High-Precision Vital Signs Monitoring Using FMCW Millimeter-Wave Radar

Digital Signal Processing (DSP) techniques for non-contact detection of respiration and heart rate.

Why This Research?

- **Non-contact vital sign monitoring** is crucial for:
  - Burn patients, newborns, elderly, and infectious disease monitoring.
  - Applications like home healthcare and driver fatigue detection.
- **Challenges**:
  - Hardware noise → **Low SNR** (signal-to-noise ratio)
  - Extracting small motions like breathing/heartbeat accurately.

Proposed System Overview

FMCW Radar-Based Monitoring System

- **Radar Type**: 77 GHz FMCW millimeter-wave radar.
- **Scenario**: Monitor a person sitting in an office environment.
- **Data Acquired**:
  - **Respiration rate**
  - **Heart rate**
- **DSP Chain**: Key innovation of the paper.

Signal Processing Chain

Steps in DSP Workflow

1. **Signal Preprocessing**:
    - Static clutter removal (background interference).
    - DC offset compensation (correct hardware bias).
2. **Phase Extraction In Range Window**:
    - Use extended DACM algorithm to extract phase.
3. **Noise Reduction**:
    - Iterative VMD Wavelet-Interval-Thresholding.
4. **Feature Extraction**:
    - Respiration: FFT-CZT hybrid algorithm.
    - Heartbeat: Time-domain peak-seeking & FFT.
5. **Final Output**:
    - Accurate respiration and heart rate with low relative errors.

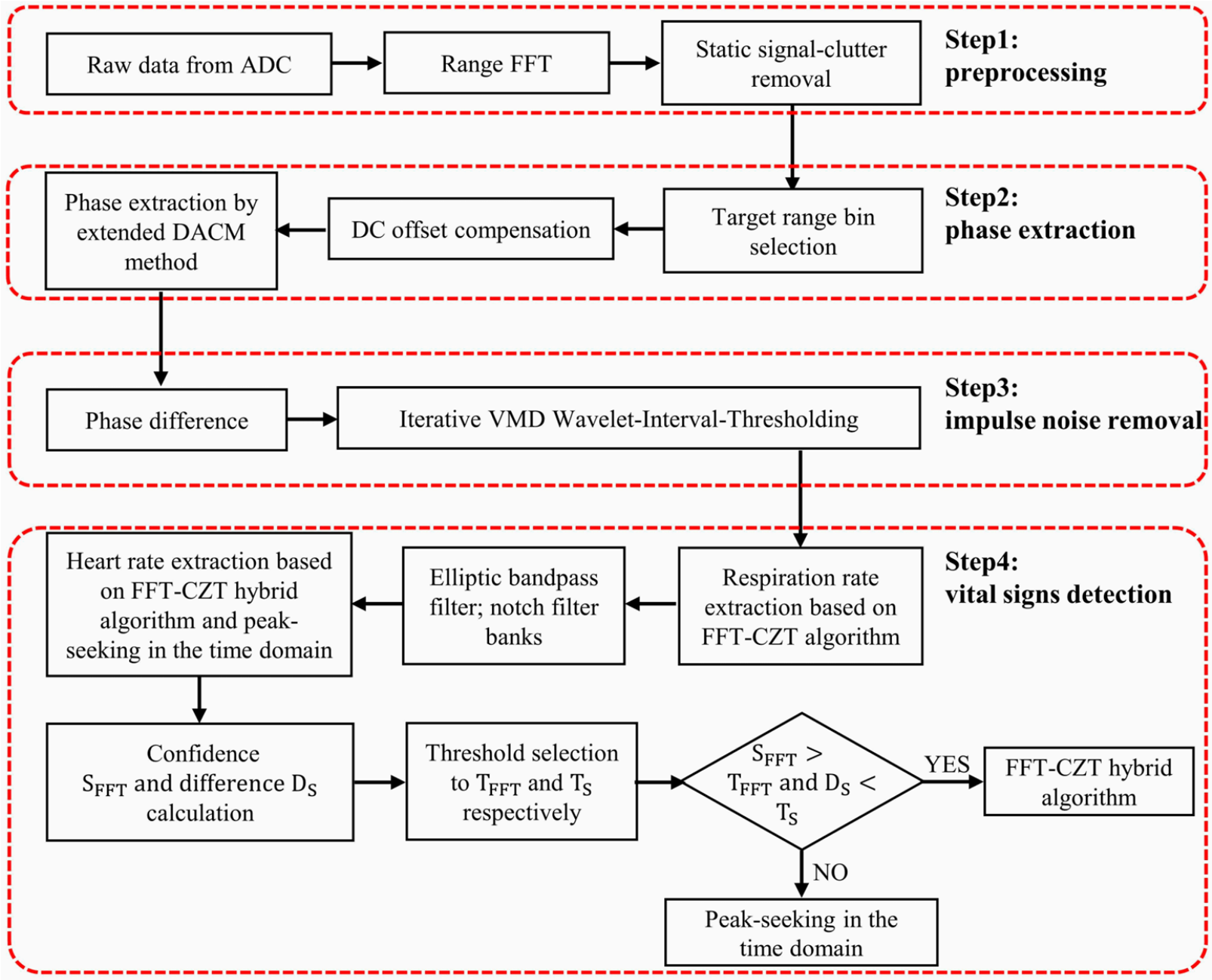


Figure 1. The proposed signal processing algorithm chain.

Range FFT and Static Clutter Removal

Range FFT

- Converts radar raw data (in time domain) into frequency domain.
- Identifies the **distance (range)** of targets by analyzing signal frequencies.

Static Signal Clutter Removal

- Eliminates interference from stationary objects (e.g., walls or furniture).
- Focuses only on signals reflected from moving targets (e.g., human breathing or heartbeat).

Range FFT

Key Concepts:

- **Radar Signal:** Reflected signals contain time delays proportional to the distance of objects.
- **FFT (Fast Fourier Transform):** Converts the time-delay signal into frequencies to calculate distances.

Steps:

1. **Raw Data:** Radar captures signals over multiple fast-time intervals.
2. **Apply FFT:** Transforms time-domain data into frequency domain.
3. **Identify Range:** The frequency peaks correspond to the distances (ranges) of objects.

Static Signal Clutter Removal

Key Concepts:

- Stationary objects (e.g., walls, furniture) cause "clutter" in radar data.
- Moving targets (e.g., human chest movements) create dynamic signals.

Method:

$$y[m,n] = y_0[m,n] - \frac{1}{N_{\text{frames}}} \sum_{n=1}^{N_{\text{frames}}} y_0[m,n]$$

where $m = 1, 2, 3, \ldots, N_{\text{samples}}; n = 1, 2, 3, \ldots, N_{\text{frames}}$. N_{samples} means the number of sampling points of each chirp; and N_{frames} means the number of frames.

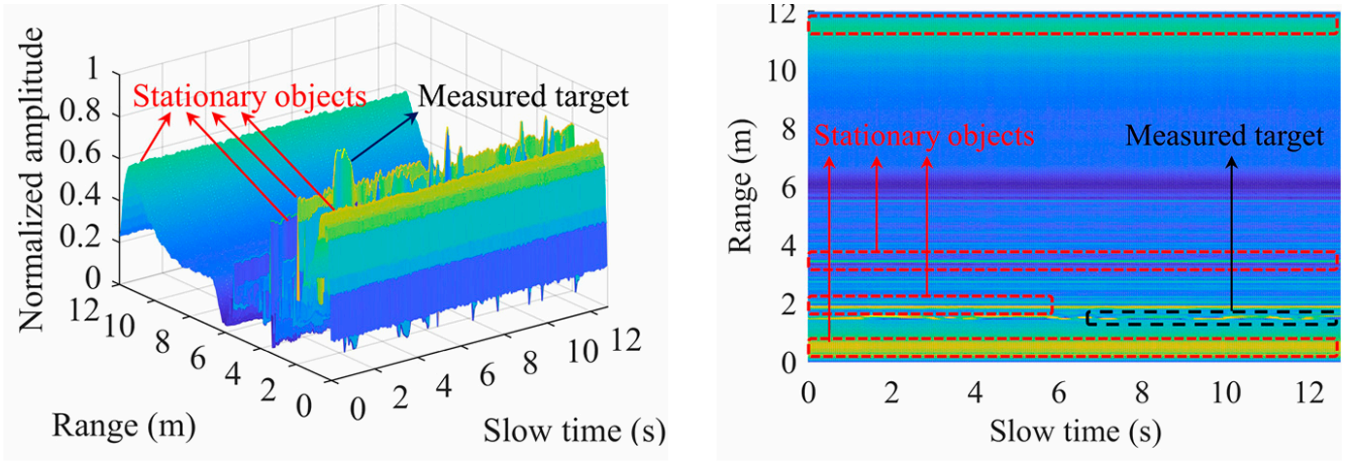
Why Are These Steps Important?

Range FFT:

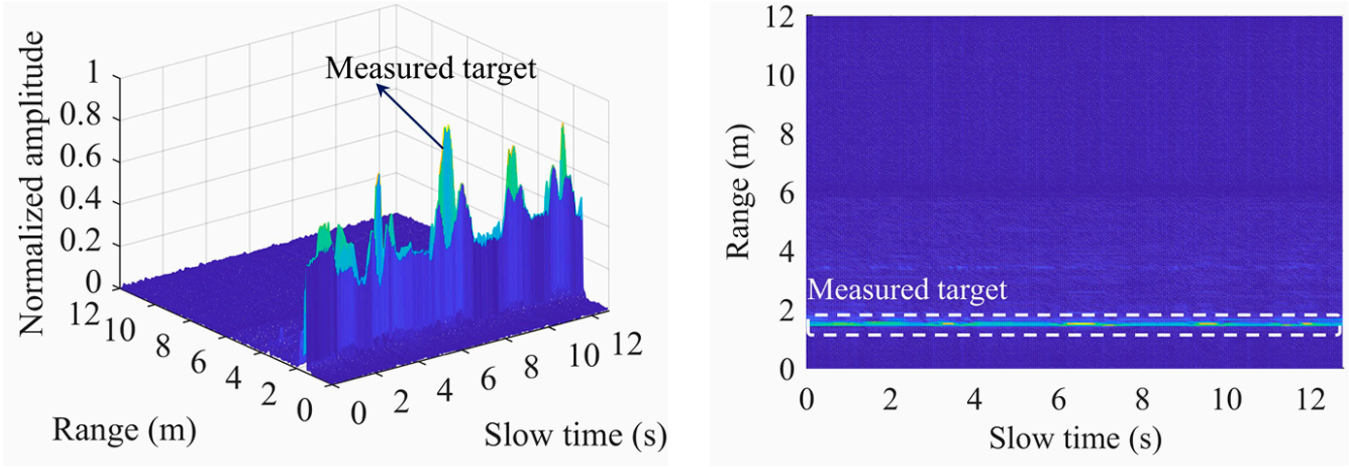
- Determines **where** the targets are located (distance).
- Creates the **range bins** for further processing.

Static Signal Clutter Removal:

- Focuses on **dynamic movements** of interest.
- Improves signal-to-noise ratio (SNR) for vital signs detection.



(**a**)



(**b**)

Figure 2. Range-FFT: (**a**) before static signal-clutter removal; (**b**) after static signal-clutter removal.

Experiments and Results

Experimental Setup

- **Radar Used**: TI AWR1642 with DCA1000 acquisition board.
- **Subjects**: 11 people, 2 groups.
  - Group 1: Normal respiration & heart rates.
  - Group 2: Accelerated breathing/heart rates.
- **Test Scenarios**: Distances of 0.8m, 1m, 1.3m, 1.5m.

Results

- **SNR Improvement**:
  - Respiration: +1.89 dB.
  - Heartbeat: +1.44 dB.
- **Accuracy**:
  - Respiration: Avg. error = 1.33%.
  - Heartbeat: Avg. error = 1.96%.

Contributions of the Paper

Why This Paper Matters

- Combines FMCW radar with advanced DSP techniques.
- Demonstrates non-contact vital sign monitoring with high accuracy.
- Addresses challenges like:
  - Low SNR.
  - Hardware imperfections.
  - Small motion extraction.
- **Applications**:
  - Healthcare monitoring.
  - Emergency alerts.
  - Home-based elderly care.

Summary and Conclusion

Key Takeaways

- FMCW radar + DSP = High-precision monitoring.
- **DSP Techniques**:
  - Iterative VMD Wavelet-Interval-Thresholding.
  - FFT-CZT hybrid algorithm.
  - DC offset compensation.
- **Results**:
  - Accurate respiration and heart rate monitoring.
  - Applicable in noisy, real-world environments.
- **Future Scope**:
  - Real-time processing.
  - Broader healthcare applications.