TH-3C

Effect of respiration harmonics on beat-to-beat analysis of heart signal

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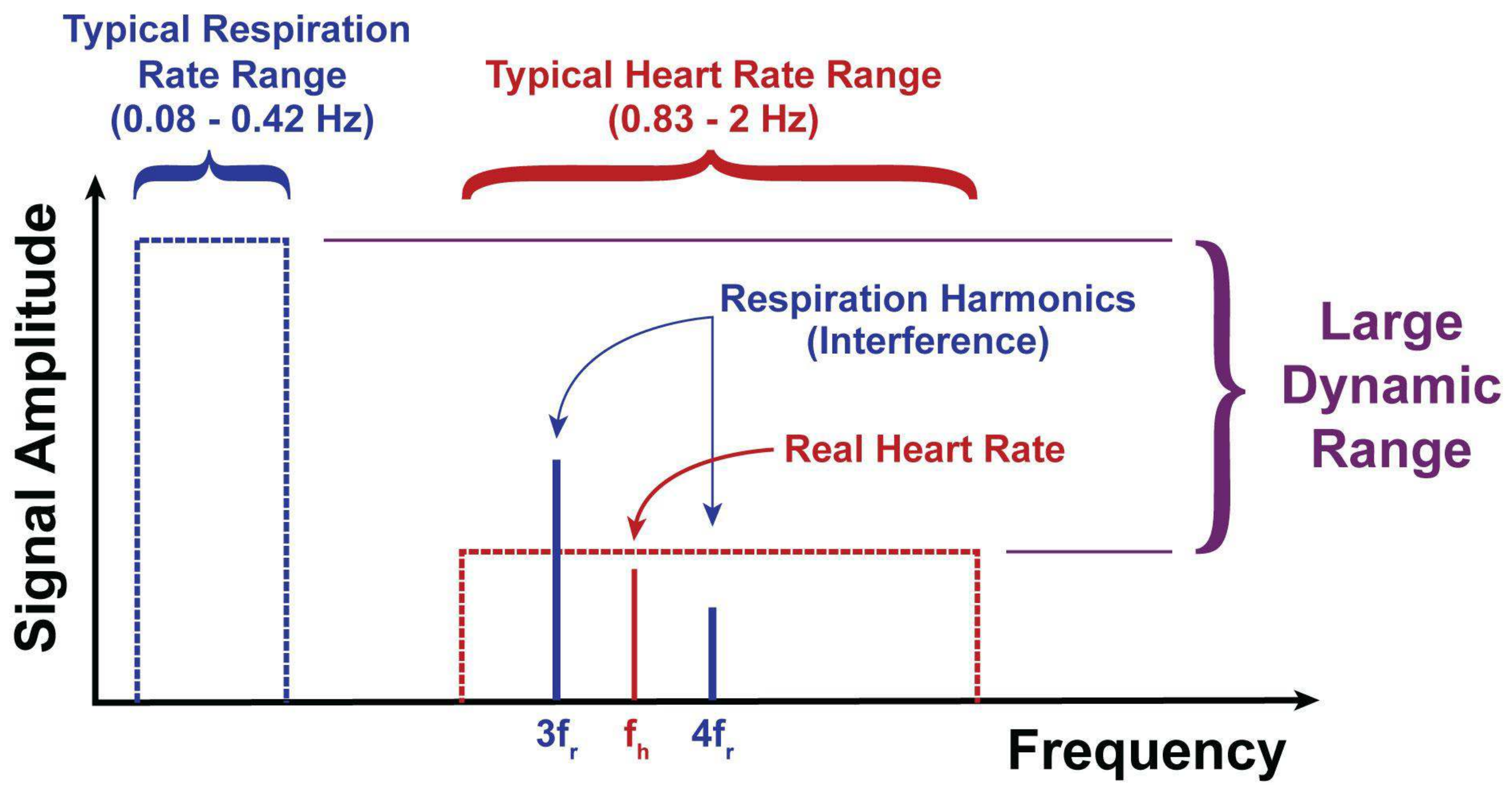
Introduction

- Physiological monitoring-
  - Heart and respiratory rate
  - Heart rate variability
  - Tidal volume
  - Pulse pressure
- Advantages -
  - Continuous
  - Unobtrusive
- Application-
  - Occupant-centered control of indoor environmental quality (IEQ)

Respiration harmonics interference in heart signals

- Respiratory signal
  - Frequency range- 5-25 breaths per minute (b/m)
  - 0.08 Hz-0.42 Hz
  - Amplitude - 4-12mm
- Heart signals-
  - 50-120 beats per minute(bpm)
  - Amplitude- 0.2-0.5mm
  - 0.83 Hz-2 Hz
- Respiration harmonics-
  - Non-linearity of the radar output signal
  - Inherent features of respiration



f_r = *Fundamental respiration frequency*

Study of respiration harmonics interference

Previous work-

1. Adaptive Notch filter
2. Complex signal demodulation

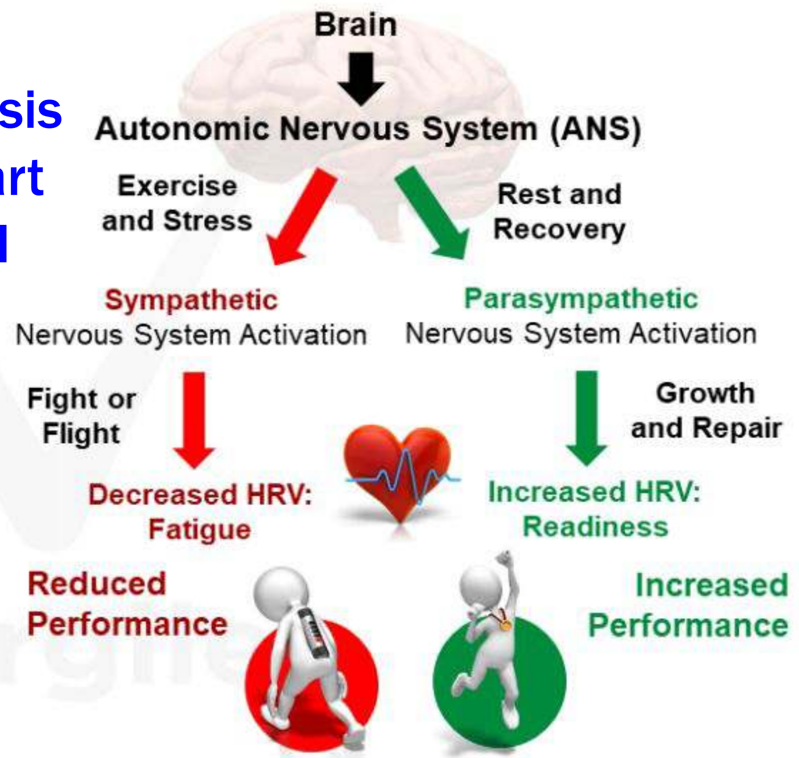
Limitation-

1. Focused on heart rate finding only.

This work-

1. Studies the origin of respiration harmonics
2. Its effect on heart rate finding
3. Its effect on beat to beat analysis of heart signals
4. Compares proposed method with the current solutions.

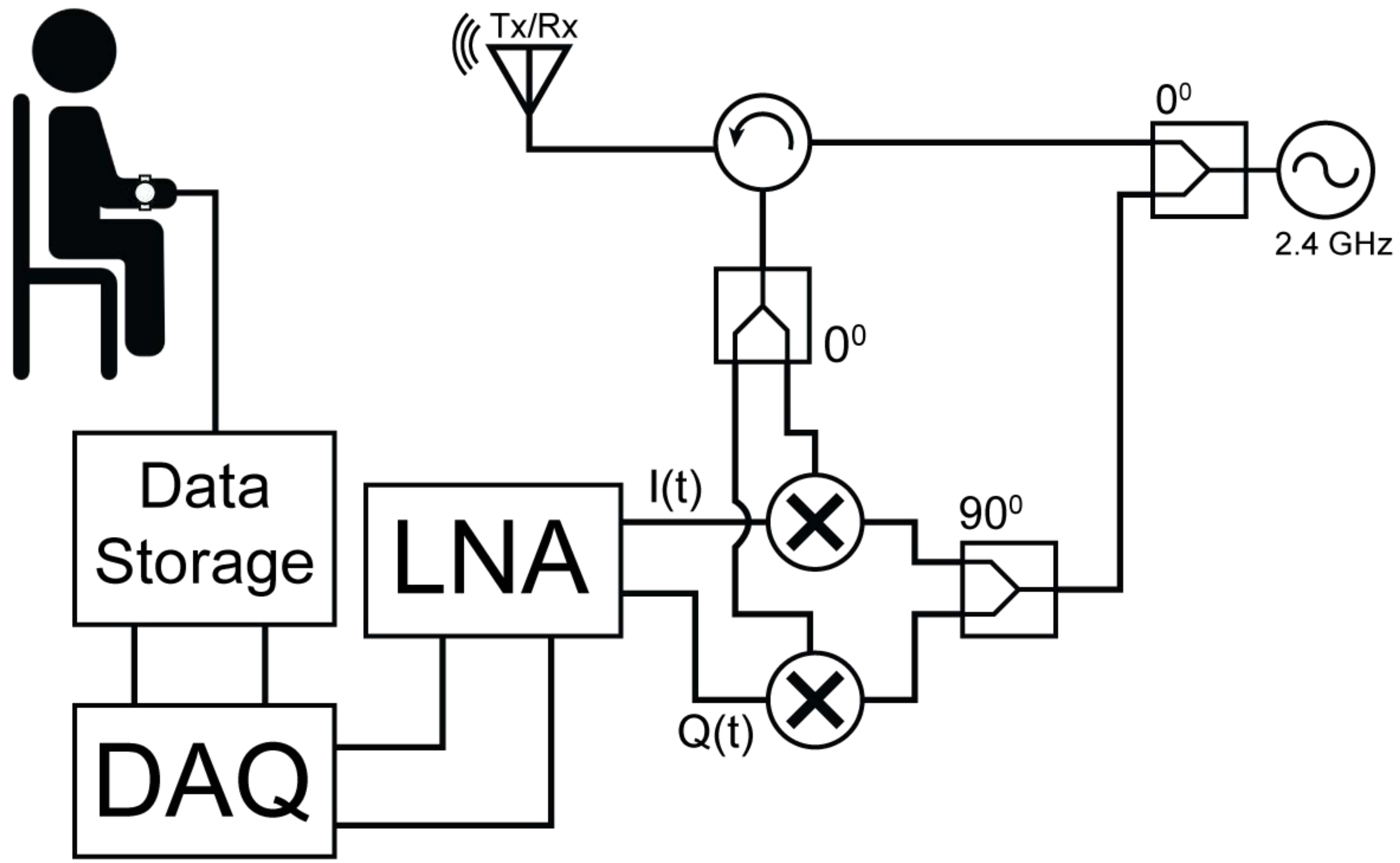
Accurate HRV analysis requires correct heart beat to beat interval extraction!



https://adamvirgile.com/2018/06/03/heart-rate-variability-hrv-in-sport-a-review-of-the-research/

- HRV- Marker of vagal activity
- Lowered HRV can indicate-
  - increased stress
  - decreased autonomic activity,
  - sleep apnea,
  - diabetic neuropathy, and
  - increased risk of sudden cardiac death.

Radar Non-linearity-



Transmitted signal:

$$T(t) = A_T cos(2\pi ft + \phi(t))$$

Baseband I & Q outputs:

$$B_I(t) = A_B cos(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t))$$

$$B_Q(t) = A_B sin(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t))$$

Non-linearity of cosine transfer function

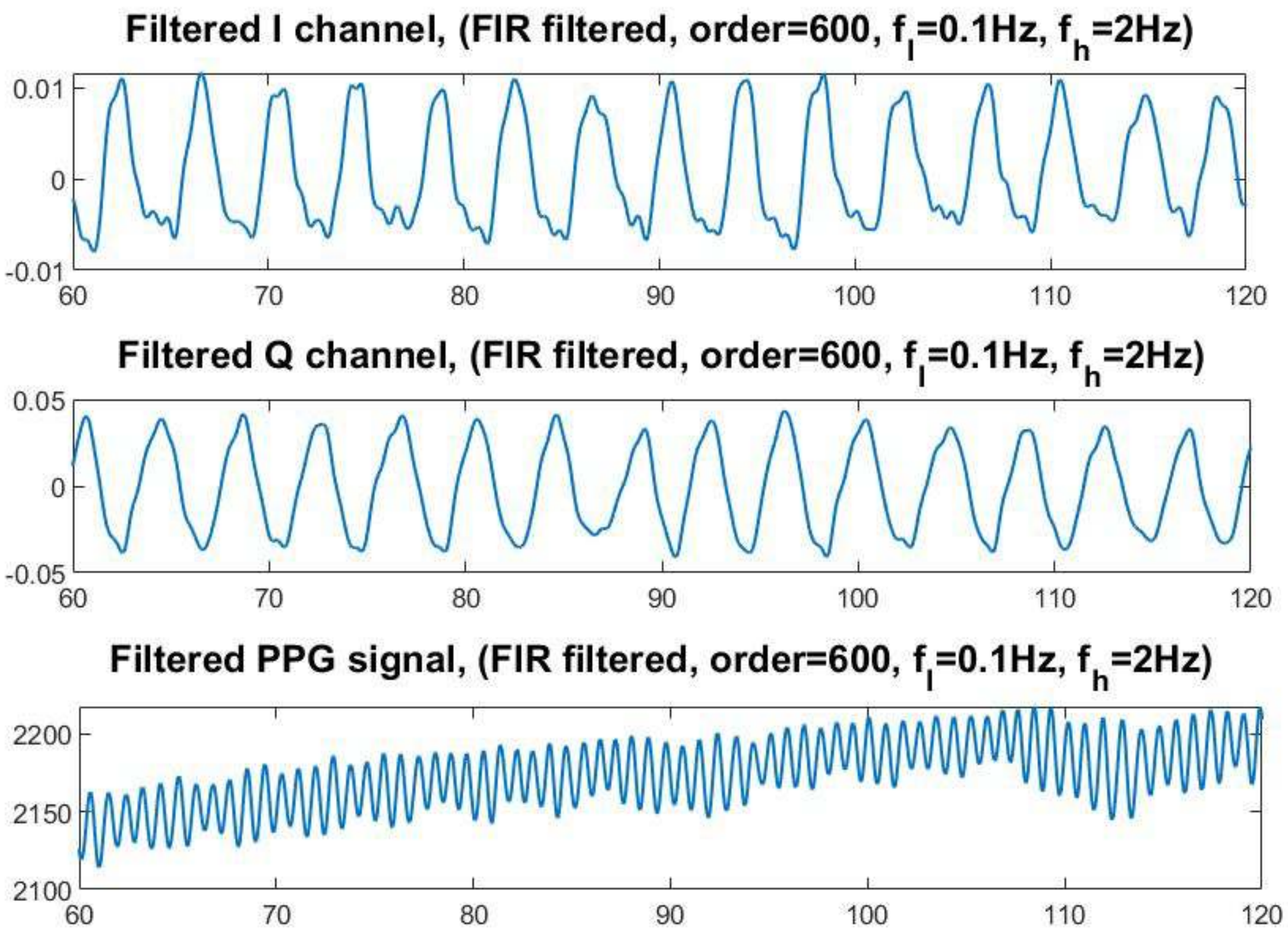
$$B(t) = \cos\left[\frac{4\pi x(t)}{\lambda} + \phi\right] = \sum_{n=-\infty}^{\infty} J_n(\frac{4\pi m}{\lambda}) \cos(n\omega + \phi)$$

Intermodulation

$$B(t) = \mathrm{Re}\left(\sum_{k=-\infty}^{\infty} J_k(\frac{4\pi m_r}{\lambda}) e^{jk\omega_r t} \sum_{l=-\infty}^{\infty} J_l(\frac{4\pi m_h}{\lambda}) e^{jl\omega_h t} \cdot e^{\phi}\right)$$

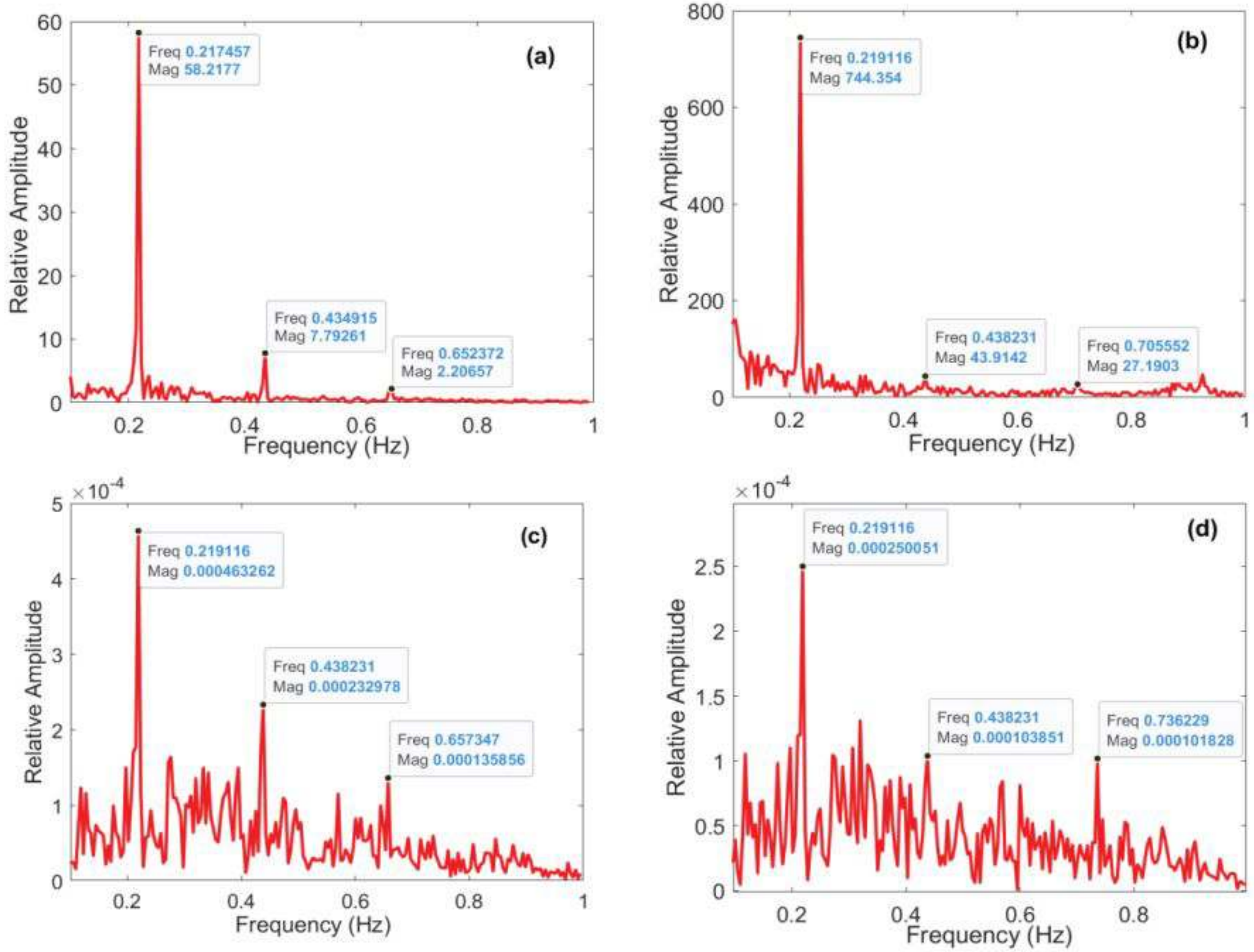
$$= \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_l(\frac{4\pi m_h}{\lambda}) J_k(\frac{4\pi m_r}{\lambda}) \cos(k\omega_r t + l\omega_h t + \phi)$$

Non-linearity of respiratory feature-



Radar

PPG



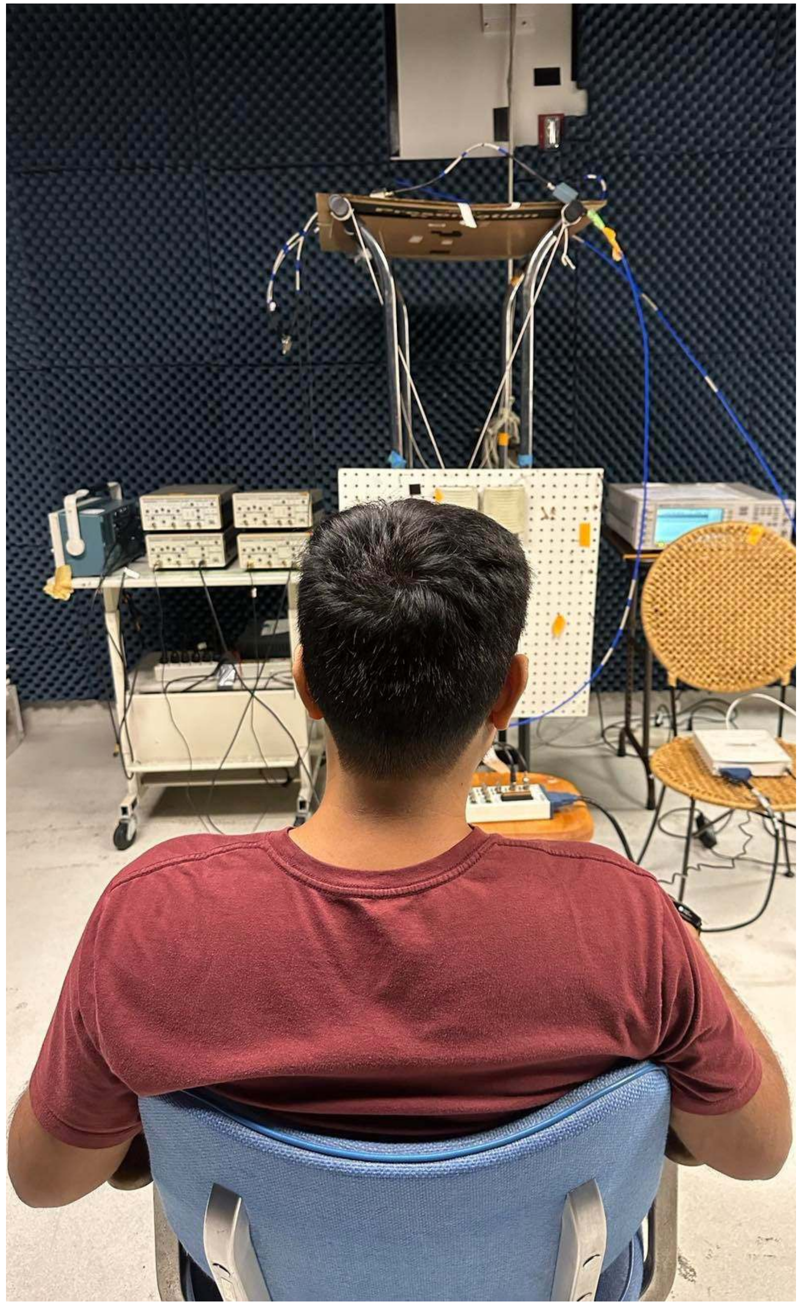
X-axis accelerometer

Y-axis accelerometer

Experimental setup-

No. of Subjects	3, sitting still
Breathing rates	13b/m, 15b/m, 18b/m
Distance of Radar from subject's sternum	1 metres
Frequency & power	2.4GHz, 16dBm
Sampling frequency	100 Hz
Gain(LNA)	20
Filtering(LNA) - DC Coupled	10 Hz Low pass
NI DAQ resolution	18 bit

Reference PPG-
MAXREFDES103#

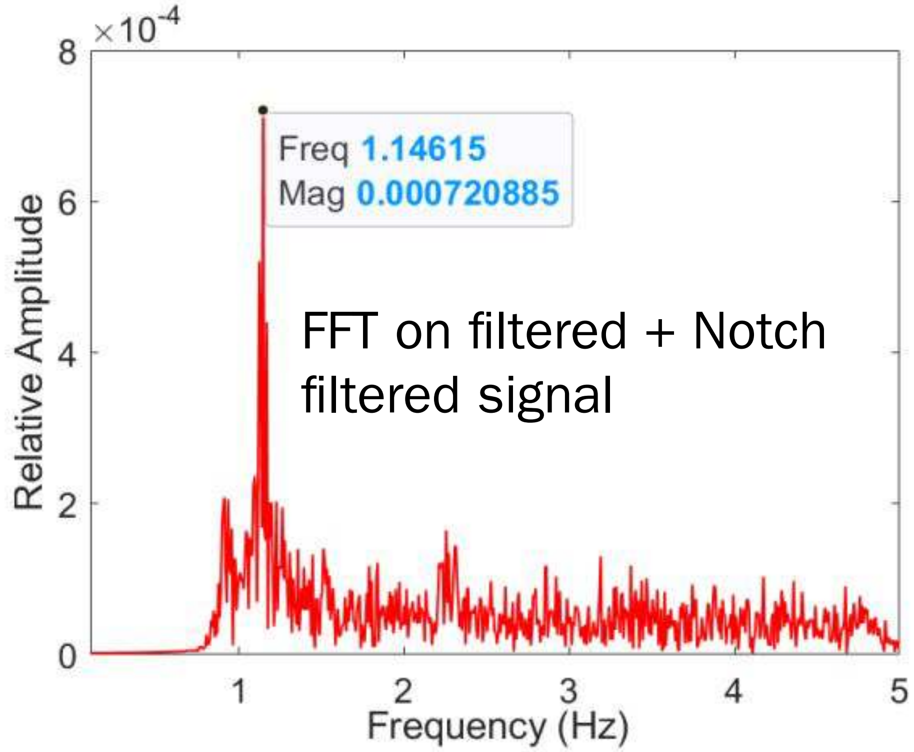


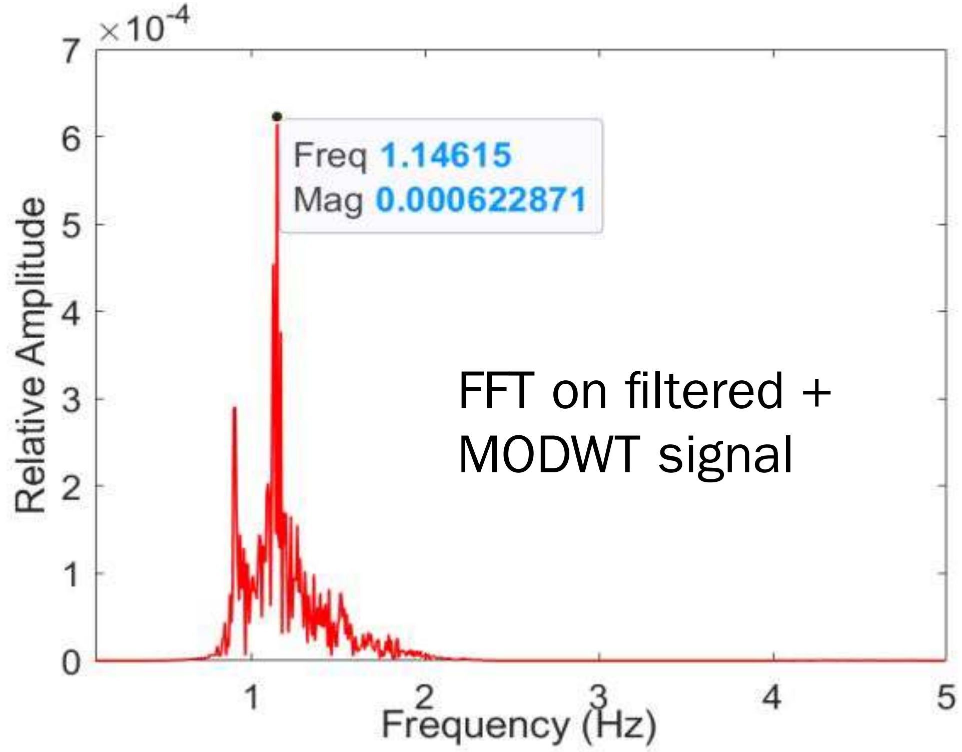
Proposed method-

Bandpass FIR filter (Cut off at 0.85 - 5Hz & Order =600)

Adaptive IIR single notch filter

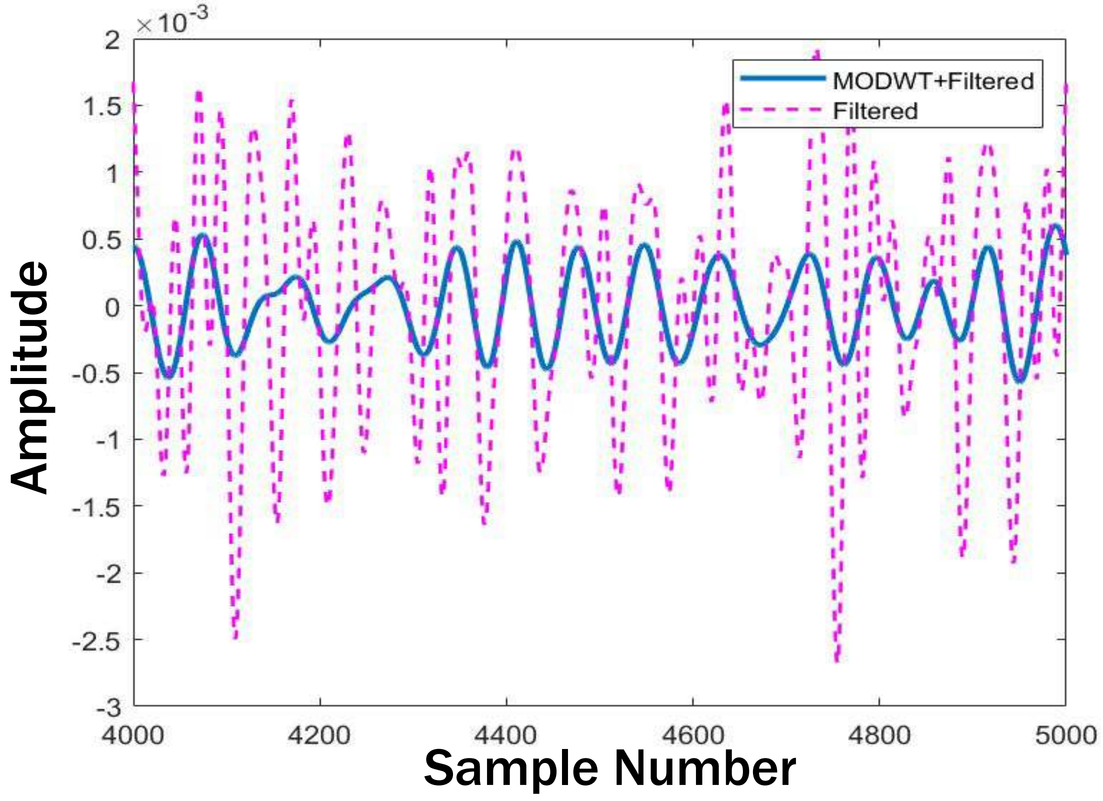
Maximal Overlap discrete wavelet transform (MODWT)
(Mother wavelet- sym4 & Reconstruction level - 6)





MODWT-

- Ability to reconstruct signals from any levels
  - Avoid levels containing respiration harmonics.



Decomposition level	Frequencies (Hz)	Relative Energy
Level 1	25-50	0.00%
Level 2	12.1-25.9	0.01%
Level 3	6.03-12.9	0.59%
Level 4	3.02-6.46	10.63%
Level 5	1.51-3.23	35.84%
Level 6	0.754-1.62	48.74%
Level 7	0.377-0.808	3.19%
Level 8	0.189-0.404	0.46%
Level 9	0.0944-0.202	0.16%
Level 10	0.0473-0.101	0.08%
Level 11	0.0244-0.050	0.04%
Approximate	0-0.0235	0.27%

MODWT

Time series -

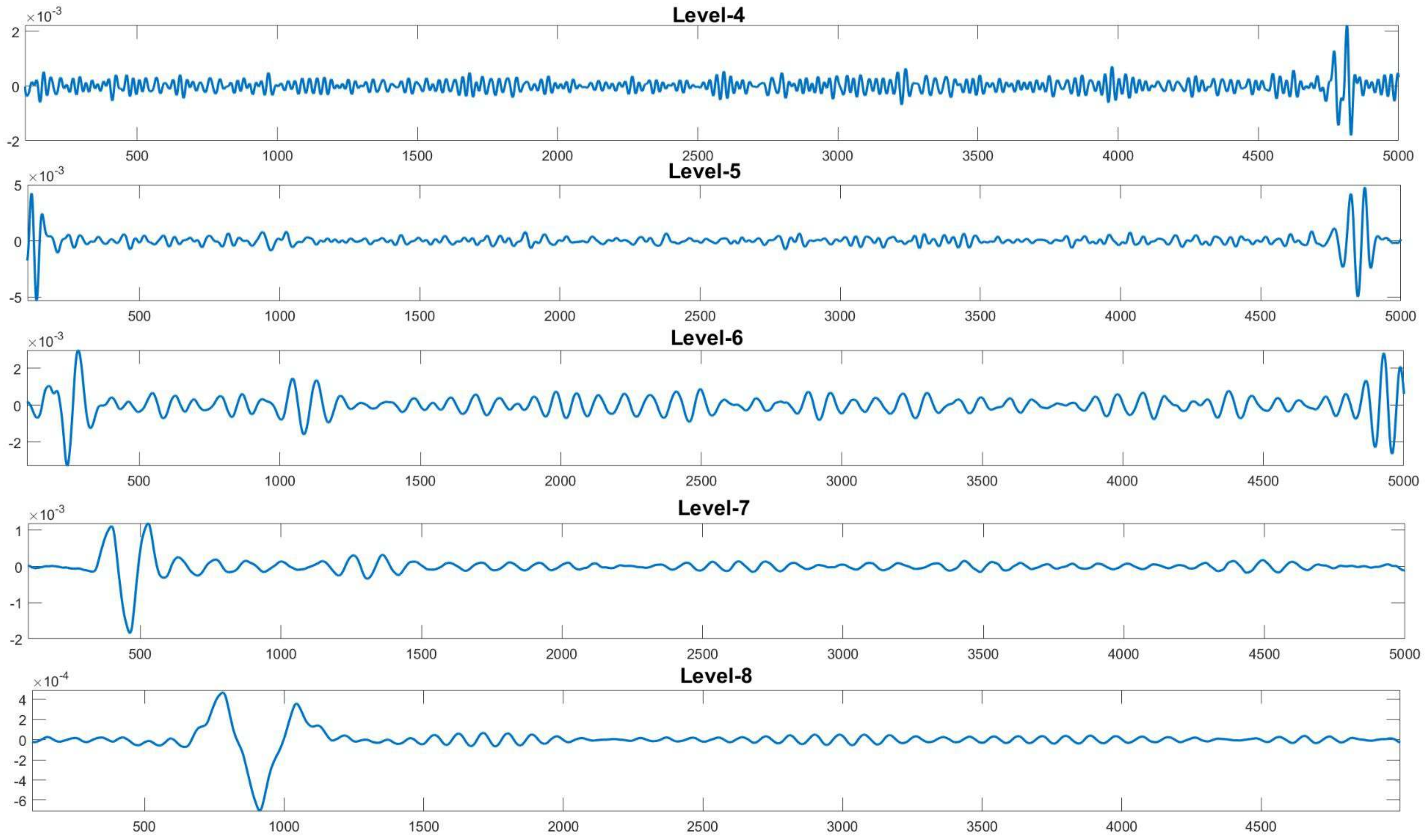
$$C^{(M)}_{(o,n)} = x_n$$

Wavelet Coefficient-

$$d_j^{(M)}, n = \sum_{l=0}^{L-1} \tilde{h}_L C^{(M)}_{j-1}, (n - 2^{j-1} l) mod N$$

Scaling Coefficient-

$$C^{(M)}_{j,n} = \sum_{l=0}^{L-1} \tilde{g}_L C^{(M)}_{j-1}, (n - 2^{j-1} l) mod N$$



- Unlike DWT, MODWT is defined for all sample sizes.
- MODWT of level J_0 has $(J_0 + 1)N$ coefficients, whereas DWT has N coefficients for any given J_0
- The scaling and wavelet filters are not downsampled and unaffected by circular shift in MODWT.

Average heart rate (bpm) -

Dataset	With notch filters			With MODWT			Reference
	I-Channel	Q-Channel	LD	I-Channel	Q-Channel	LD	
Subject A (13b/m)	67.8	71.09	68.63	66.57	66.53	66.98	70.34
Subject A (15b/m)	66.38	69.79	67.23	69.74	70.32	70.18	69.16
Subject A (18b/m)	67.94	76.32	67.94	67.45	67.88	67.94	67.95
Subject B (13b/m)	72.27	68.18	81.81	73.22	74.22	74.25	70.34
Subject B (15b/m)	72.27	91.36	90.68	72.99	73.19	73.03	72.6
Subject B (18b/m)	69.57	71.3	71.3	69.72	68.77	68.73	68.75
Subject C (13b/m)	64.91	71.64	71.63	73.01	73.03	72.16	70.09
Subject C (15b/m)	72.79	73.22	72.79	69.74	69.75	69.73	70.6
Subject C (18b/m)	68.77	68.77	68.77	68.83	68.76	67.55	66.67

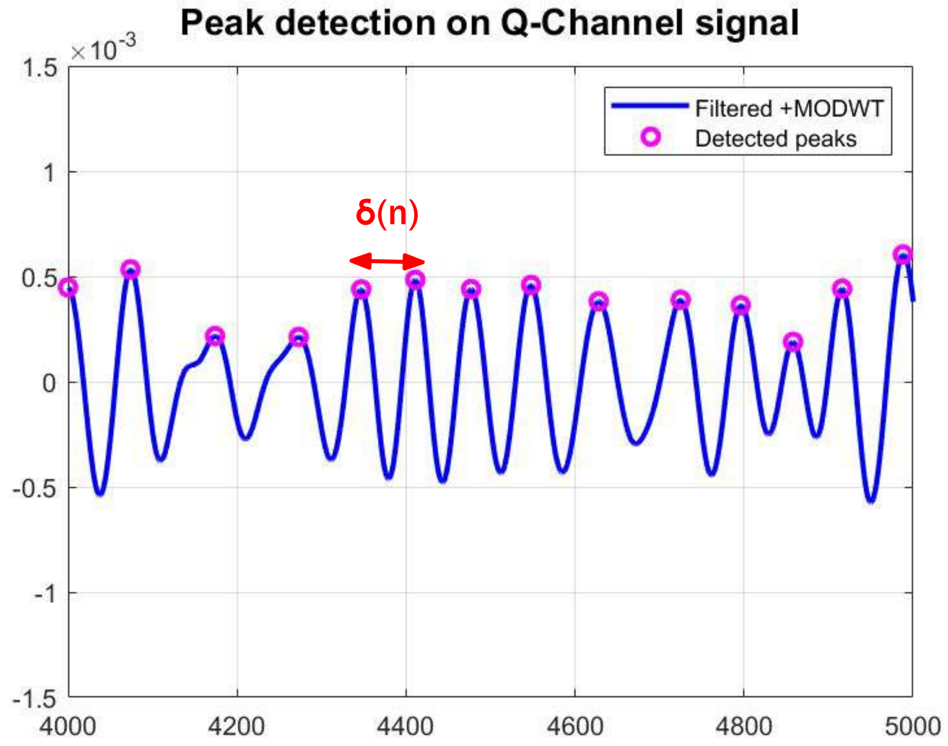
Beat to beat analysis-

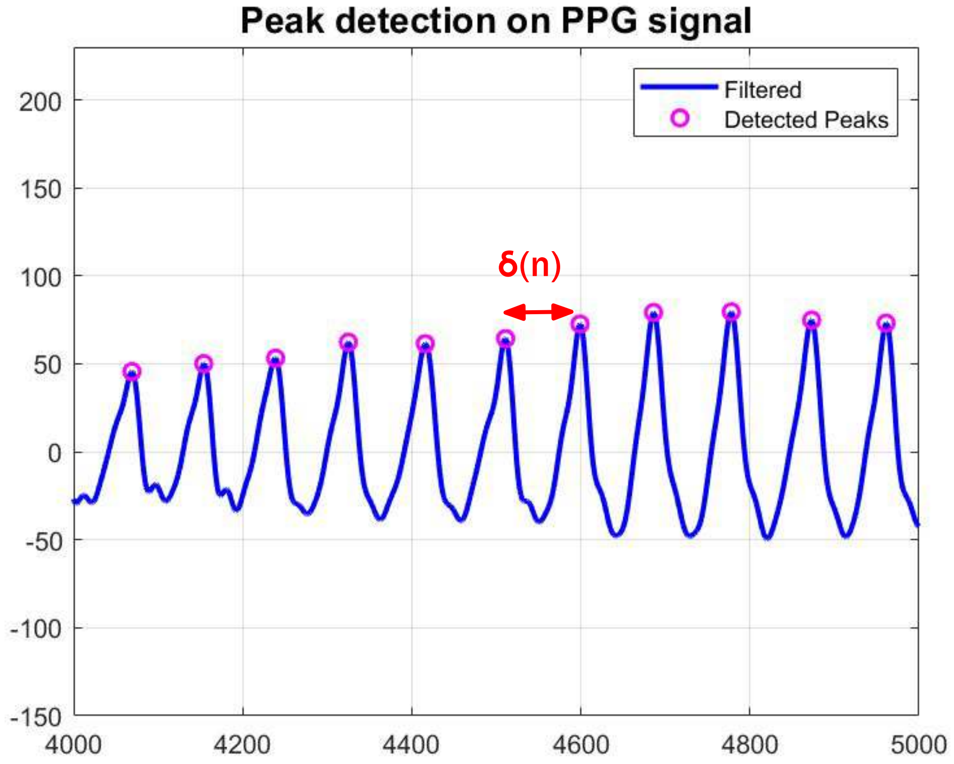
Standard deviation of NN interval (SDNN) -

- Most common metric
- Suitable for short term measurement

$$\mathrm{SDNN} = \sqrt{\frac{1}{N-2}\sum_{n=2}^{N}\left(\delta(n)-\overline{\delta}\right)^2}$$

Where,
N- No. of heart beats.





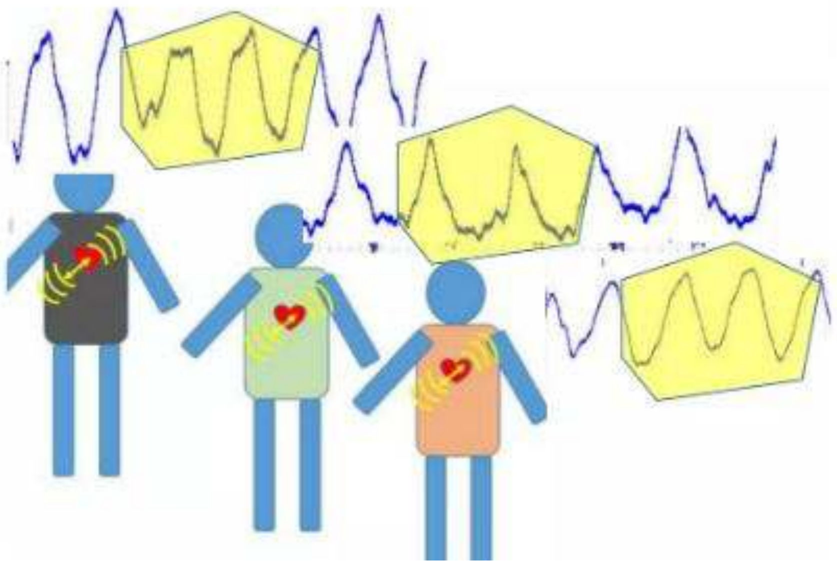
Difference of SDNN of heart signals from the radar and PPG signal in milliseconds (ms) -

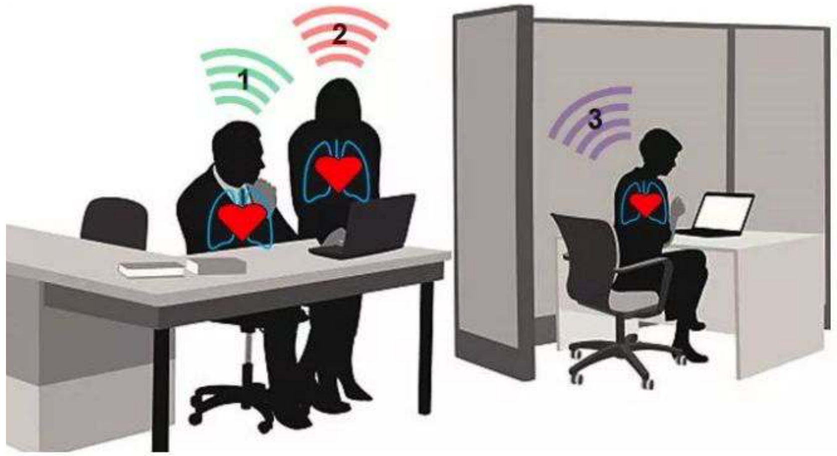
Dataset	With notch filters only			With MODWT		
	I-channel	Q-channel	LD	I-channel	Q-channel	LD
Subject-A (13b/m)	75.22	182.69	170.81	71.37	145.39	**149.54**
Subject-A (15b/m)	92.24	141.41	125.6	75.03	109.62	**115.01**
Subject-A (18b/m)	78.74	181.57	131.99	64.52	141.26	**118.46**
Subject-B (13b/m)	64.64	65.68	48.9	**5.54**	21.89	**18.56**
Subject-B (15b/m)	112.73	71.16	93.9	65.82	82.75	**78.92**
Subject-B (18b/m)	130.4	93.05	123.12	110.89	**100.67**	**80.71**
Subject-C (13b/m)	122.34	99.37	112.03	43.32	38.44	**36.33**
Subject-C (15b/m)	37.44	74.81	68.77	34.81	36.07	**30.32**
Subject-C (18b/m)	95.29	95.9	95.15	42.02	44.09	**34.88**

Increase by 8.19% **Decrease by by 91.43%** **Consistent improvement in LD**

Conclusion-

- Results-
  - Improvement in average HR using MODWT
    - The mean difference of the average HR of I-Channel and reference PPG signal decreases from 1.99 bpm to 1.67 bpm when MODWT is used instead of the notch filter
  - Consistent improvement in SDNN difference for LD signals from 18.15% to 63.34%.
- Future plan-
  - Studying subject variations
  - Noise mitigation





Reference-

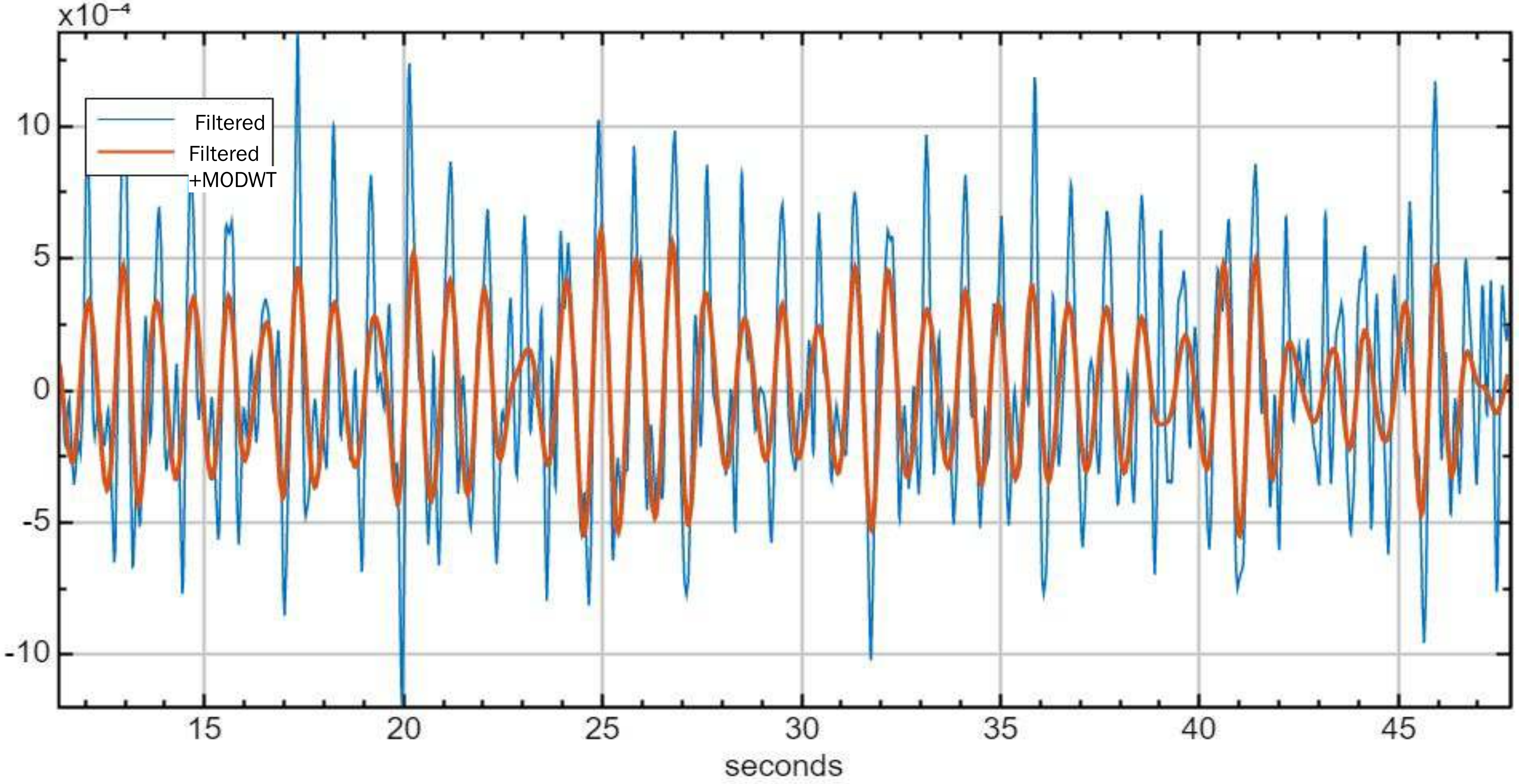
[1] M. He, Y. Nian, L. Xu, L. Qiao, and W. Wang, “Adaptive separation of respiratory and heartbeat signals among multiple people based on empirical wavelet transform using uwb radar,” Sensors, vol. 20, no. 17, p. 4913, 2020.
[2] T.-Y. Huang, L. Hayward, and J. Lin, “Adaptive harmonics comb notch digital filter for measuring heart rate of laboratory rat using a 60-ghz radar,” in 2016 IEEE MTT-S International Microwave Symposium (IMS). IEEE, 2016, pp. 1–4.
[3] J. Tu and J. Lin, “Respiration harmonics cancellation for accurate heart rate measurement in non-contact vital sign detection,” in 2013 IEEE MTT-S International Microwave Symposium Digest (MTT). IEEE, 2013, pp. 1–3.
[4] Y. Ding, X. Yu, C. Lei, Y. Sun, X. Xu, and J. Zhang, “A novel real-time human heart rate estimation method for noncontact vital sign radar detection,” IEEE Access, vol. 8, pp. 88 689–88 699, 2020.
[5] O. Boric-Lubecke, V. M. Lubecke, B.-K. Park, W. Massagram, and B. Jokanovic, “Heartbeat interval extraction using doppler radar for health monitoring,” in 2009 9th International Conference on Telecommunication in Modern Satellite, Cable, and Broadcasting Services. IEEE, 2009, pp. 139–142.
[6] M. Mabrouk, S. Rajan, M. Bolic, M. Forouzanfar, H. R. Dajani, and I. Batkin, “Human breathing rate estimation from radar returns using harmonically related filters,” Journal of Sensors, vol. 2016, 2016.
[7] S. Quirk, N. Becker, and W. Smith, “External respiratory motion analysis and statistics for patients and volunteers,” Journal of Applied Clinical Medical Physics, vol. 14, no. 2, pp. 90–101, 2013.

Reference (Cont.)-

[8] C. Li and J. Lin, “Optimal carrier frequency of non-contact vital sign detectors,” in 2007 IEEE Radio and Wireless Symposium. IEEE, 2007, pp. 281–284.
[9] W. Massagram, V. M. Lubecke, A. HØst-Madsen, and O. Boric-Lubecke, “Assessment of heart rate variability and respiratory sinus arrhythmia via doppler radar,” IEEE Transactions on microwave theory and techniques, vol. 57, no. 10, pp. 2542–2549, 2009.
[10] S. Gurumoorthy, N. B. Muppalaneni, and G. S. Kumari, “Eeg signal denoising using haar transform and maximal overlap discrete wavelet transform (modwt) for the finding of epilepsy,” in Epilepsy-Update on Classification, Etiologies, Instrumental Diagnosis and Treatment. IntechOpen, 2020.
[11] V. Alarcon-Aquino and J. Barria, “Change detection in time series using the maximal overlap discrete wavelet transform,” Latin American applied research, vol. 39, no. 2, pp. 145–152, 2009.
[12] D. Castaneda, A. Esparza, M. Ghamari, C. Soltanpur, and H. Nazeran, “A review on wearable photoplethysmography sensors and their potential future applications in health care,” International journal of biosensors & bioelectronics, vol. 4, no. 4, p. 195, 2018.
[13] F. Shaffer and J. P. Ginsberg, “An overview of heart rate variability metrics and norms,” Frontiers in public health, p. 258, 2017.

Appendix

MODWT on filtered signal

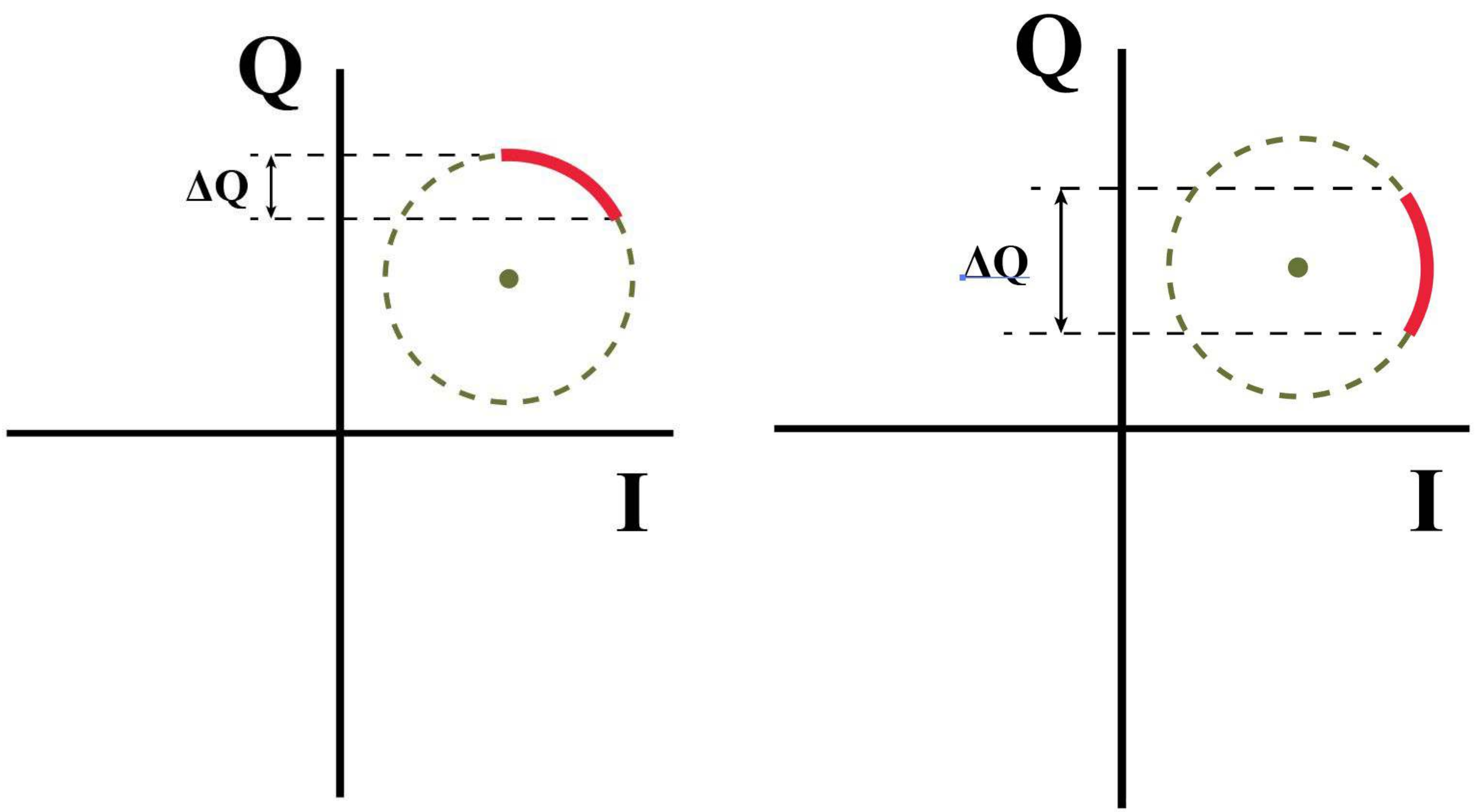


MODWT Vs DWT

Property	MODWT	DWT	Comment
Orthonormal	✖	✔	
Defined for all sample sizes	✔	✖	*For DWT, N needs to be the power of 2*
Multiresolution analyses	✔	✔	
Same power spectrum of input signal and its circular shifts	✔	✖	*Unaffected by circular shifts*
Downsampling	✖	✔	*The scaling and wavelet filters are downsampled in DWT*
Redundant	✔	✖	*MODWT of level J_0 has $(J_0 + 1)N$ coefficients, whereas DWT has N coefficients for any given J_0. DWT of level J_0 requires N to be integer multiple of 2^{J0} and MODWT of level J_0 is well-defined for any sample size N.*
Alignment artifact	✖	✔	*MODWT details and smooths are associated with zero phase filters*

Linear demodulation

- IQ arc is rotated about the center of the arc.
- The channel with highest resolution is used after being rotated to the degree maximising its resolution.



$$\hat{x}[n] = d^T r[n]$$

IQ arc rotation

- The equation for rotation of a collection of points around the origin.

$$x' = x\cos(\theta) - y\sin(\theta)$$
$$y' = x\sin(\theta) + y\cos(\theta)$$

- (x, y) is the collection of original points
- (x’, y’) is the collection of rotated points.

- The modified equation for rotation around a point not the origin.

$$x' = (x - C_x)\cos\theta - (y - C_y)\sin\theta + C_x$$
$$y' = (x - C_x)\sin\theta + (y - C_y)\cos\theta + C_y$$

- where Cx and Cy are cartesian coordinates of the external point about which rotation occurs.