Monitoring a Person's Heart Rate and Respiratory Rate on a Shared Bed Using Geophones

Zhenhua Jia

Joint work with

Sugang Li, Amelie Bonde, Chenren Xu, Jingxian Wang, Pei Zhang, Richard E. Howard, Yanyong Zhang

In-Bed Vital Sign Monitoring

Potential users

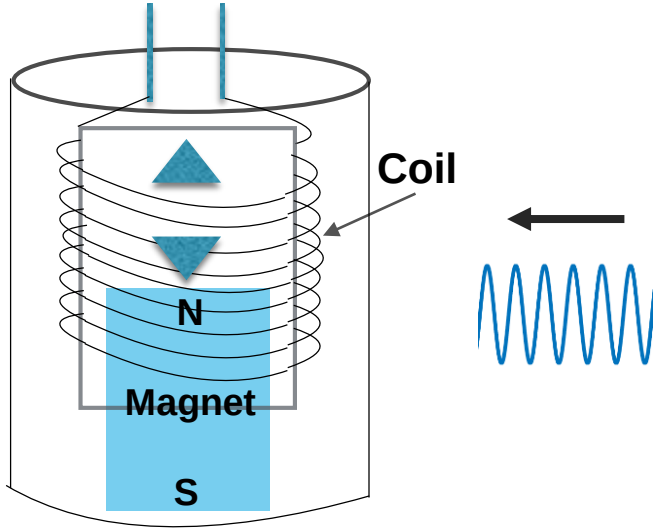
- Accurate sleep monitoring
- Discharged patients after surgery
- People with heart problem, e.g., congestive heart failure

Existing work

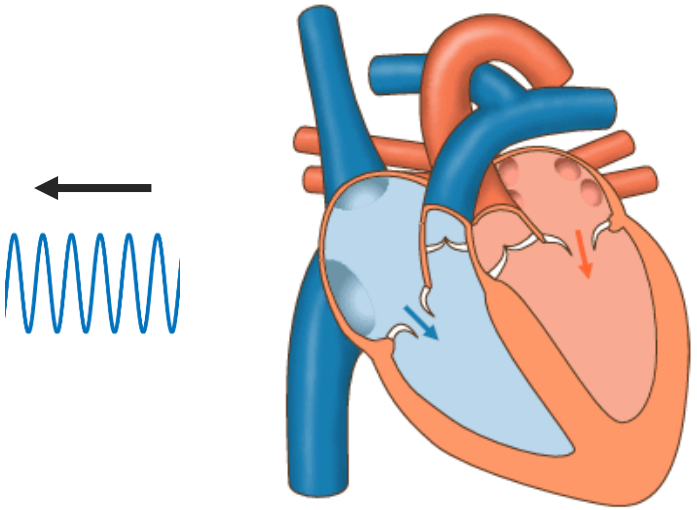
- Inconvenient (e.g., wearables)
- Sensitive to environment (e.g., RF)
- Cumbersome (e.g., pressure mattress, force sensor bed)

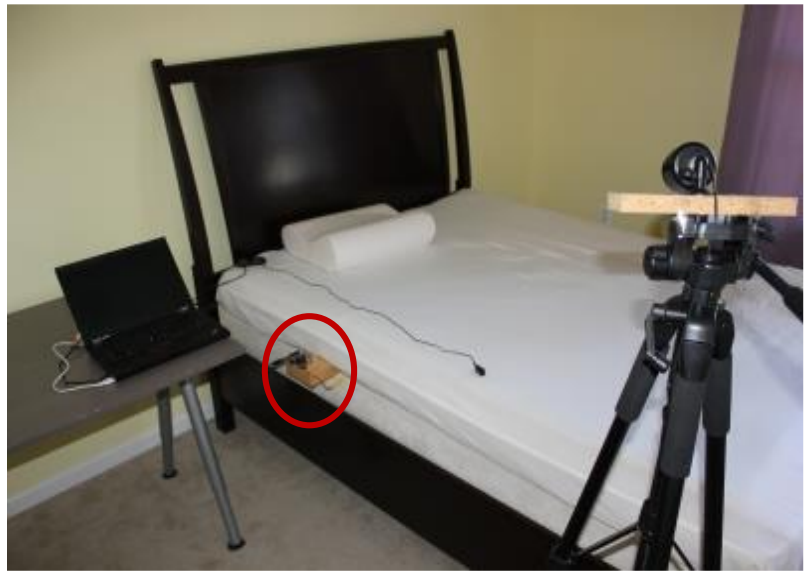
Our Previous Work

- **HB-Phone (Heartbeat Phone)**
  - **Can sense the vibration caused by the ballistic force of each heartbeat**
  - **Only works for a single user**



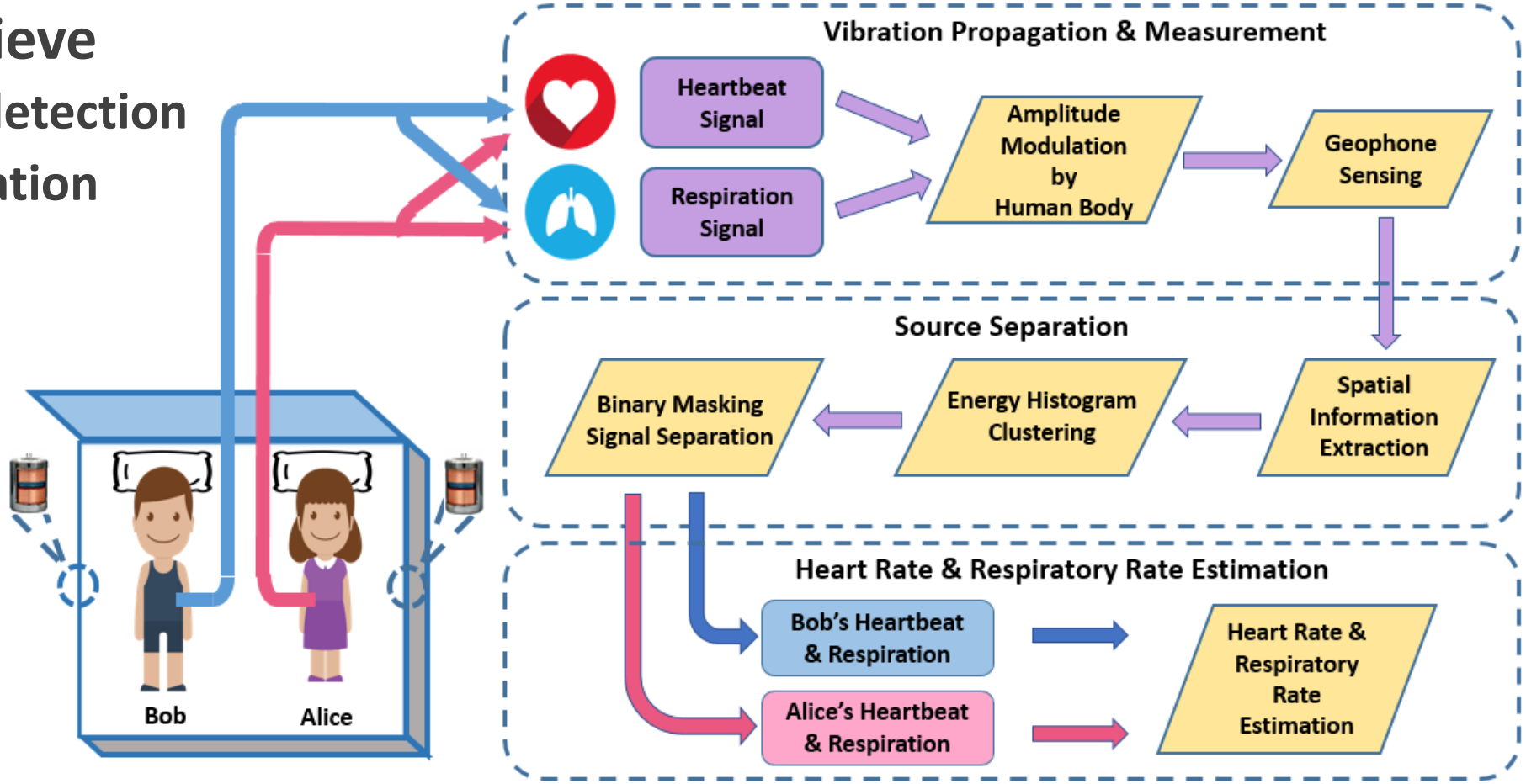
Geophone





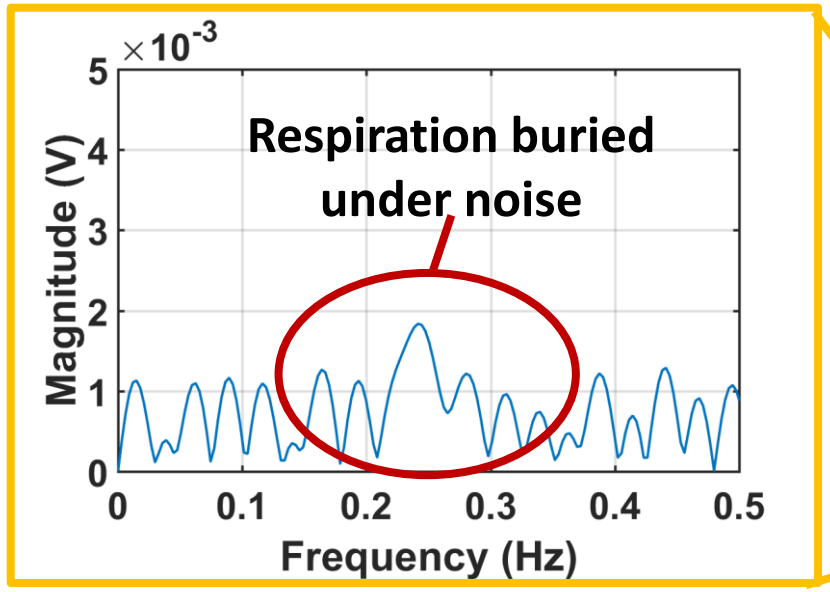
From HB-Phone to VitalMon

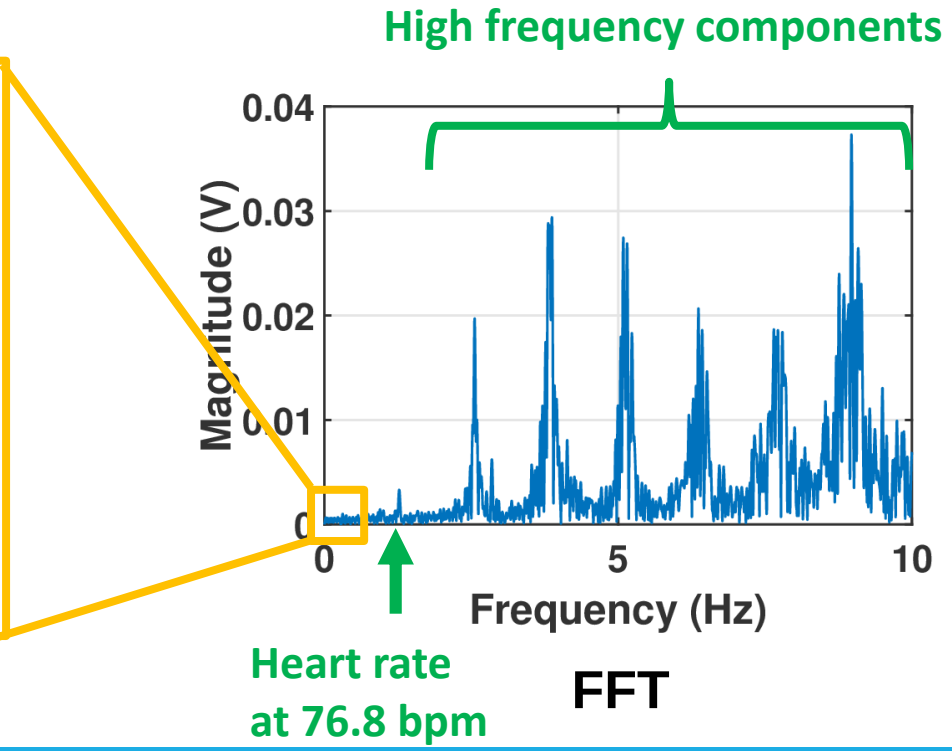
- Aim to achieve
  - respiration detection
  - signal separation



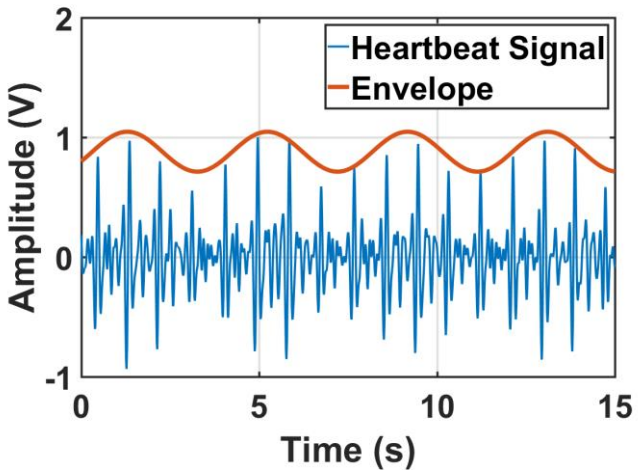
Respiration Detection: Challenges

- **Geophone is a second-order high-pass filter**
  - Respiration has very low frequency (< 1 Hz)
  - Hard to capture directly

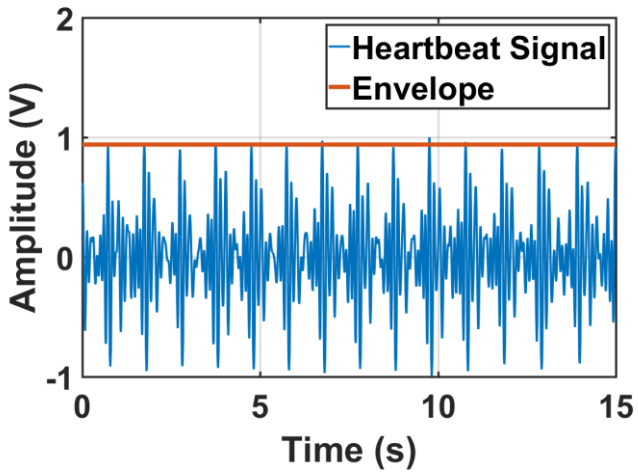




An Interesting Observation



Normal Breathing



Holding breath

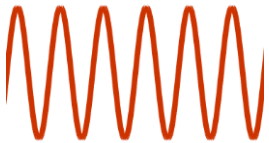
The pattern looks familiar? Amplitude Modulation (AM)!

Heartbeat and Respiration
- Natural Communication inside Human Body

- A person's respiration is amplitude modulated with his/her heartbeat signal

Inhale, chest full of air

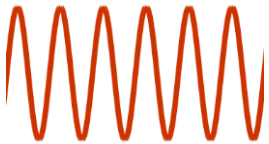
Heartbeat vibration through *stiff* chest

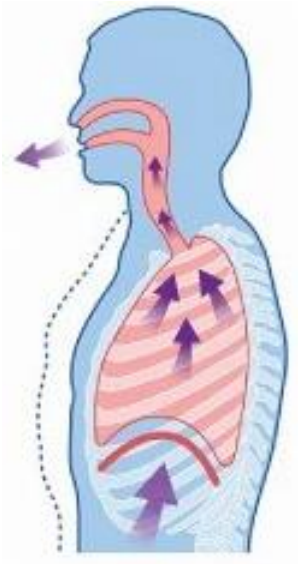


***Slight* attenuation**

Exhale, chest with little air

Heartbeat vibration through *floppy* chest





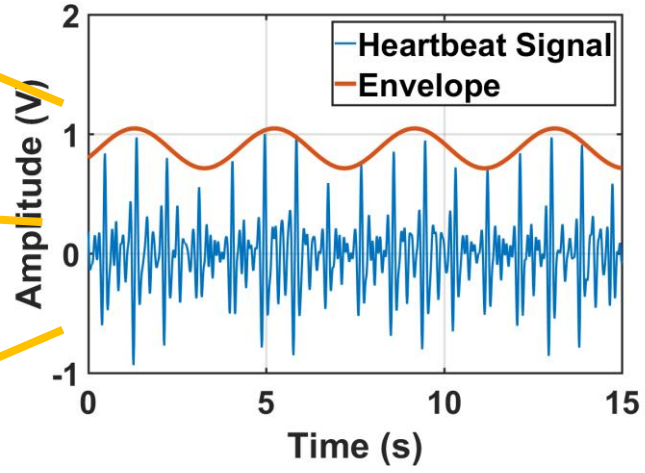
***Significant* attenuation**

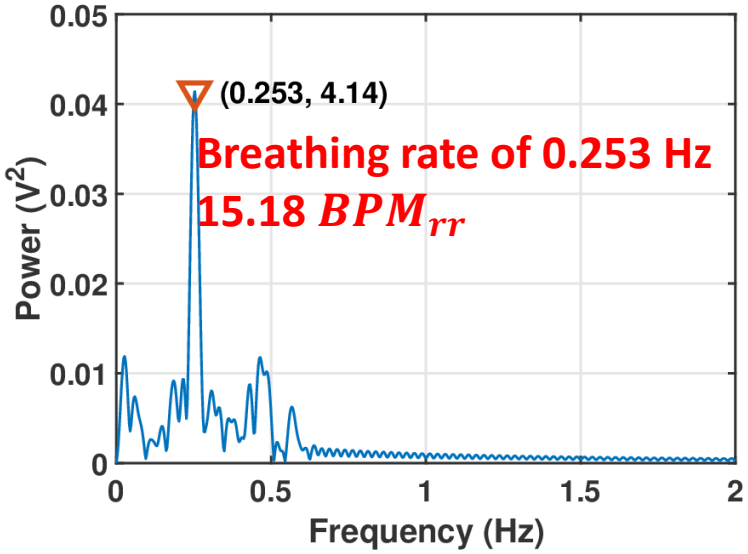
Amplitude Modulation

Respiration (info) signal

Amplitude Modulated signal

Heartbeat (carrier) signal



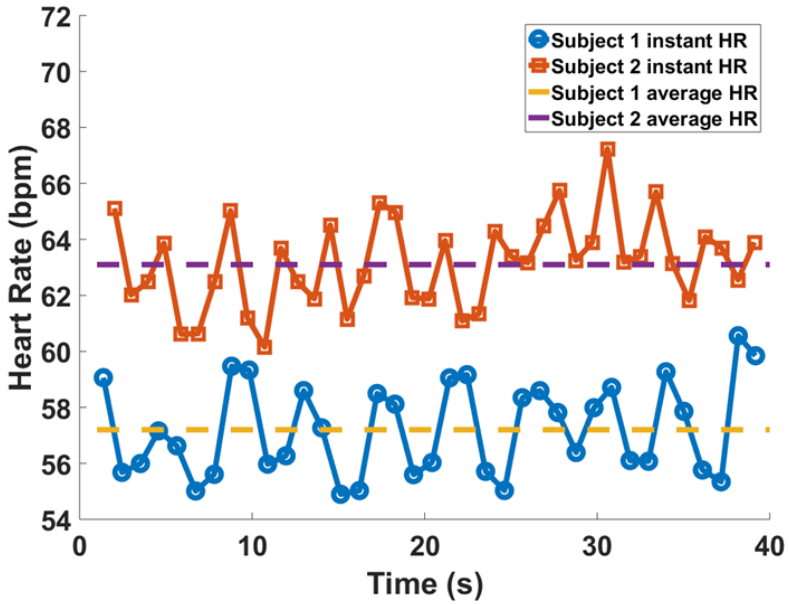


Square-Law Amplitude Demodulation

- Square of the signal
- Low-pass filter to remove high frequency energy (heartbeat part)
- Residue are mostly respiration signal

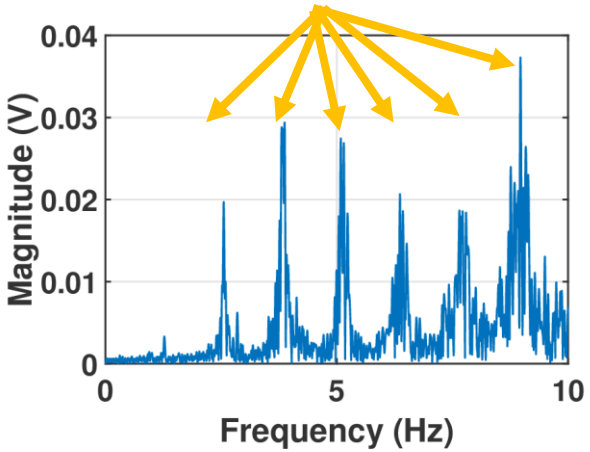
Heartbeat Separation: Challenges

- Heartbeats are quasi-periodic and may vary over time
- Frequency components from two heartbeats often close and mixed together



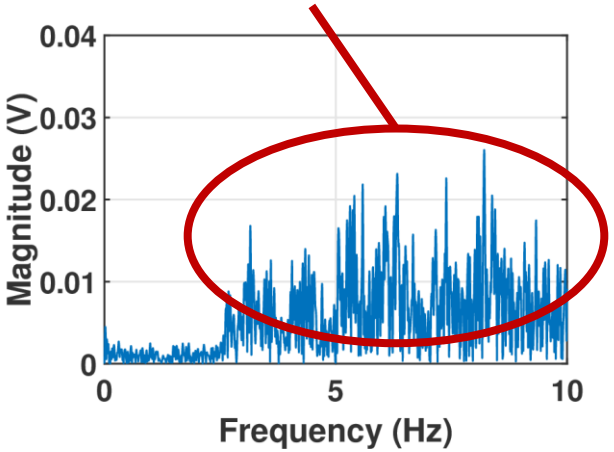
FFT - Subject 1

obvious harmonics



FFT – Subject 2 & 3

No obvious frequency pattern

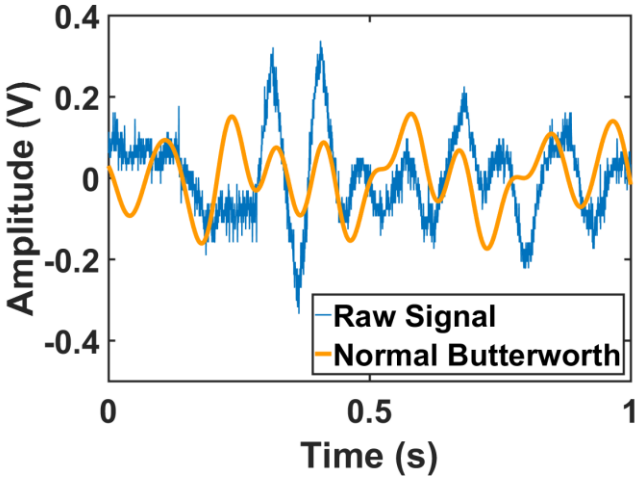


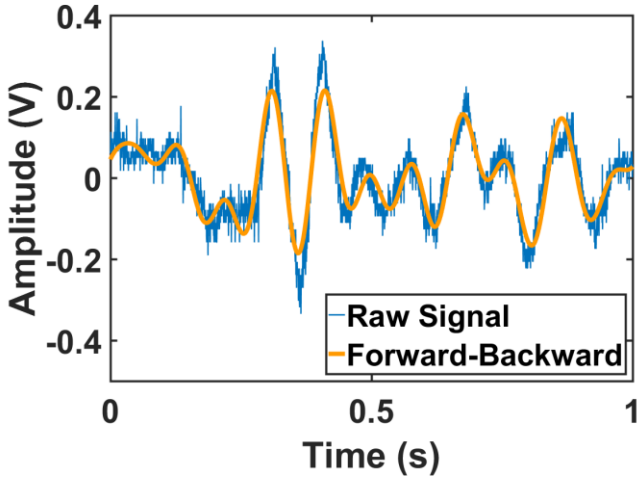
Inspiration: Blind Source Separation at a Cocktail

- **How to separate different voices?**
- **Each voice has a unique spatial feature (**attenuation, delay**)**

Noise Reduction

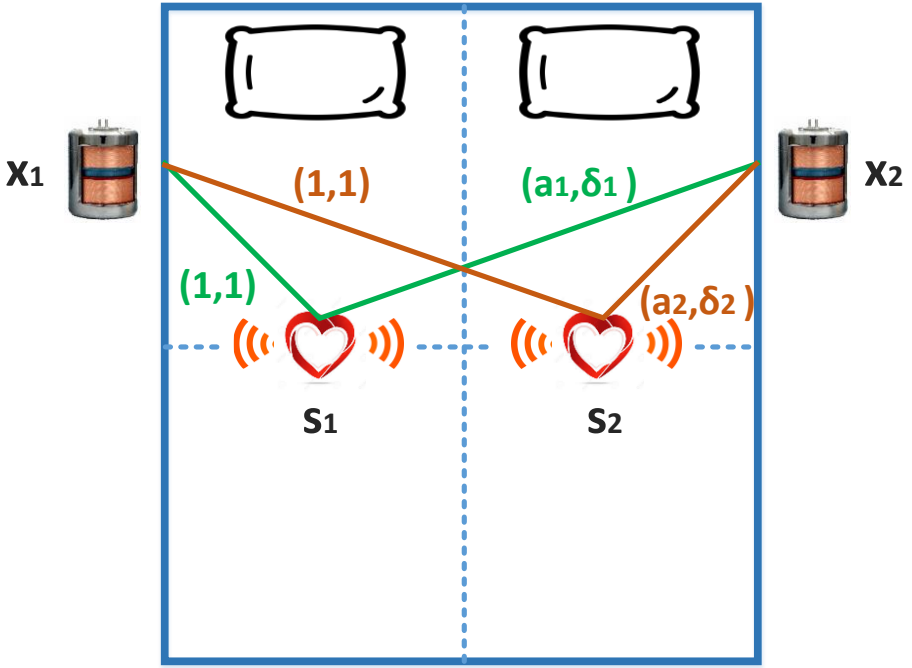
- Spatial signatures can be destroyed by distortion caused by filters
- Forward-backward Filtering
  - Apply a filter in the forward and backward direction
  - Phase distortions from both directions cancel each other





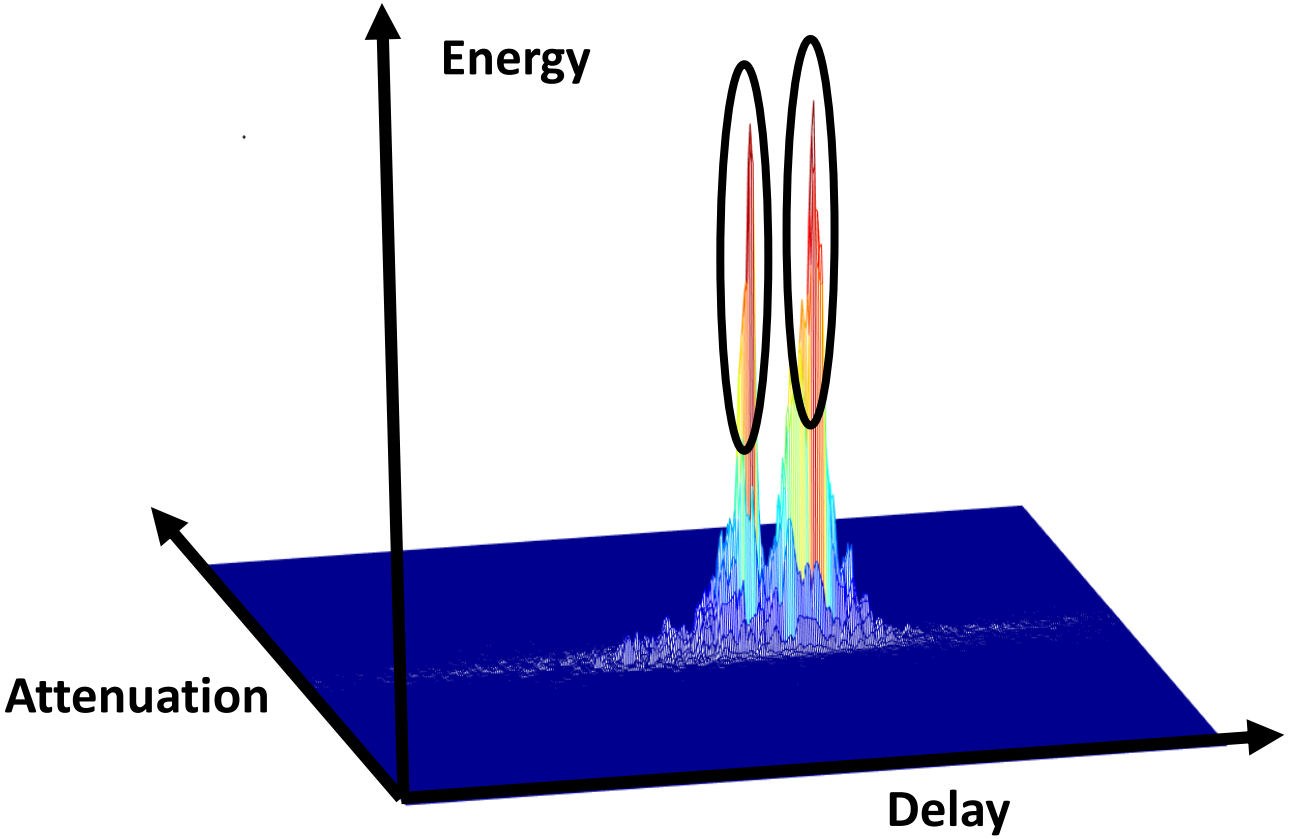
Separating Two Heartbeats

- Spatial signatures
  - (attenuation, delay) pair
  - Considering two heartbeats received by x_1 as reference
  - Two heartbeats received by x_2 has spatial signatures: $(a1, \delta 1)$ and $(a2, \delta 2)$



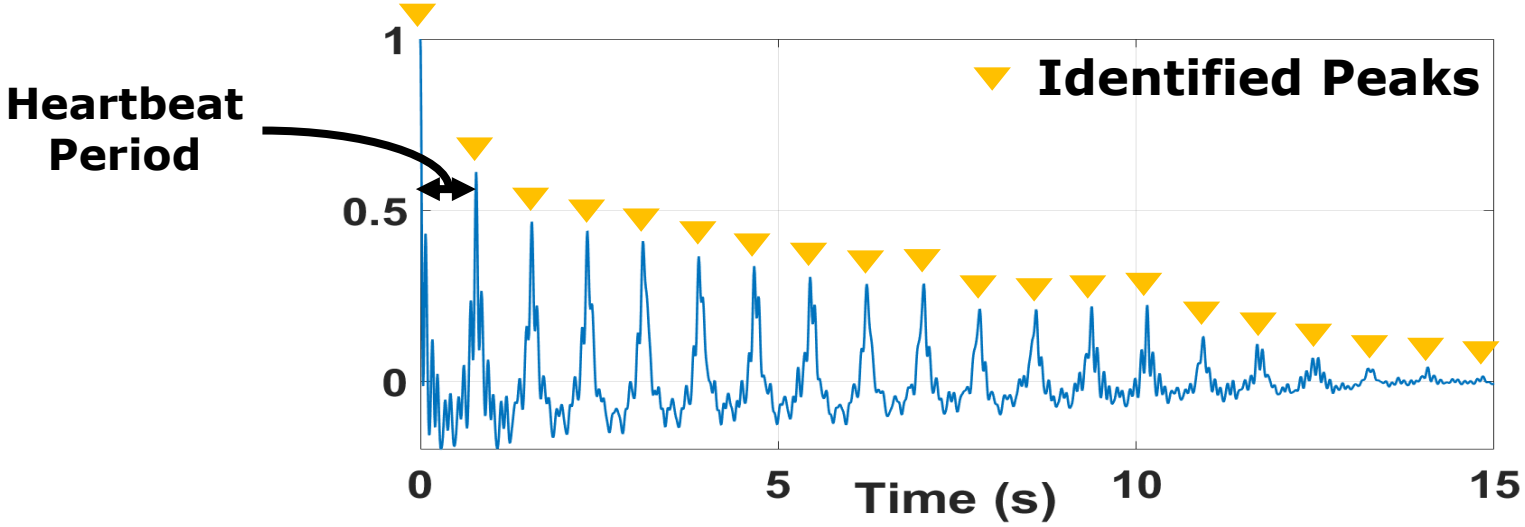
Frequency Domain Mapping and Unmixing

- Clustering signals of different frequency bins based on the attenuation and delay
- Unmixing signals by separating the clusters
- Converting the signal back to time domain



Time Domain Periodicity Extraction

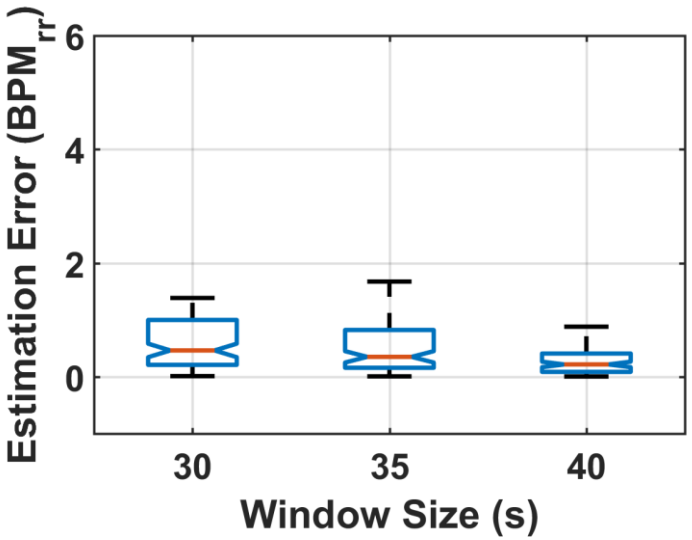
- Heart rate extraction
  - Instantaneous signal power
  - Sample Auto-correlation Function (Sample ACF)
  - Peak finding and measurement

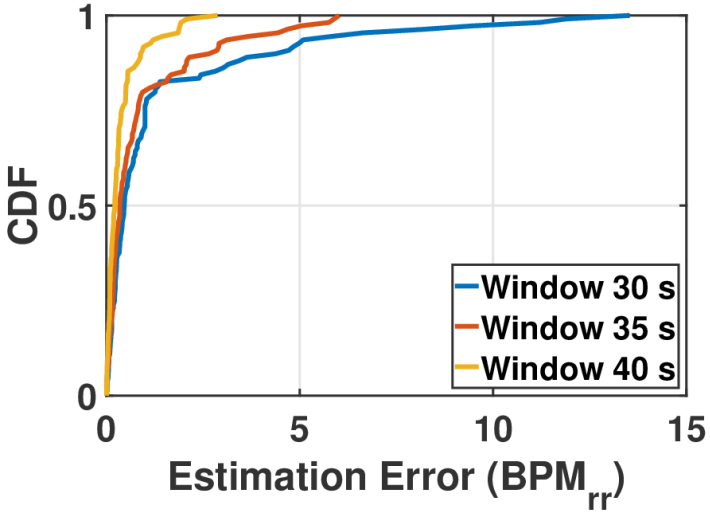


- Respiratory rate extraction by Square-Law Amplitude Demodulation

Evaluation

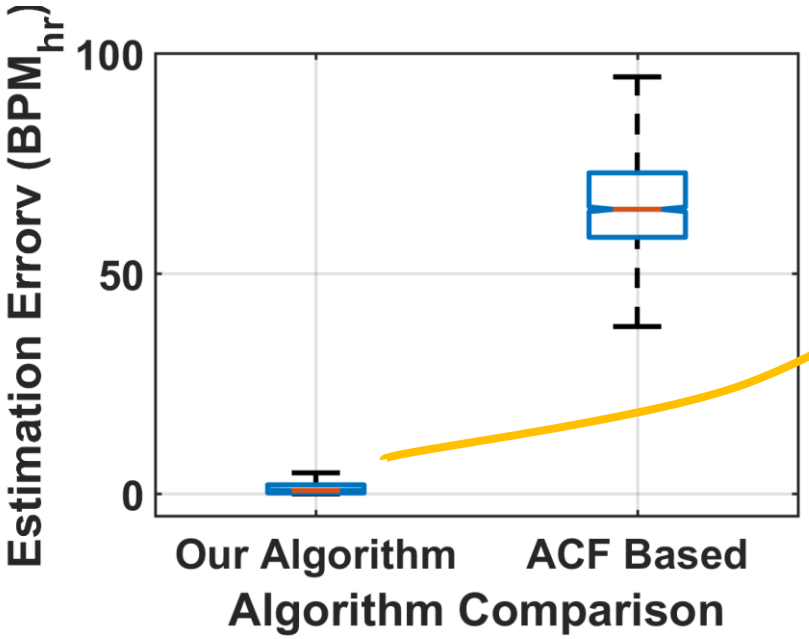
- Participants
  - 86 healthy adults (48 males, 38 females), >5000 trials
  - Age from 21 to 35 years, mean 25.12, SD 3.28
- Respiratory rate of a single subject (mean error 0.38 BPM_{rr}, median error 0.22 BPM_{rr})

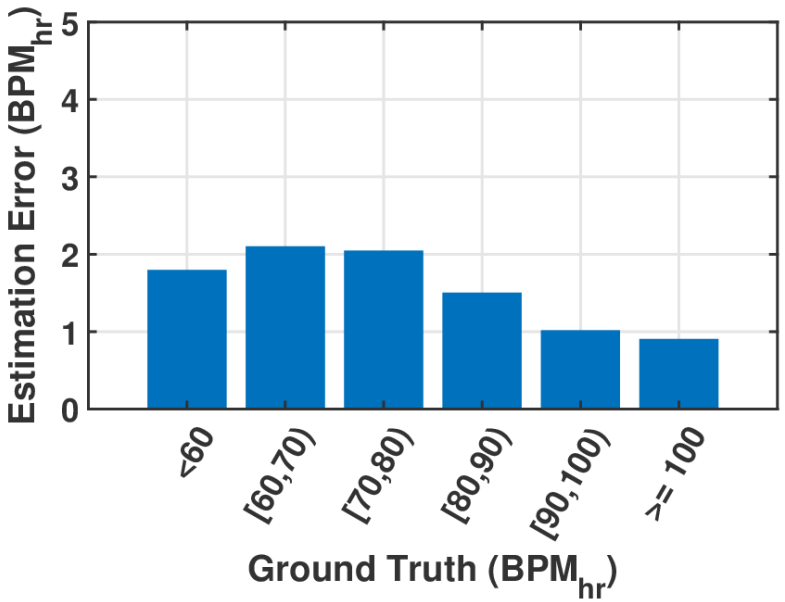




Better Heartbeat Separation than ACF alone

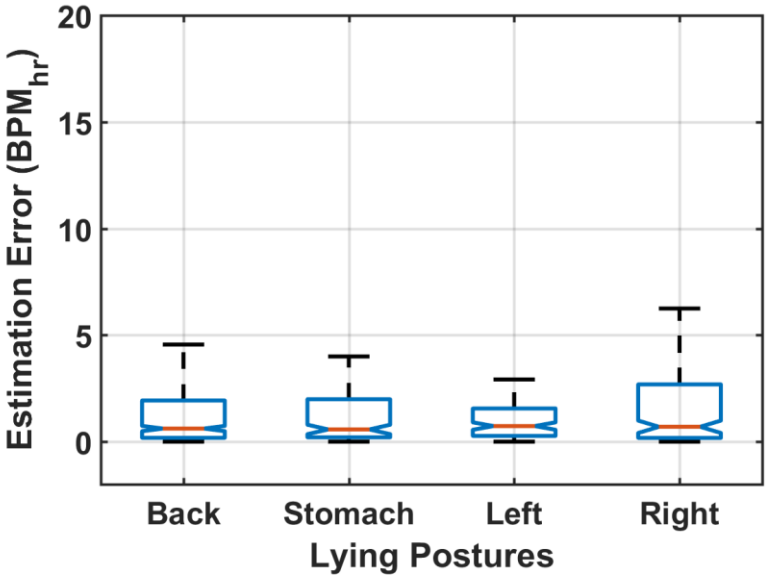
- **Compared with stand-alone Sample ACF algorithm**
  - **ACF attempts to capture both heartbeats at the same time, thus estimation error is a person's avg heart rate**
  - **Our proposed algorithm is more accurate over a wide-range test**

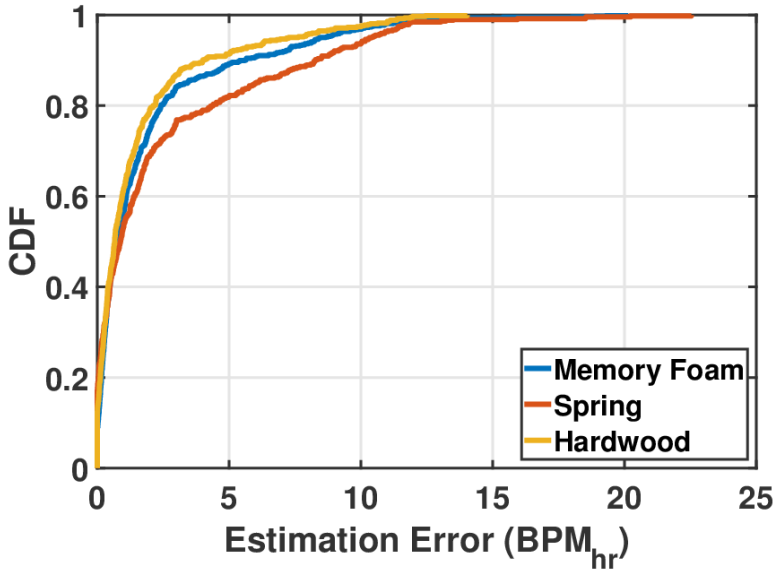




Robust across Lying Positions and Mattress Types

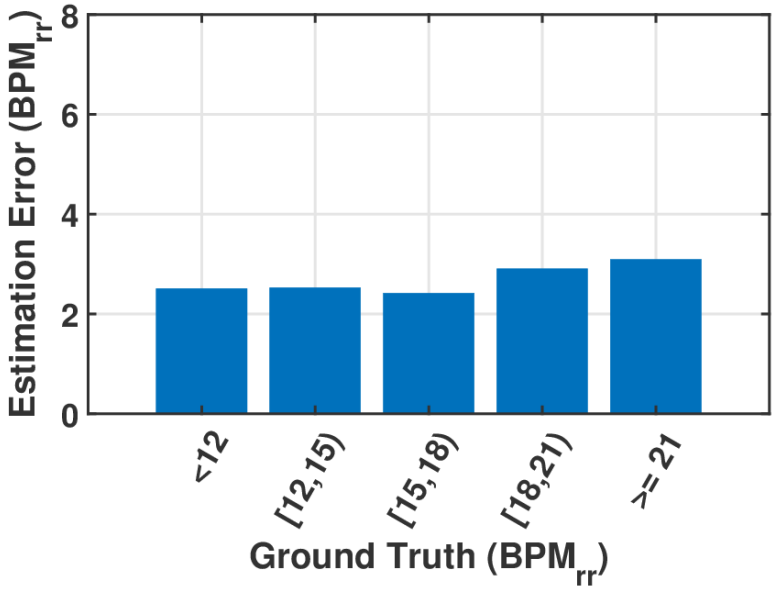
- For lying position, lying on the left gives the best performance
  - less attenuation within human body
- For mattress types, hardwood gives the best performance
  - least oscillations and less attenuation

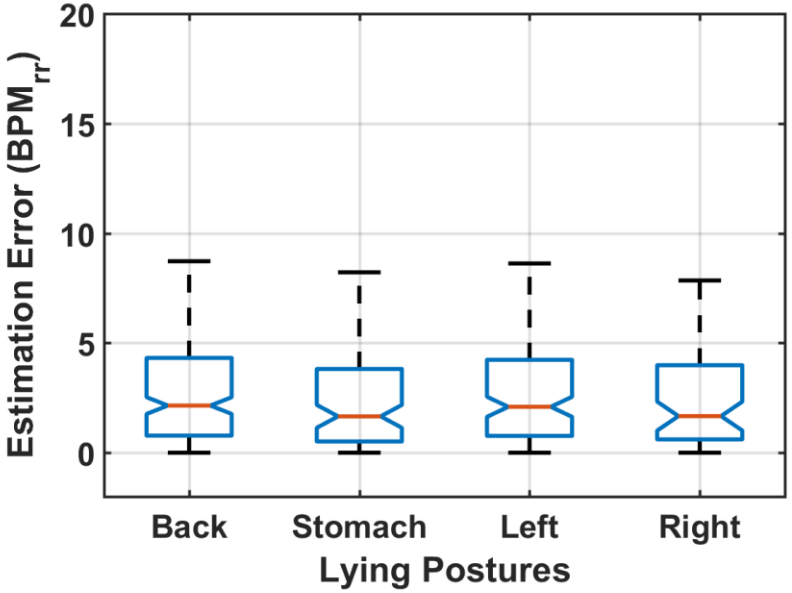




Respiratory Rate Estimation for Two Subjects

- Our proposed system is robust and accurate across different lying positions
  - Larger error compared to the single-subject scenario
    - heartbeat separation brings extra distortion
  - For lying positions, all positions are almost comparable





Conclusion

- VitalMon is a heart rate and respiratory rate monitoring system
  - an amplitude demodulation algorithm to extract respiration from heartbeat signal
  - a heartbeat separation algorithm
- VitalMon is
  - Accurate
  - Robust over a wide hr/rr range
  - Robust across different lying positions and different mattress types

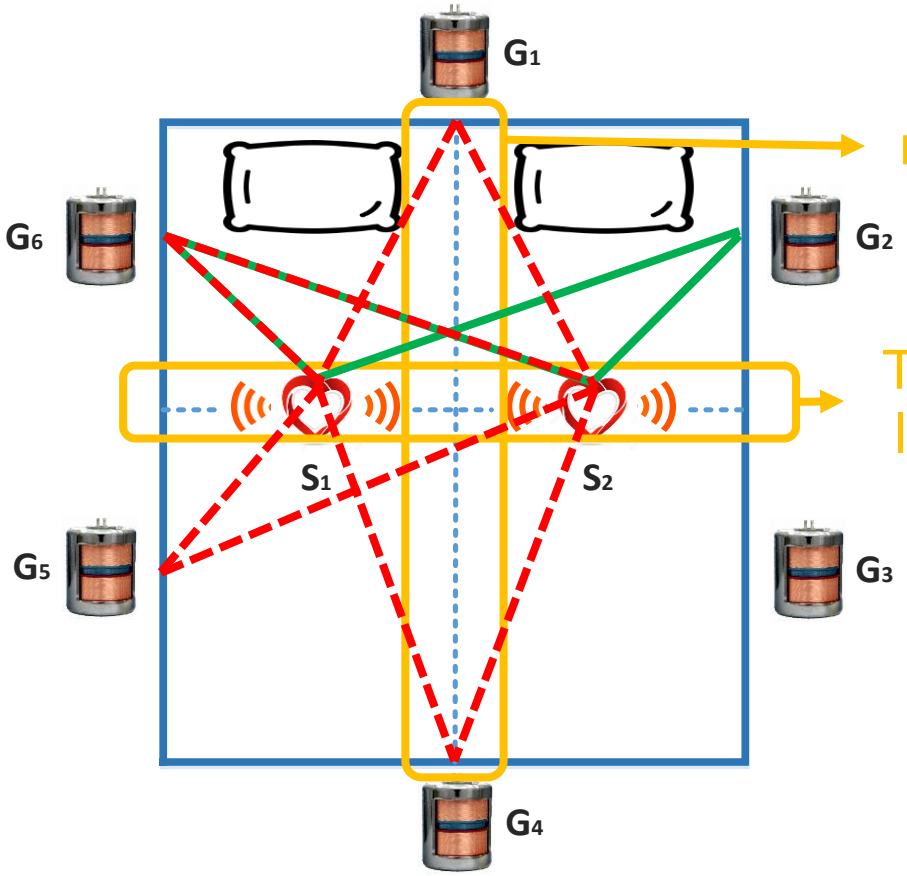
Questions and Answers

Our Heartbeat Separation Technique

- Blind source separation based on the time-frequency masking
  - Take advantage of spatial signatures (attenuation and delay)
  - Not rely on knowing the frequency components

- Assumptions
  - Two sources don't have exactly the same frequency component
  - No phase wrap (wavelength >> length of bed)
  - No same spatial signatures (ensure it by installing the sensor)

Ensure we get different spatial signatures



The line is midperpendicular of the locations of two hearts

The line goes across the locations of two hearts.

Geophone has its own challenge

- Second-order high-pass filter
  - Insensitive to low frequency movements
  - e.g., heartbeat at 60bpm, respiration is even worse