- Might not work well if the target is moving (even slowly).
- The sensing distance is short.