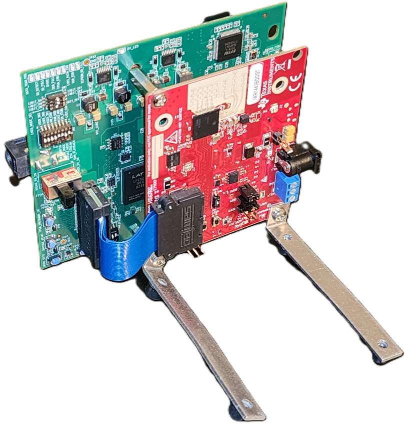
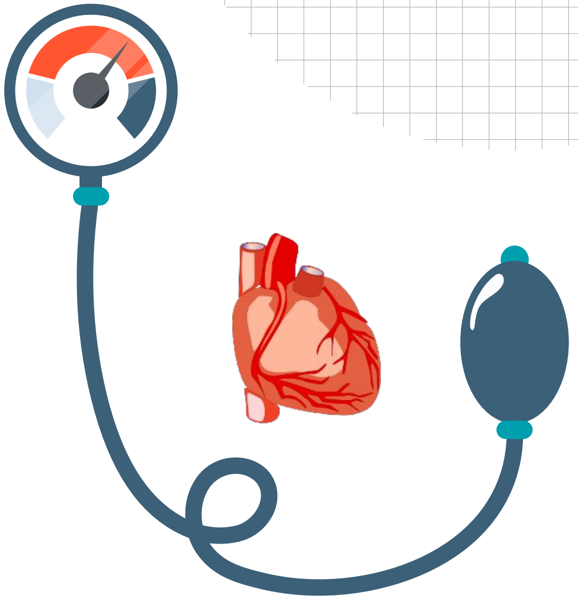


Radar System for Indoor Health Monitoring



Project Objectives

- To develop and implement a **non-invasive, wireless health monitoring system** using FMCW radar technology. This system enhances patient **comfort** and **privacy** by accurately measuring vital signs such as heart rate and respiratory rate without physical contact and without the use of visually invasive methods such as infrared cameras. By eliminating the need for direct contact with diagnostic instruments, our system also **reduces** the potential for **transmission of diseases and viruses**, making it safer for both patients and healthcare providers. BioNest aims to improve patient care in **hospitals, specialized care facilities**, and **home healthcare settings**, ensuring a more **adaptable, less intrusive**, and **privacy-respecting** approach to vital sign monitoring.

Initial **Functional** Requirements (1/2)

- **Radar Wave Emission**: The system emits millimeter radio waves in the 77-81 GHz band, covering at least one transmitting channel with a 3-4 GHz chirp bandwidth.
- **Distance Measurement**: The system measures the distance to objects within a monitoring range of up to 5 meters using reflections of the emitted radio waves, effectively distinguishing the subject (patient) from other background objects.
- **Subject Recognition and Monitoring**: Upon identifying a subject within the monitoring area, the system engages in an initial 15-second sensing phase to estimate the subject's heart and respiratory rates.
- **User Interface (UI) Management**: The UI displays operational statuses, including the initiation and completion of the sensing phase, and updates the subject's physiological state in real-time. It also provides visual and audible alerts if the subject's physiological state exceeds configured thresholds.

Initial **Functional** Requirements (2/2)

- **Data Logging and Review**: The system logs the subject's physiological and positional data with timestamps and allows the subject to review their physiological history through the UI.
- **System Initialization and Calibration**: Upon powering up, the system collects necessary personal and physiological data from the subject to set threshold levels and calibrate the vital signs monitoring algorithms, ensuring personalized and accurate monitoring.
- **Power Management**: The system enters a powered down mode when the subject exits the monitoring area, ceasing data collection and shutting down hardware to conserve energy.

Initial **Non-Functional** Requirements (1/2)

- **Performance and Efficiency**: The BioNest system is designed to achieve high performance by recognizing a subject's presence in the monitoring area within five seconds and updating physiological state estimates on the user interface in under one second. It operates efficiently on a hardware platform constrained to 400 KB of RAM and a 200 MHz microcontroller.
- **Scalability and Accuracy**: The system offers scalable monitoring capabilities, effectively covering areas as defined by the radar's operational range without dead zones. It ensures accuracy, with physiological state recalculations maintaining at least 90% of the precision of traditional medical devices.

Initial **Non-Functional** Requirements (2/2)

- **Robustness and Availability**: Robustness is a key feature, with the system maintaining functionality despite changes in room layout or the failure of one radar unit. In cases where more than one radar unit fails, it continues to operate at 80% accuracy. Additionally, the system retains essential operational parameters and logged data even after being powered down, ensuring 99% operational uptime throughout the year.
- **Usability, Safety, and Security**: Usability is prioritized by presenting physiological states and system settings in an easily accessible and understandable format. Safety measures include quick-response audible and visual alerts for abnormal physiological states, audible within at least a 10-meter radius. Security and privacy are upheld by securely storing all physiological data internally, preventing unauthorized access.

Design Specifications Review (1/2)

Table 1: Project's Design Specifications

#	Parameter	Test Conditions	Values			Units
			Min	Typ	Max	
1.	Heart Rate Detection	Normal*	0	80	120	bpm
2.	Breathing Rate Detection	Normal*	0	16	30	breaths/min
3.	Movement Detection	Normal*	-	-	1.5	m/s
4.	Data Test Duration	Normal*	15	-	-	seconds
5.	Person's Age	Normal*	18	-	-	years
6.	Person's Weight	Normal*	40	-	150	kg
7.	Person's Height	Normal*	150	-	210	cm

Design Specifications Review (2/2)

Normal*:

- *Test Conditions* imply testing is done at an ambient room temperature of **23°C** and up to **60%** room humidity.
- Test subjects are wearing **standard casual clothing**, and are **seated** or **standing still**.
- Test subjects are also to be **facing** the radar and can be at most **faced 60°** away from the radar's antennas.
- Testing is conducted indoors in a room of **At Least L/W/H = 3/3/2.4 m**.
- The room can be furnished in a manner consistent with a **typical residential living space**.
- The placement and type of furniture should **not obstruct** the radar's line of sight to the test subject or introduce **abnormal reflections.**
- Objects with **large metal surfaces**, which reflect signals strongly, should not be in the same range of the targeted patient. Additionally, these objects should not exhibit slow, periodic movements at frequencies similar to breathing in the radar's line of sight.

Justification of Design Choices

Why pick FMCW Radar?

Operating modes

RADAR transmit signal operating mode	Doppler or CW (Continuous wave)	FSK (Frequency shift keying)	FMCW (Frequency modulated continuous wave)
Movement	✓	✓	✓
Range		✓	✓
Radial speed and direction			✓
Moving/static target		Moving target only	Moving and static target

Comparison of Radar Signal Operating Modes and Their Detection Capabilities, provided by Infineon Technologies AG (2022).

Clutter Suppression and Precision:
FMCW radar performs well in detecting vital signs by effectively suppressing clutter and background noise.

Low Interference and High Penetrability:
FMCW radar operates at frequencies that allow it to penetrate through soft materials, such as clothing, without being affected by them.

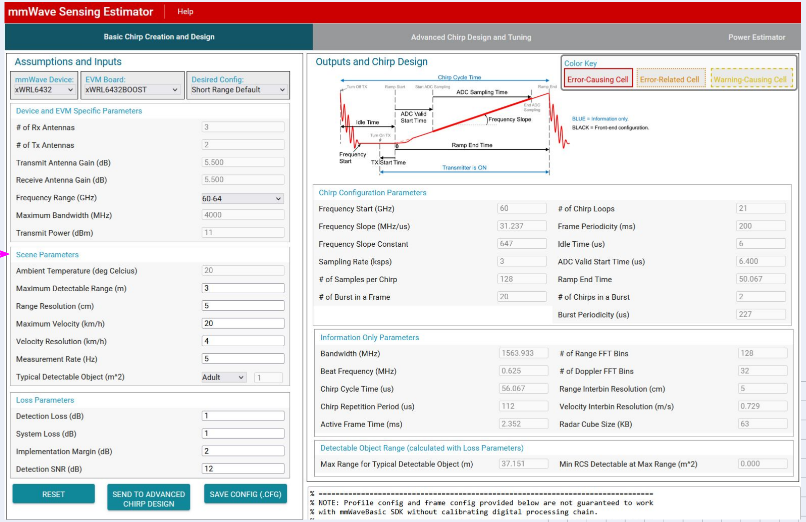
Power Efficiency:
FMCW radar consumes less power than **UWB** radar and **LiDAR**.

Environmental Sensitivity:
Another key advantage of **FMCW** radar over **LiDAR** is its capability to operate effectively in complex indoor environments where **multipath** interference from walls and furniture could degrade the performance of optical systems like **LiDAR.**

Justification of Design Choices

Table 2: Radar Parameters based on mmWaveSensingEstimator from Texas Instruments.

Parameters	IWR**1443**BOOST	IWR**6843**ISK	IWR**1642**BOOST
# of Rx Antennas	4	4	4
# of Tx Antennas	3	3	2
Transmit Antenna Gain (dB)	9	7	10.5
Receive Antenna Gain (dB)	9	7	10.5
Frequency Range (GHz)	77-81	60-64	77-81
Transmit Power (dBm)	12	12	12.5
Scene Parameters (Inputs)			
Maximum Detectable Range (m)	6	6	6
Range Resolution (cm)	3.78	3.78	3.76
Maximum Velocity (km/h)	5.5	5.4	5.5
Velocity Resolution (km/h)	0.9	0.9	0.6
Measurement Rate (Hz)	120	90	80
Chirp Parameters			
Frequency Start (GHz)	77	60	77
Frequency Slope (MHz/µs)	6.035	4.442	4.007
Frequency Slope Constant	125	92	83
Sampling Rate (ksps)	3	3	3
# of Samples per Chirp	1965	2676	2969
# of Burst in a Frame	1	1	1
# of Chirp Loops	4	4	6
Frame Periodicity (ms)	10	11.111	12.5
Idle Time (us)	7	7	7
ADC Valid Start Time (us)	6.4	6.4	6.4
Ramp End Time	662.4	899.4	997.067
# of Chirps in a Burst	8	8	12
Burst Periodicity (us)	5469.66	7365.66	12163
Information Only Parameters			
Beat Frequency (MHz)	0.242	0.178	0.16
Chirp Cycle Time (us)	669.4	906.4	1004.06
Chirp Repetition Period (us)	2008	2719	2008
Active Frame Time (ms)	8.032	10.876	12.048
FFT Parameters			
# of Range FFT Bins	2048	4096	4096
# of Doppler FFT Bins	4	4	8
Range Interbin Resolution (cm)	3.627	2.47	2.725
Velocity Interbin Resolution (m/s)	0.25	0.25	0.125
Radar Cube Size (KB)	384	768	768



From: https://dev.ti.com/gallery/view/mmwave/mmWaveSensingEstimator/ver/2.4.0/

Justification of Design Choices

Table 3: Radar Alternatives Selection (1/3)

Parameter	Weight /10	Relevance to our project	IWR1443BOOST [A] + (score/10)		IWR6843ISK [B] + (score/10)		IWR1642BOOST [C] + (score/10)	
Processing	**3**	**DSP**: Helps with Pre-Processing Functions, reduced load to laptop **HWA**: Higher Speed Processing which will reduce latency.	MCU + HWA	7	MCU + HWA + DSP	8	MCU + DSP	7
Frequency Range	**6**	Allow for improved resolution in detecting small movements, which is crucial for accurate monitoring of human vital signs.	76 to 81 GHz	10	60 to 64 GHz	7	76 to 81 GHz	10
Range Resolution (LOWER IS BETTER)	**10**	Enables better separation of the area of interest (e.g. chest) from other limb movements and also allows better separation of one person's vital signs from another.	37.5 mm	-	37.5 mm	-	37.5 mm	-
Maximum Velocity	**4**	Has the capability to identify occasional spontaneous body movements and is capable of tracking moving targets in later stages of development	1.3 km/h = **36.1 cm/s**	6	1.6 km/h = **44.4 cm/s**	8	1.7 km/h = **47.2 cm/s**	9

Justification of Design Choices

Table 3: Radar Alternatives Selection (2/3)

Parameter	Weight /10	Relevance to our project	IWR1443BOOST [A] + (score/10)		IWR6843ISK [B] + (score/10)		IWR1642BOOST [C] + (score/10)	
Velocity Resolution (LOWER IS BETTER)	**4**	Crucial for detecting small velocity changes in chest movement involving breathing **irregularities** and heart **anomalies**.	0.9 km/h = **25 cm/s**	7	0.9 km/h = **25 cm/s**	7	0.6 km/h = **16.7 cm/s**	10
Horizontal FOV	**6**	Provides an adequate range for monitoring someone in the room.	+/-60 deg	-	+/-60 deg	-	+/-60 deg	-
Horizontal Angular Resolution (LOWER IS BETTER)	**7**	Determines the system's ability to distinguish fine angular differences in chest displacement, enhancing detection of subtle breathing patterns.	15 deg	-	15 deg	-	15 deg	-
Elevation FOV	**3**	Ensures vertical coverage to monitor chest movements that occur in the elevation plane and depending on their height	+/-15 deg	-	+/-15 deg	-	+/-15 deg	-
Elevation Angular Resolution	**3**	Similar to horizontal resolution, this defines the precision in the elevation plane.	60 deg	-	58 deg	-	60 deg	-
Peak Gain (isotropic radiator)	**9**	Influences the radar's sensitivity and signal strength, impacting the **accuracy** of vital sign detection and overall system reliability.	10.5 dBi	10	7 dBi	7	9 dBi	9

Justification of Design Choices

Table 3: Radar Alternatives Selection (3/3)

Parameter	Weight /10	Relevance to our project	IWR1443BOOST [A] + (score/10)		IWR6843ISK [B] + (score/10)		IWR1642BOOST [C] + (score/10)	
Max real sampling rate	**6**	Enhances the granularity of **distance** measurement data, enabling more precise detection of position changes	37.5 Msps	10	25 Msps	6	12.5 Msps	3
Max complex sampling rate	**6**	Improves the fidelity of speed measurement data, allowing for more accurate tracking of **velocity** variations	18.75 Msps	10	12.5 Msps	8	6.25 Msps	4
Cost (LOWER IS BETTER)	**8**	Shows the cost effectiveness of our purchase.	$525.73	4	$307.70	6	$525.73	4
Total Scores				**375**		**321**		**312**

Note on the range resolution

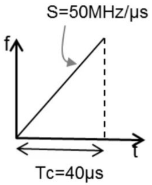
We are not simply relying solely on the range resolution to acquire the movement in the chest displacements, we are utilising the phase analysis as explained in this slide provided by Texas Instruments video tutorials:

Sensitivity of the IF signal for small displacements in the object(1/2)

Recall that for an object at a distance d from the radar, the IF signal will be a sinusoid:

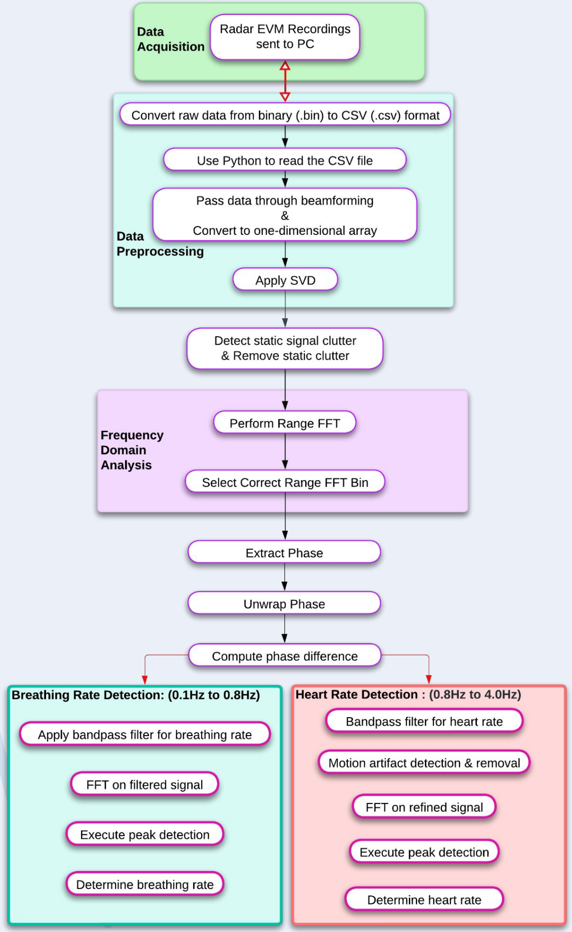
$$A\sin(2\pi f t + \phi_o)$$

$$f = \frac{S2d}{c} \qquad \Delta\phi = \frac{4\pi\Delta d}{\lambda}$$



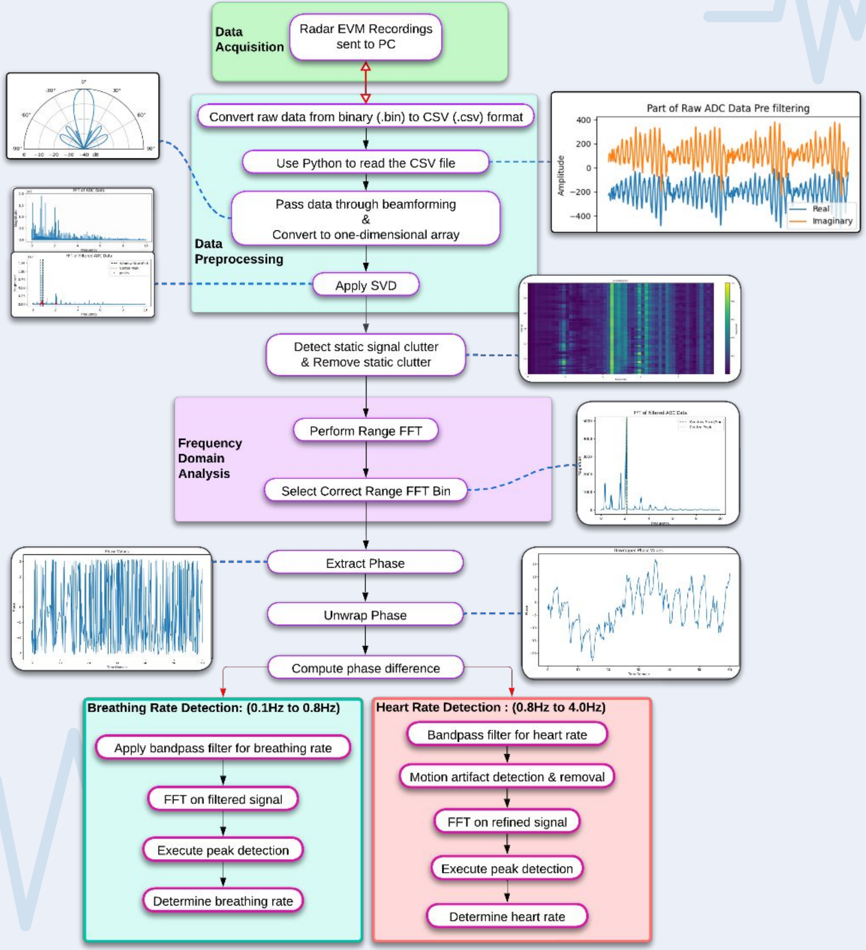
- Consider the chirp shown to the left. What happens if an object in front of the radar changes its position by 1mm (for 77GHz radar 1mm= λ/4)
- The phase of the IF signal changes by $\Delta\phi = \frac{4\pi\Delta d}{\lambda} = \pi = 180^o$
- The frequency of the IF signal changes by $\Delta f = \frac{S2\Delta d}{c} = \frac{50x10^{12}x2x1x10^{-3}}{3x10^8} = 333\text{Hz}$. Now, 333Hz looks like a big number, but in the observation window this corresponds to only additional $\Delta f T_c = 333x40x10^{-6} = 0.013$ cycles. This change would not be discernible in the frequency spectrum

Flowchart Design Overview



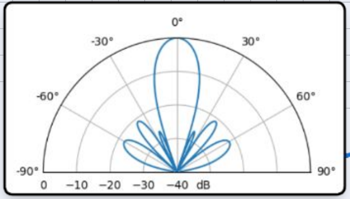
Using app.diagrams.net (Draw.io):

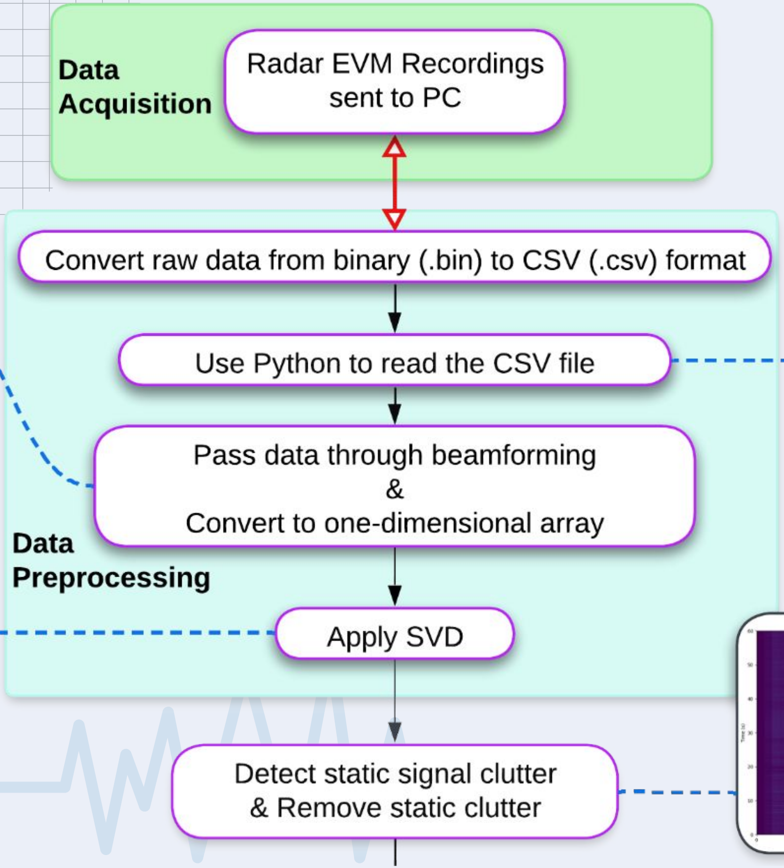
Flowchart Design Overview

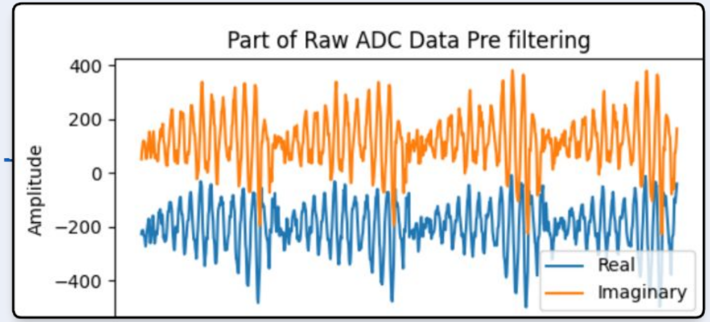


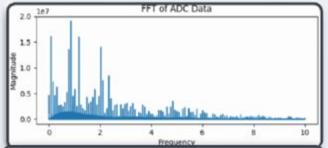
Using app.diagrams.net (Draw.io):

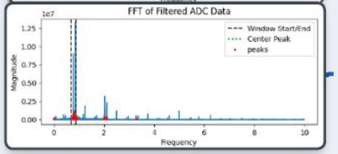
Flowchart Design Overview

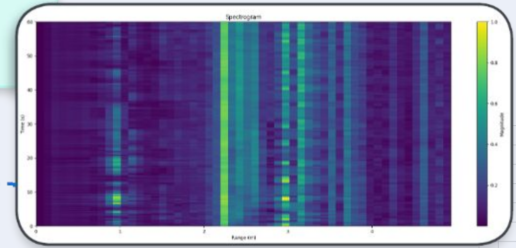








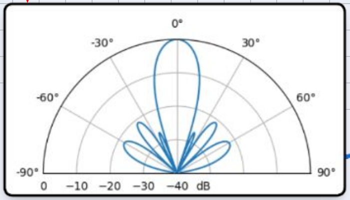


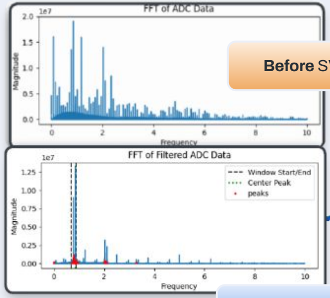


Using app.diagrams.net (Draw.io):

Flowchart Design Overview

Increase the center and reduce side lobe interference





Before SVD

After SVD

Data Acquisition

Radar EVM Recordings sent to PC

Data Preprocessing

Convert raw data from binary (.bin) to CSV (.csv) format

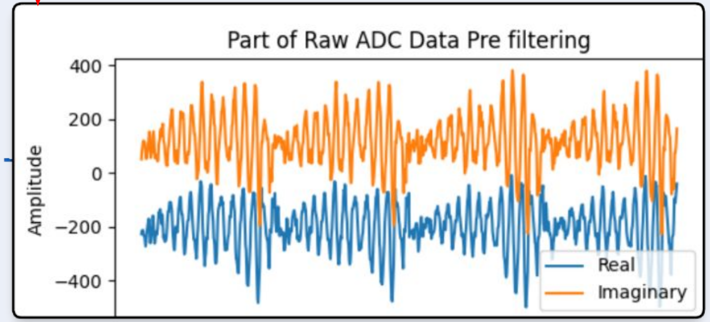
Use Python to read the CSV file

Pass data through beamforming
&
Convert to one-dimensional array

Apply SVD

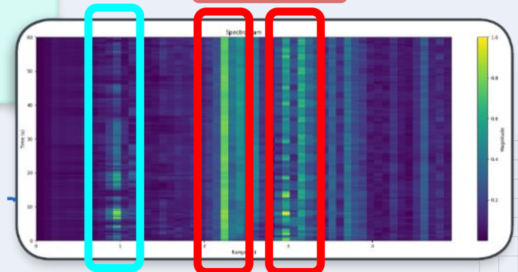
Detect static signal clutter
& Remove static clutter

A small segment of the raw data received from the radar



Person Breathing

Static Noise

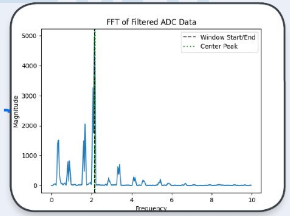


Using app.diagrams.net (Draw.io):

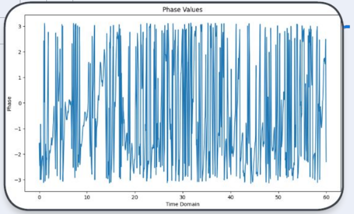
Flowchart Design Overview

Frequency Domain Analysis

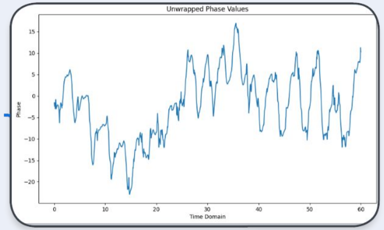
- Perform Range FFT
- Select Correct Range FFT Bin



- Extract Phase



- Unwrap Phase

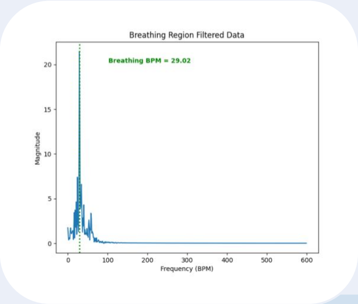


$$\Delta\phi = \frac{4\pi\Delta d}{\lambda}$$

- Compute phase difference

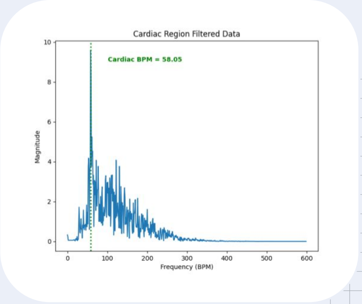
Breathing Rate Detection: (0.1Hz to 0.8Hz)

- Apply bandpass filter for breathing rate
- FFT on filtered signal
- Execute peak detection
- Determine breathing rate



Heart Rate Detection : (0.8Hz to 4.0Hz)

- Bandpass filter for heart rate
- Motion artifact detection & removal
- FFT on refined signal
- Execute peak detection
- Determine heart rate



Using app.diagrams.net (Draw.io):

Summary of demo Tests

Test Number	**Ground Thruth** Breathing Rate (BPM)	**Radar's** Breathing Rate (BPM)	**Ground Thruth** Heart Rate (BPM)	**Radar's** Heart Rate (BPM)	Distance (m)	Test Condition	Accuracy for Breathing (%)	Accuracy for Heart (%)
1	12	12	78	80	~1	(Normal Breathing)	100	97.4
2	12	10	85	82	~1	(Normal Breathing)	83.3	96.4
3	-	12 (But Console showed no breaths detected at from 15.00 to 29.95 seconds)*	75	88	~1	(Stop Breathing at 10 seconds)	Not Applicable	82.6
4	10	16	85	62	~2	(Normal Breathing)	**40**	72.9
5	10	12	86	52	~3	(Facing Away Radar)	80	**60.4**
6	16	14	105	110	~1	(Normal Breathing)	87.5	95.2
7	0	40	0	86	-	(No Patient)	**0**	**0**
8	18	18	137	148	~1	(After Running from Stairs)	100	91.9

Product Specifications

What the product does:

how it performs, how it is described, actual dimensions, etc.

– Must meet or exceed the design requirements &
specifications.

– Actual product performance, maintenance, etc.
parameters and

characteristics.

– Limitations.

– Can contain specific information about materials used.

Conclusion

Our implemented design was **capable** of doing the following:

- Display Breathing rates with **85**% accuracy when following our test conditions
- Display Heart rates with **95**% accuracy when following our test conditions
- Detect and display Non-Breathing chest motions
- Removal of Static Noise.

Improvements that could have been made:

- A visual alert system from the app when someone is not breathing or when the heart is no longer beating.
- Real Time signal processing of the heart and breathing.
- A power saving mode when someone is not present in front of the radar.
- Further range detection with better beamforming which would make the radar detection more dynamic for a room setting.