Design of Efficient Algorithms for Cuff-less and Continuous Estimation of Blood Pressure in Smart Mobile Healthcare Systems

Mohammad Kachuee

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Outline

- Blood Pressure
- BP Measurement Methods
- Background
- Proposed Methodology
- Results
- Hardware Implementation
- Conclusion

Blood Pressure (BP)

- The pressure which is applied to vessel walls
- Measured in mmHg

- Hypertension
  - Hypertension occurs when BP is higher than normal
  - Prevalent among 24% and 20% of men and women, respectively
  - Called the silent killer

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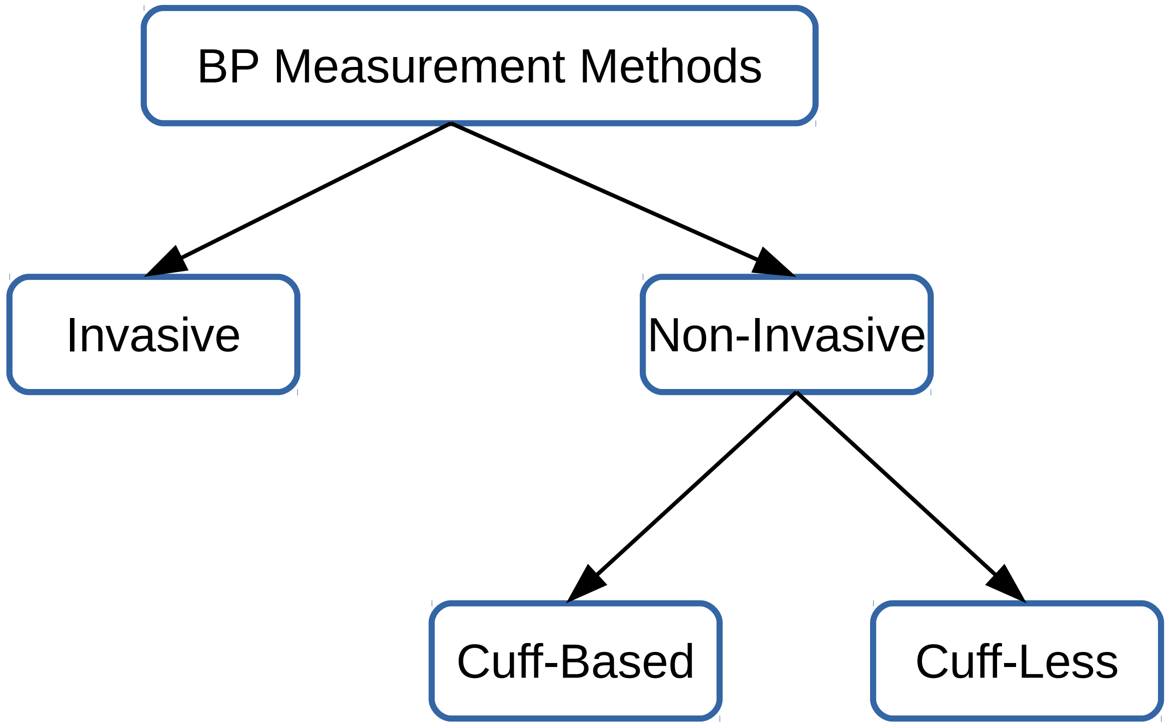
BP Measurement Methods



BP Measurement Methods: Invasive

✔ Accurate BP values by direct measurement

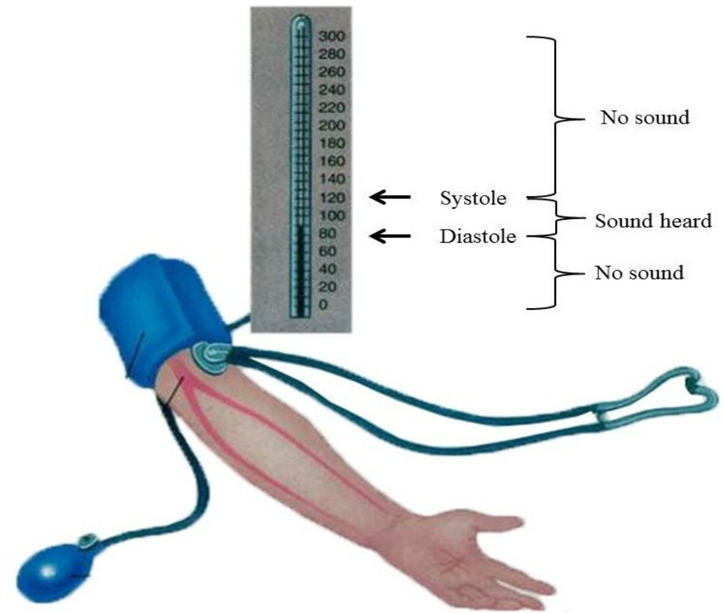
✔ Continuous and instantaneous

✗ Requires surgery to implement a pressure sensor

✗ Requires sterilized conditions

BP Measurement Methods: Non-Invasive

- **Cuff-based**
  - ✔ Non-invasive
  - ✔ established standards
  - ✗ Inconvenient
  - ✗ Discontinuous
- **Cuff-less**
  - ✔ Non-invasive
  - ✔ Convenient
  - ✔ Continuous
  - ✗ Requires Calibration
  - ✗ No established standard



(Image from www.fastbleep.com)

BP Measurement Challenges

- Capability of continuous BP monitoring
- Indirect calculation of BP
- Subject specific parameters
- Evaluation using established health standards
- mHealth design considerations

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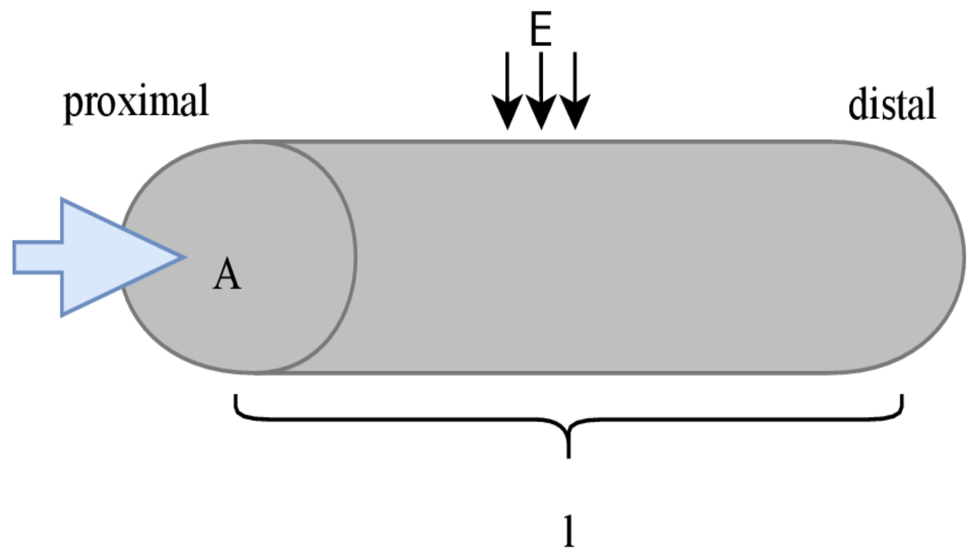
Background

- **BP and PTT relationship**
  - Wave propagation in arteries

- **Vital signals**
  - Arterial Blood Pressure (ABP)
  - Electrocardiograph (ECG)
  - Photoplethysmograph (PPG)

Background: Wave Propagation in Arteries

- Elastic tube model:



- Pulse Transit Time (PTT):

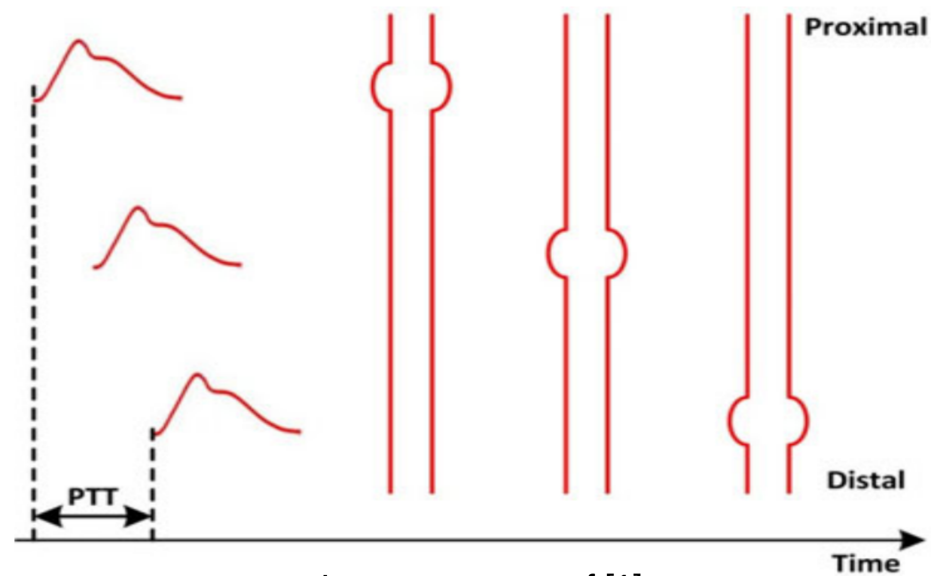


Image courtesy of [1]

Background: Wave Propagation in Arteries

Compliance ($\frac{\partial A}{\partial P}$)

$$C(P) = \frac{A_m}{\pi P_1[1 + (\frac{P-P_0}{P_1})^2]}$$

Wave propagation (see [17])

$$P(x,t) = f(x \pm t/\sqrt{LC(P)})$$

Wave velocity

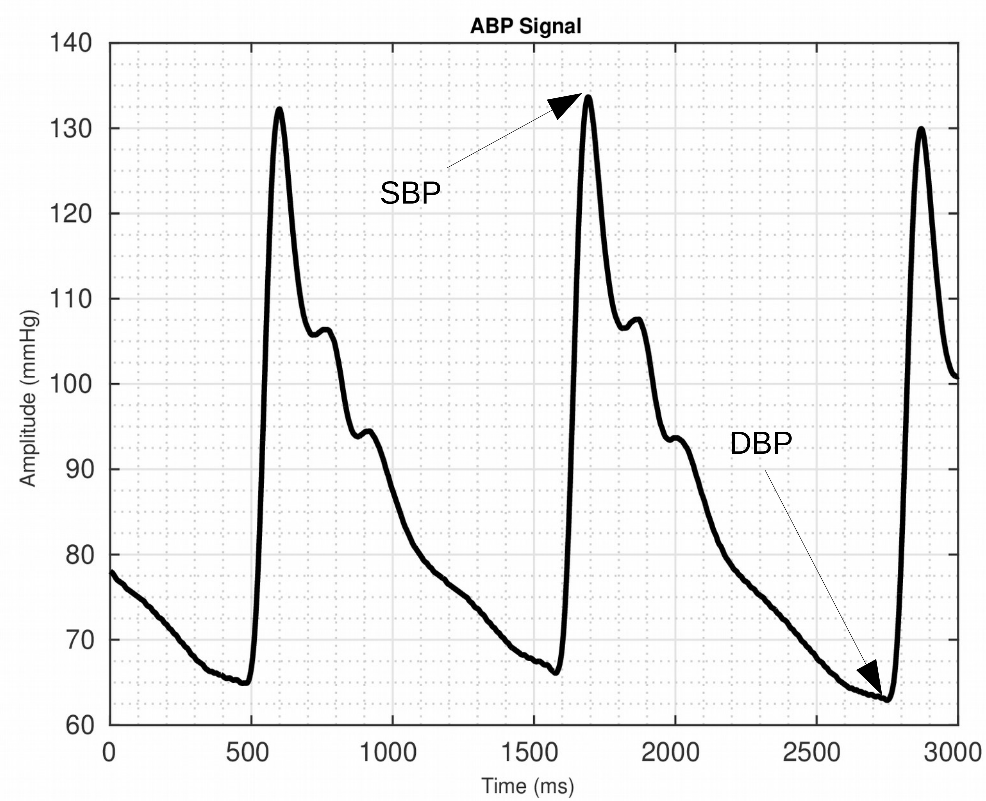
$$PTT = l\sqrt{LC(P)}$$

PTT-BP relationship

$$PTT = l\sqrt{\frac{\rho A_m}{\pi A P_1[1 + (\frac{P-P_0}{P_1})^2]}}$$

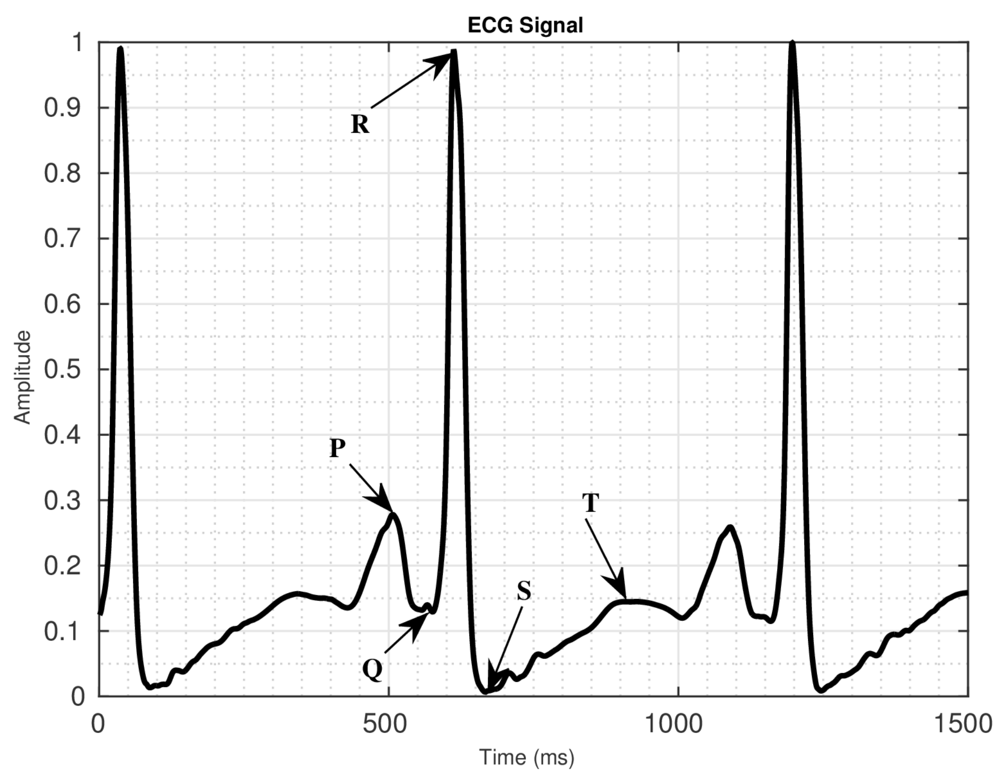
Vital Signals: ABP

- Instantaneous BP signal
- Invasive measurement method (Radial Artery Catheterization)
- Here, it is used as target:
  - SBP = ABP maximum
  - DBP = ABP minimum
  - MAP = (SBP+2*DBP)/3



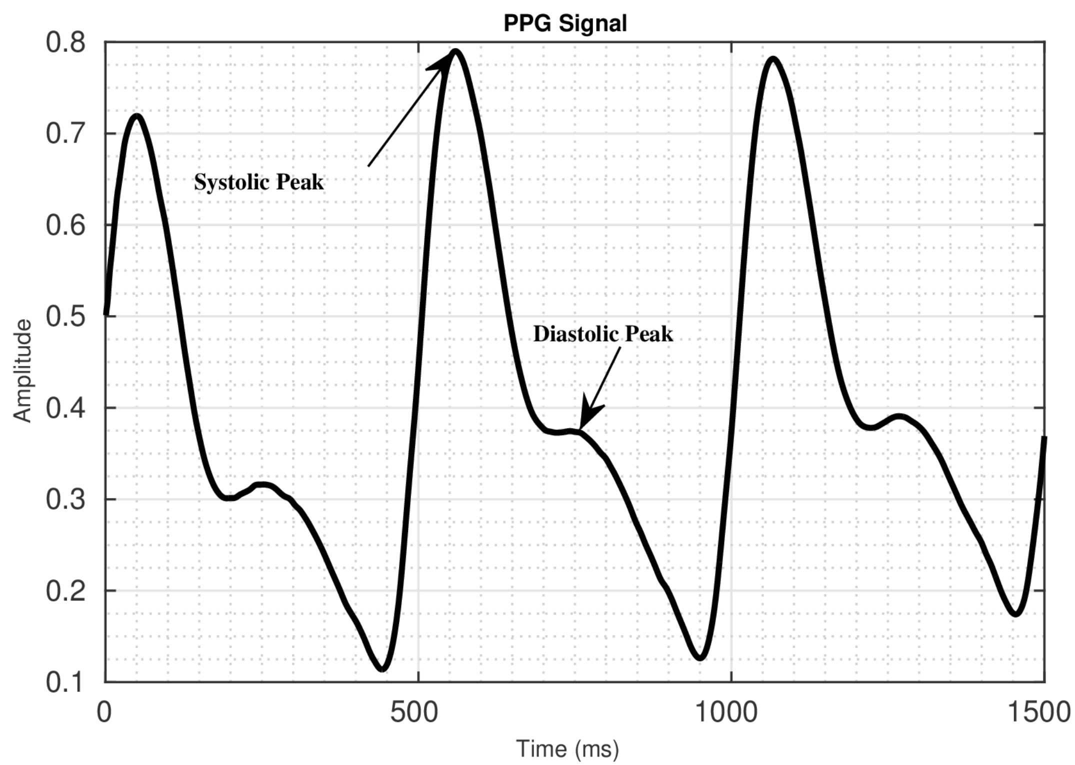
Vital Signals: ECG

- Electrocardiography (ECG or EKG)
- Recording the electrical activity of the heart by closing an electrical circuit loop inside the body



Vital Signals: PPG

- Photoplethysmograph = photo + plethysmos + graph
- Recording changes of the blood volume



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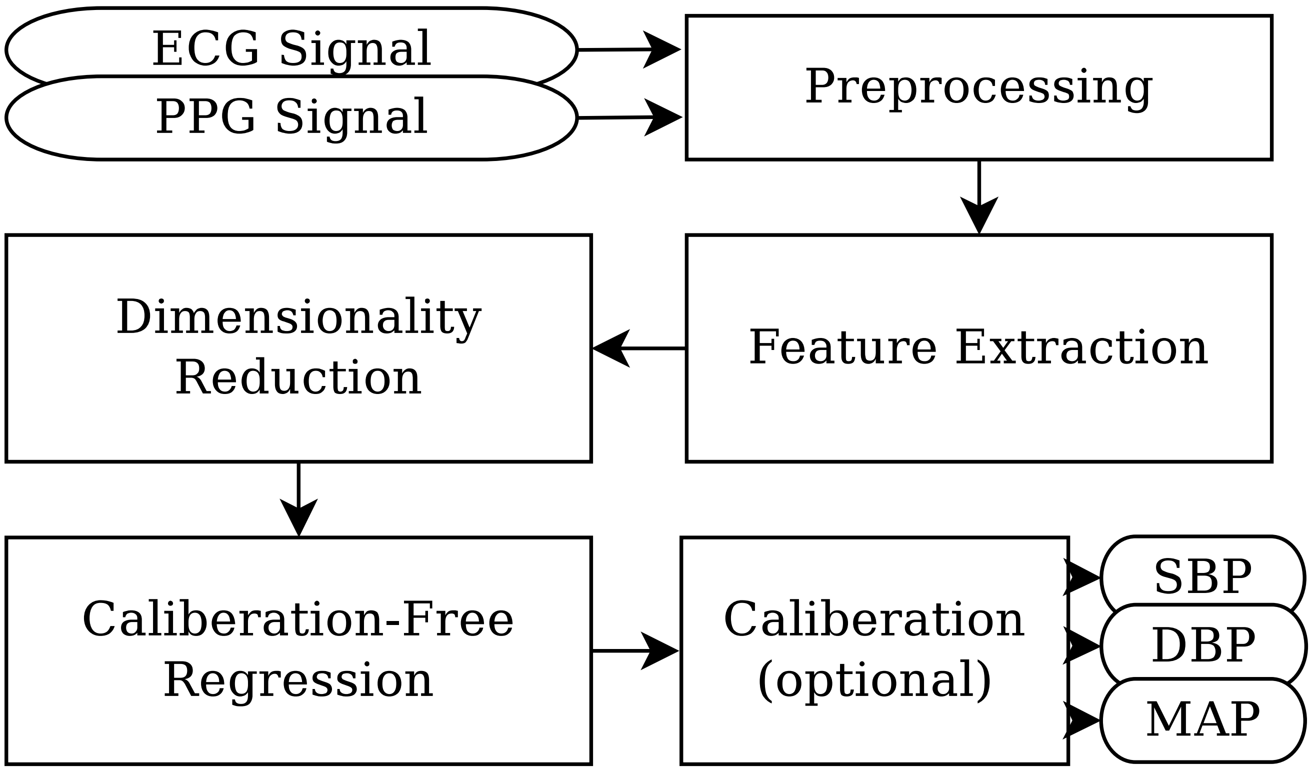
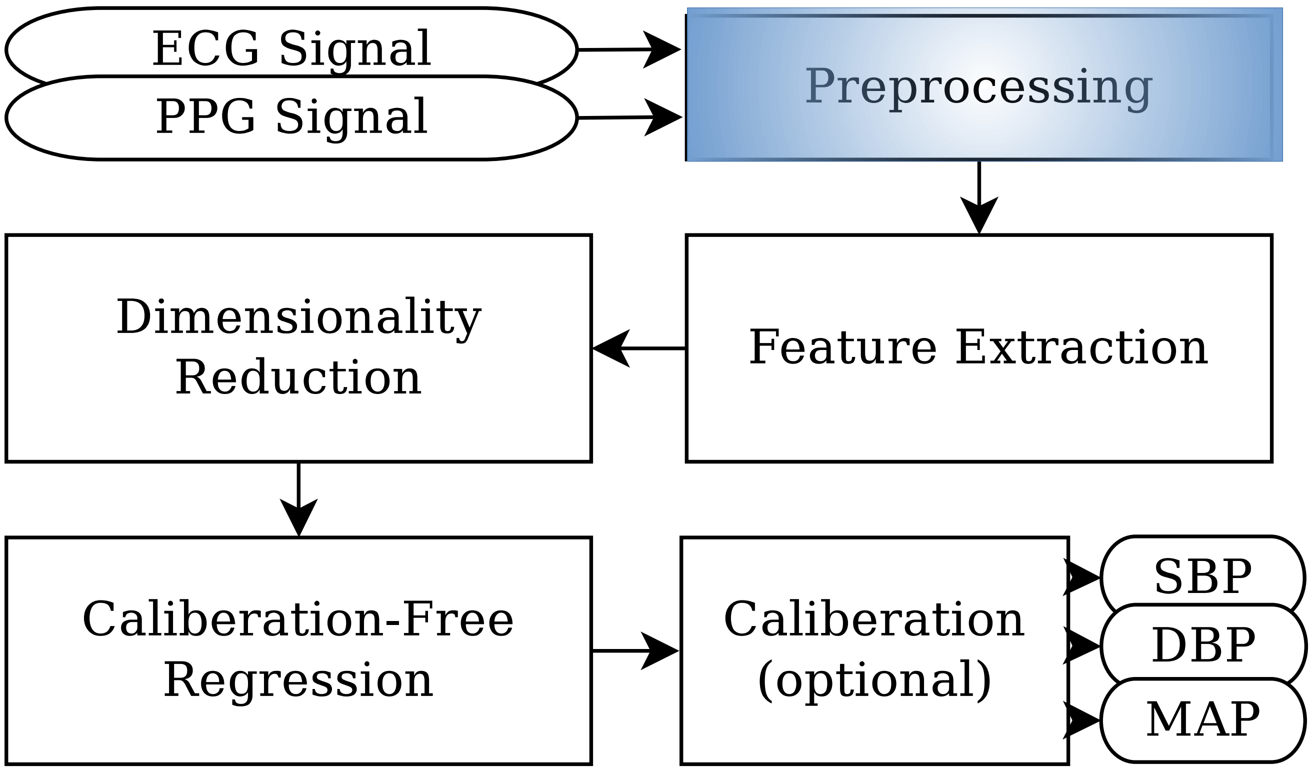
Proposed Methodology



Data Collection

- **Multi-parameter Intelligent Monitoring in Intensive Care (MIMIC) II:**
  - Online database at physionet.org
  - Consists of terabytes of medical records
  - Data is collected from ICU patients

Proposed Methodology: Preprocessing

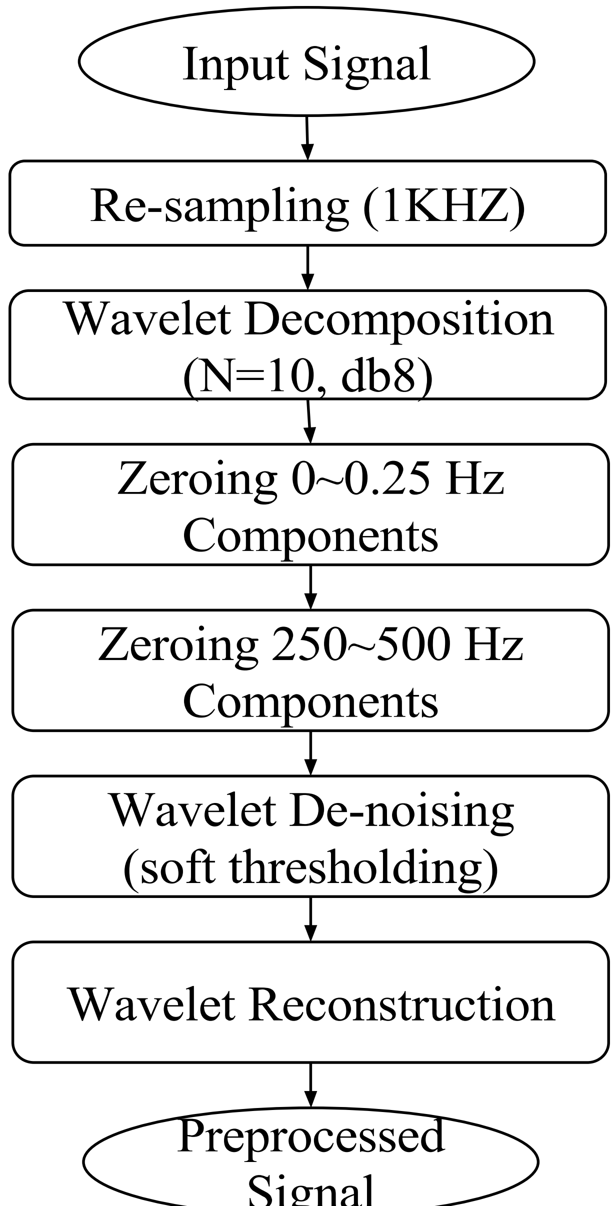


Preprocessing: Noise and Artifacts

- **Noise and artifacts:**
  - Power-line 50 or 60 Hz noise
  - Baseline wandering (low frequency)
  - Muscle activity artifacts (high frequency, non-stationary)

- **Filtering and denoising methods:**
  - Frequency selective filtering (FIR, IIR, etc.)
  - Discrete Wavelet Transform (DWT)

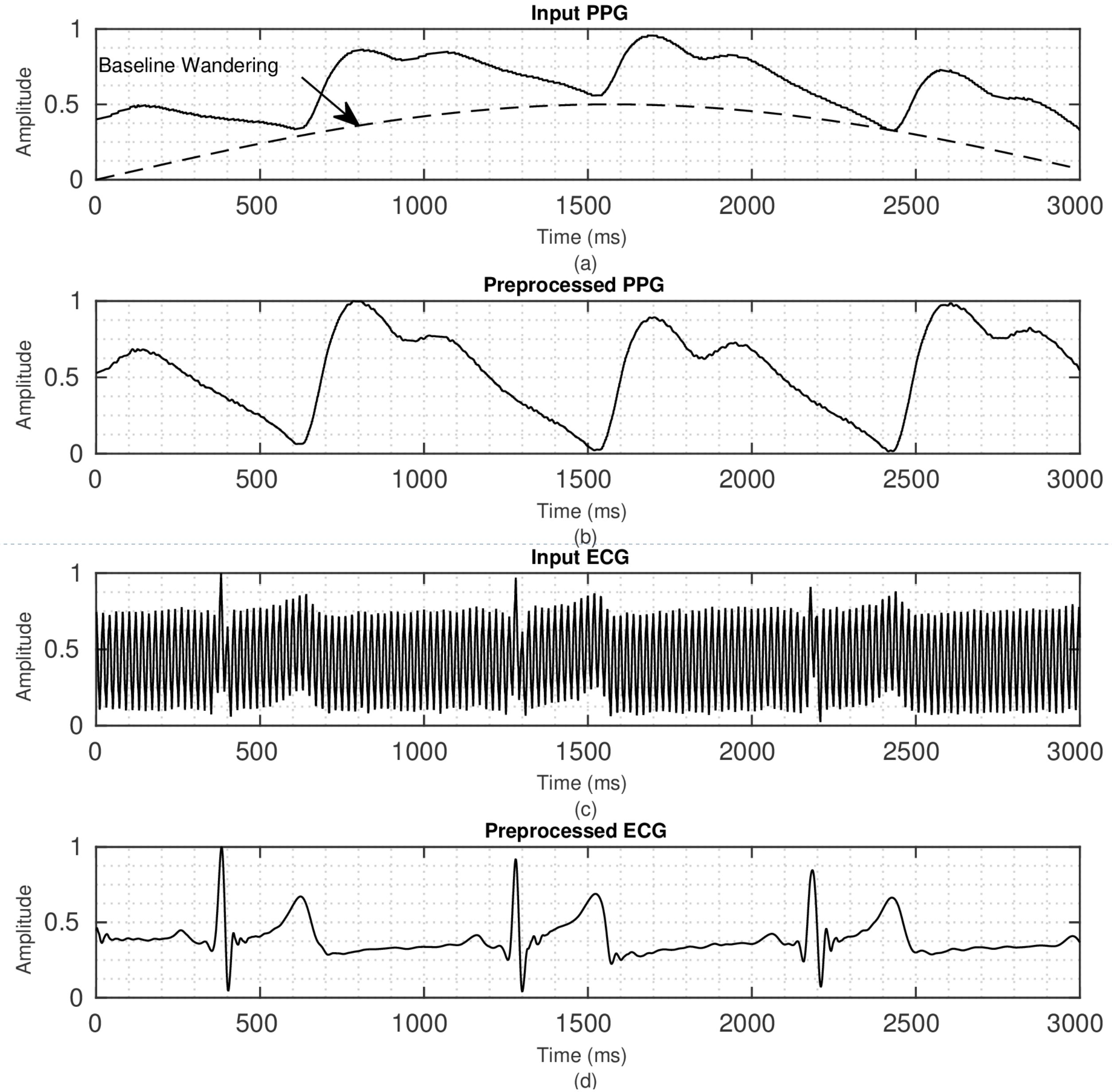
Preprocessing: Pipeline



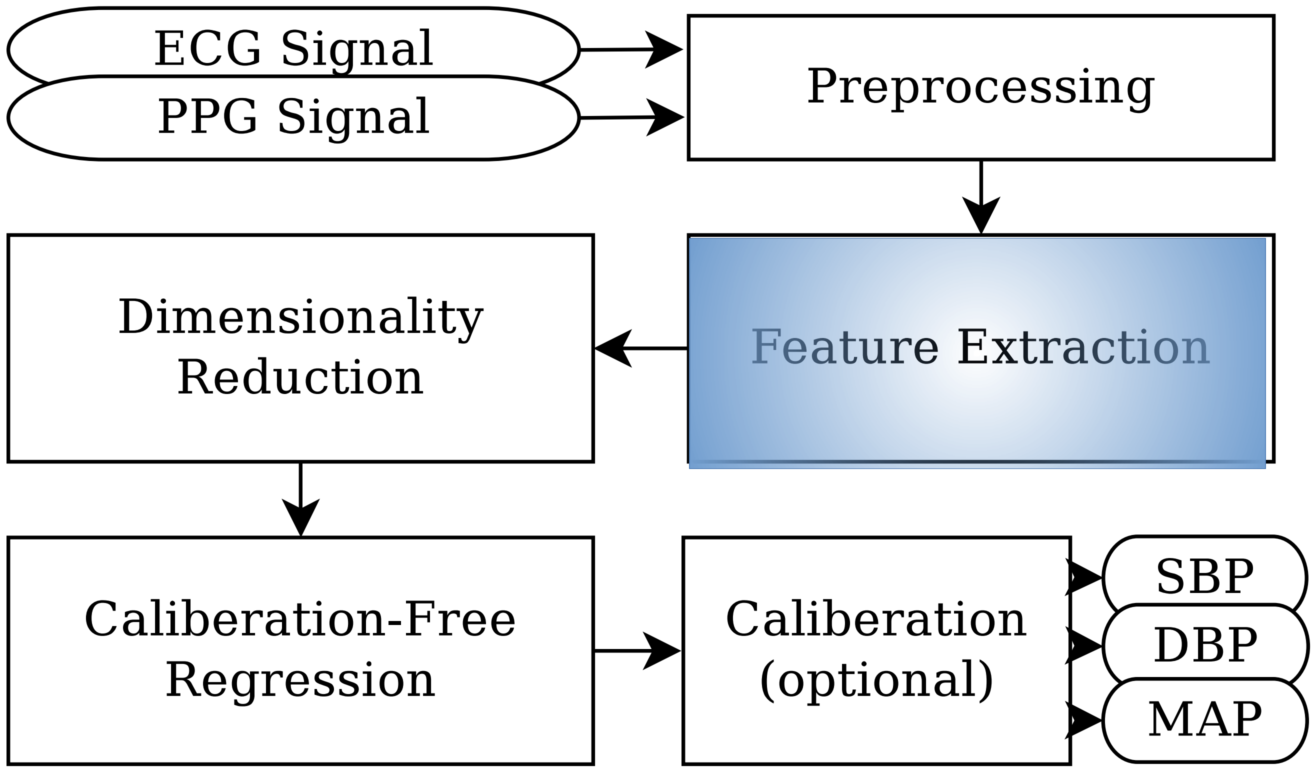
Preprocessing: Example

PPG Preprocessing Example

ECG Preprocessing Example



Proposed Methodology: Feature Extraction

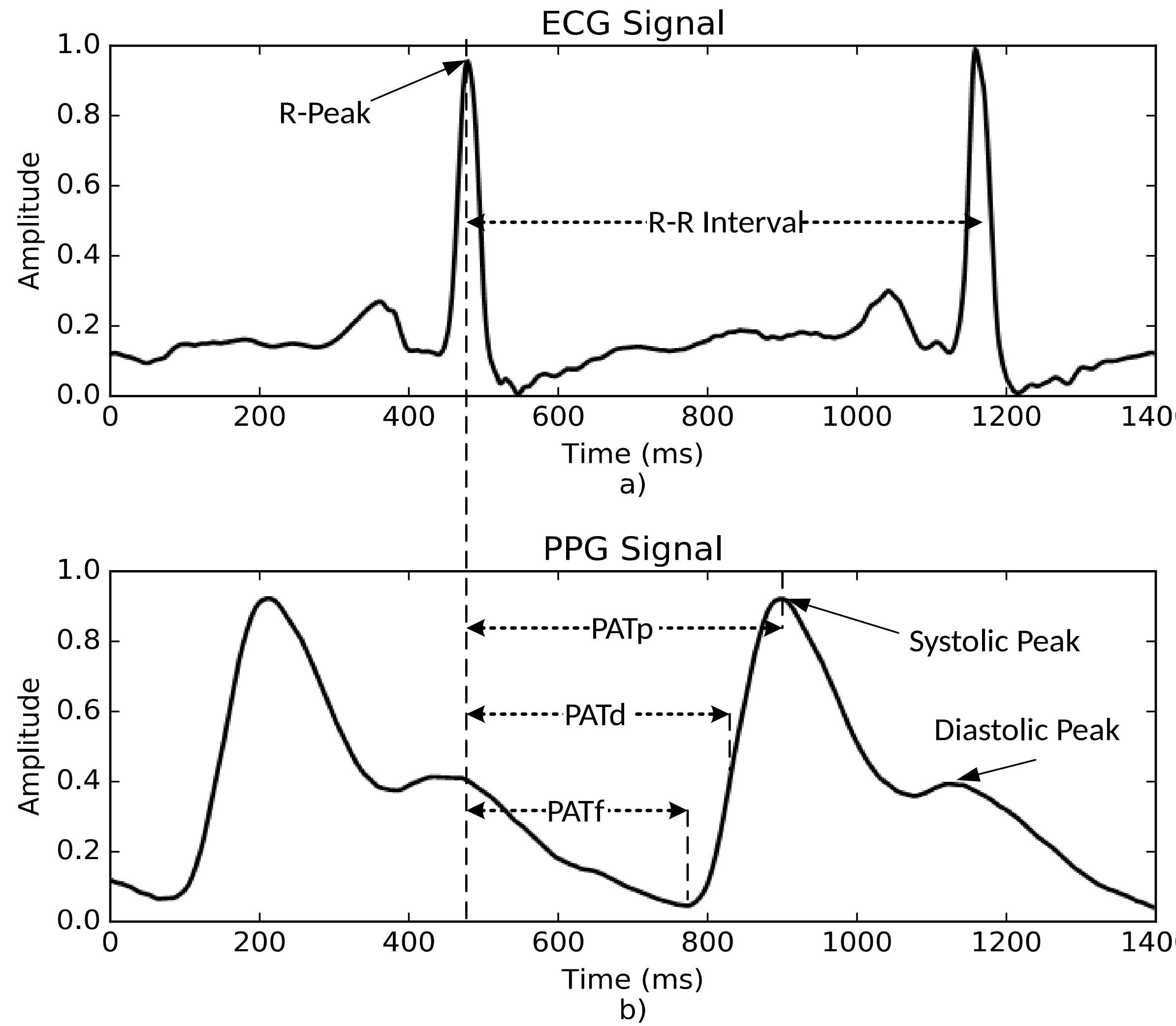


Feature Extraction Methods

- **Parameter-Based**
  - Based on physiological parameters
  - PTT features + PPG shape features
  - Small feature vector length
  - Limited by the signal morphology
- **Whole-Based**
  - Whole-based representation of signals
  - Fully automated feature extraction and selection
  - Works on almost every valid signal
  - Large and complex feature vectors

Feature Extraction Methods: Parameter-Based

1) PAT features

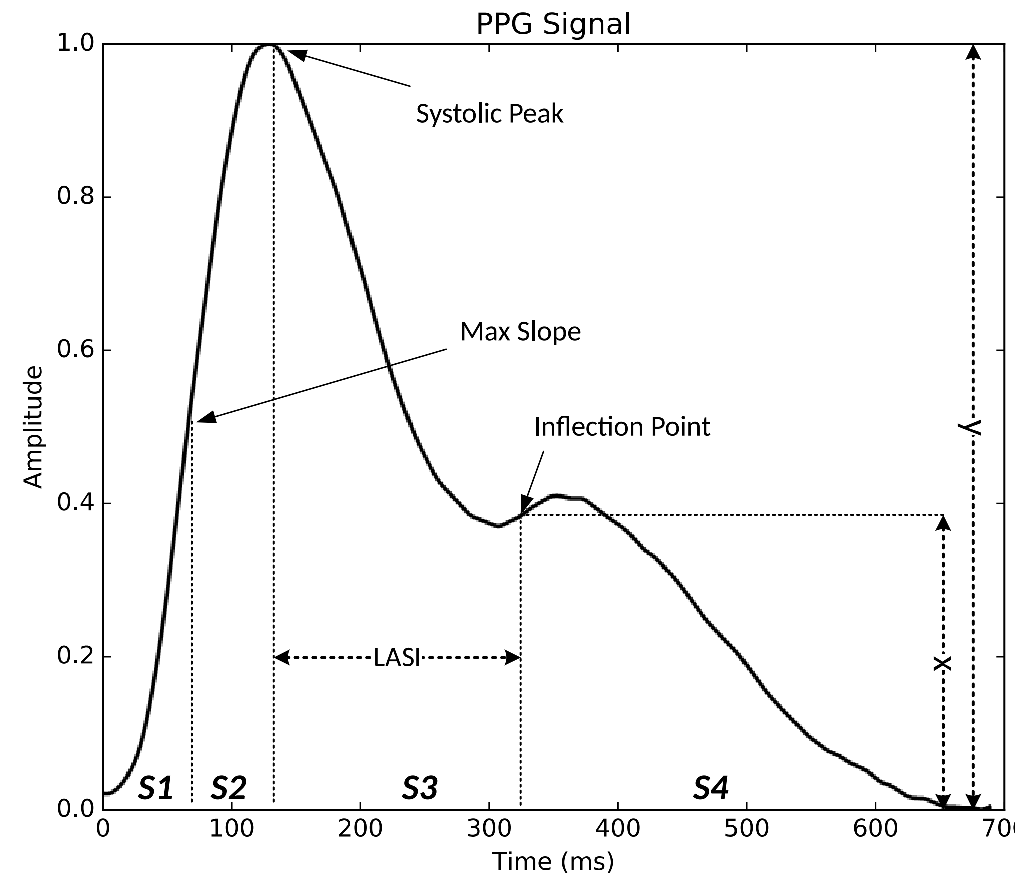


2) Heart Rate (HR)

Feature Extraction Methods: Parameter-Based

3) Augmentation Index (AI)

- A measure of wave reflection
- AI = x / y



4) Large Artery Stiffness Index (LASI)

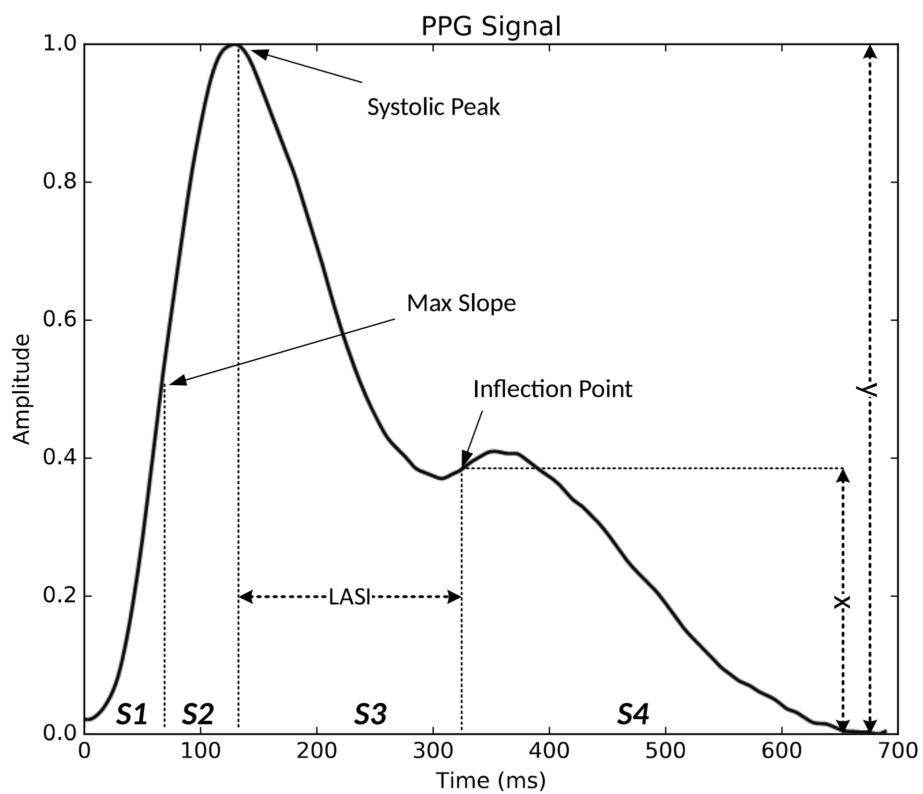
- Indicator of arterial stiffness

Feature Extraction Methods: Parameter-Based

5) Inflection Point Area ratio (IPA)

- Ratio of heart pumping and pulse wave reflection parts

$$IPA = S_4/(S_1+S_2+S_3)$$



Feature Extraction Methods: Whole-Based

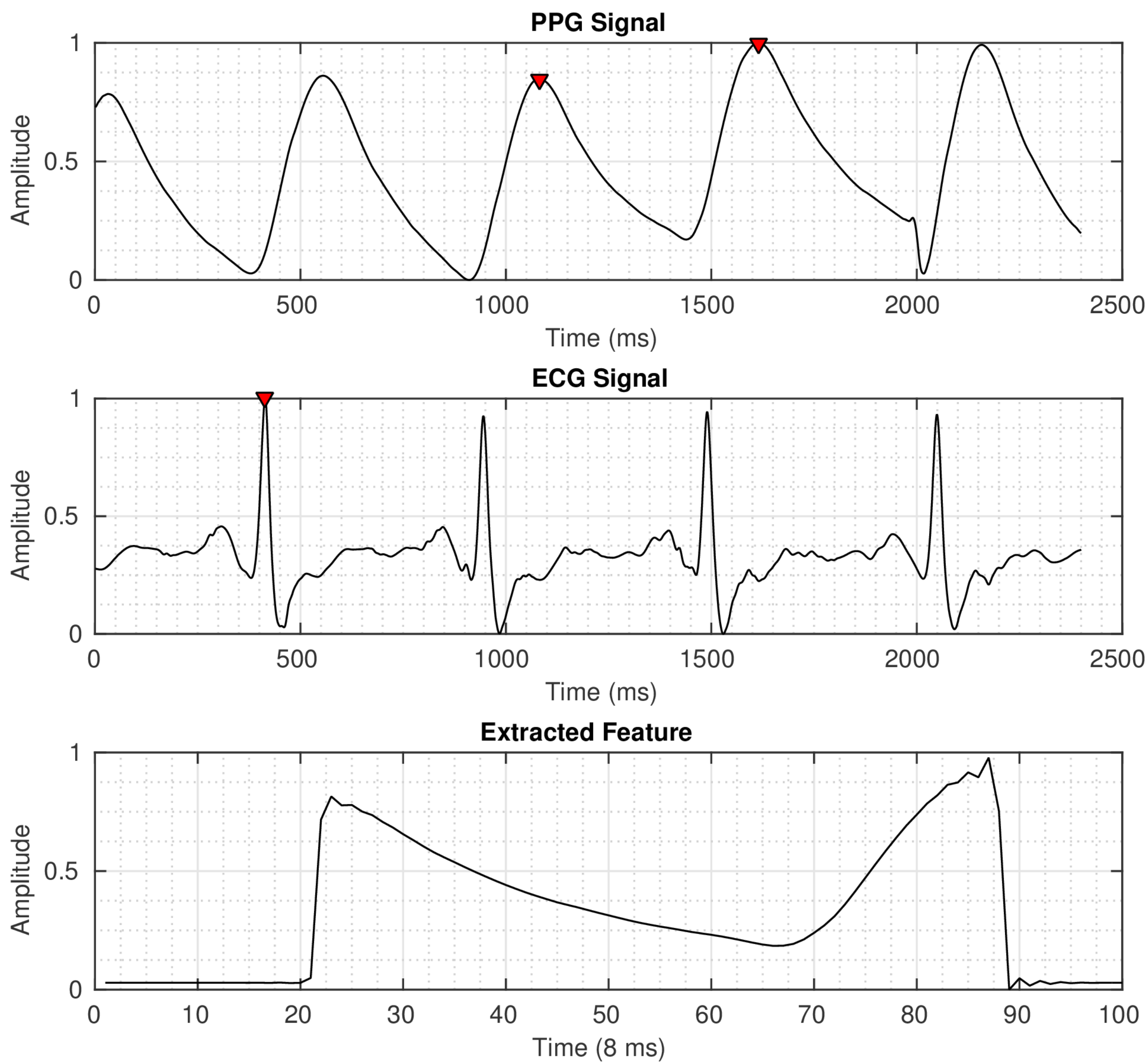
1) Selecting a processing window.

2) Determining R peaks and systolic peaks of the ECG and PPG signals.

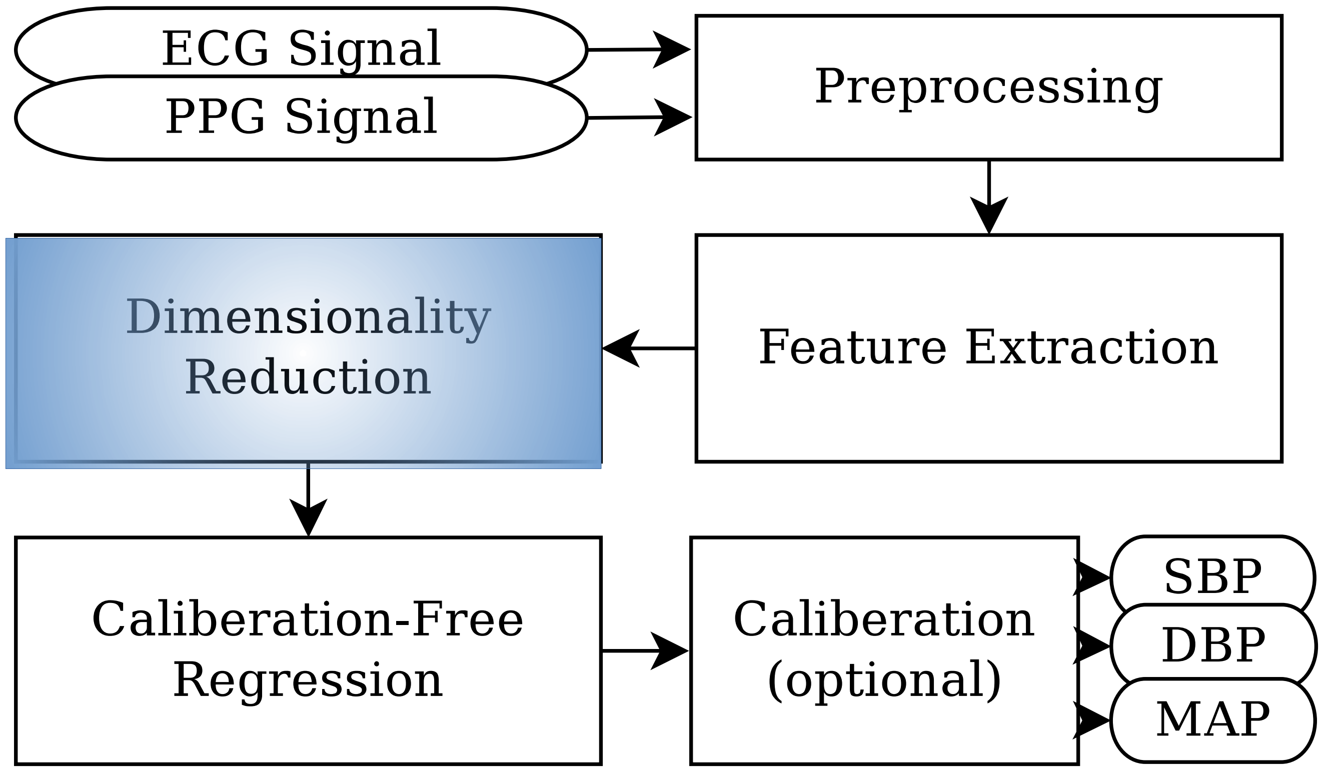
3) Selecting the first ECG R peak as a time reference, and shifting left the PPG signal is equal to the time reference.

4) Selecting and cropping the PPG signal part, which is between the first and the second PPG systolic peaks.

Feature Extraction Methods: Whole-Based

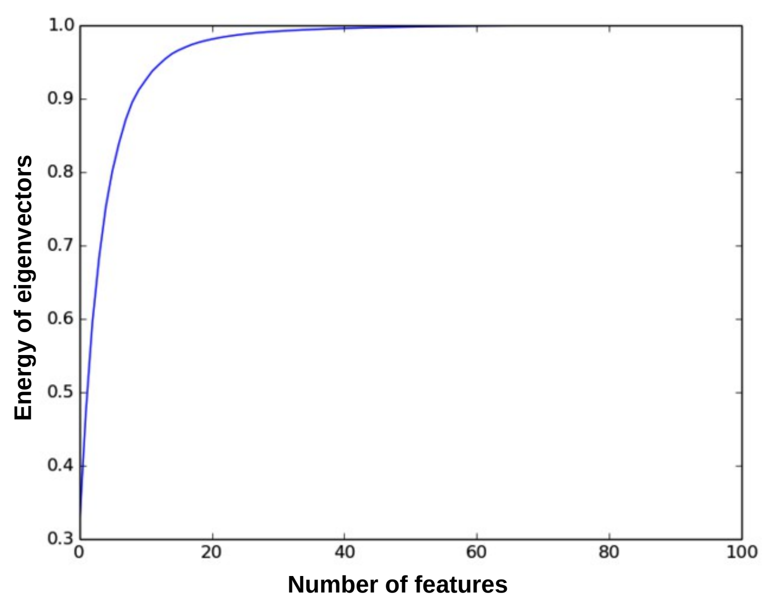


Proposed Methodology: Dimensionality Reduction

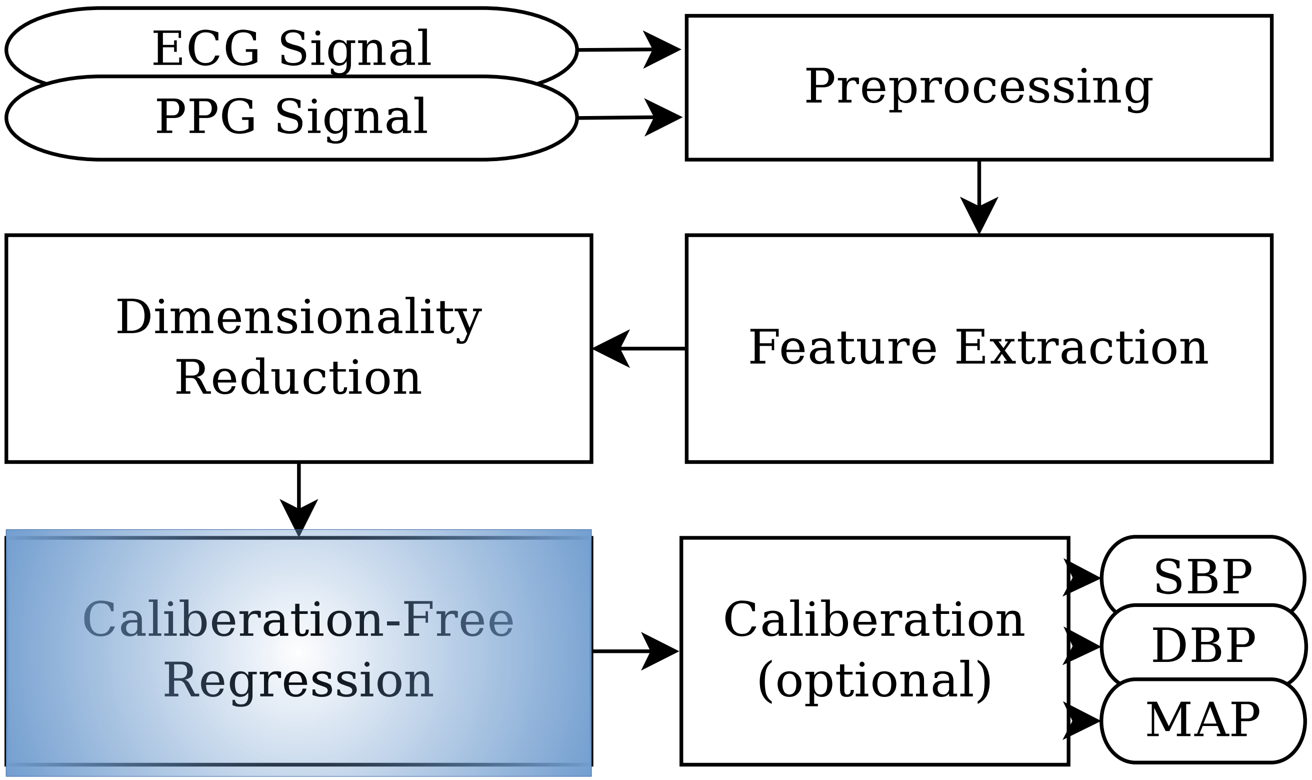


Dimensionality Reduction

- **Increasing the computational efficiency**
- **Reducing the number of required training data**
- **Using PCA on whole-based feature vectors:**
  - Preserving 98% energy of eigenvectors
  - Reducing the feature length from 190 to 15



Proposed Methodology: Calibration-free Regression



Calibration-free regression

- Here, ML is used for calibration-free BP estimation
- It is a supervised regression problem!

$$PTT = l\sqrt{\frac{\rho A_m}{\pi A P_1[1 + (\frac{P-P_0}{P_1})^2]}}$$

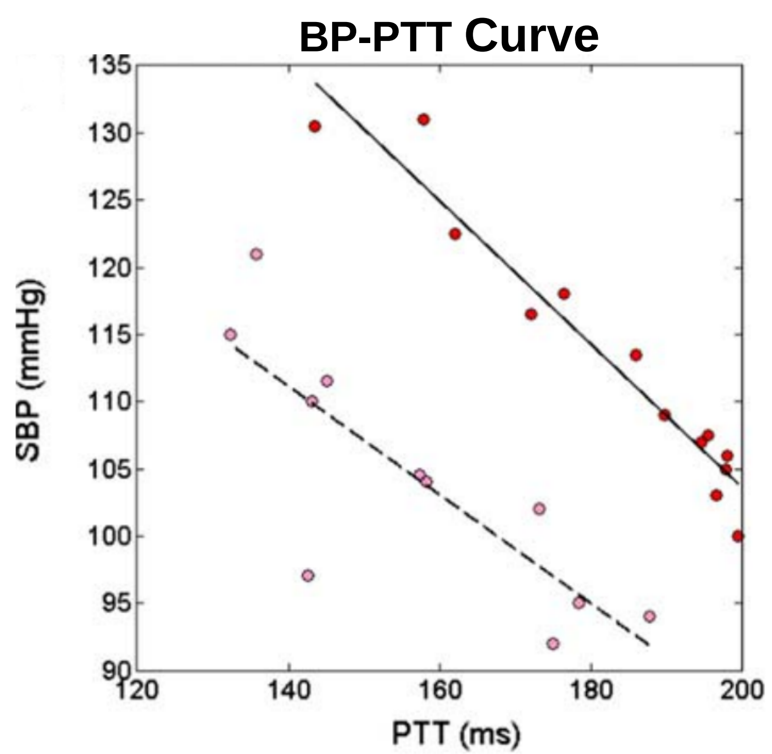
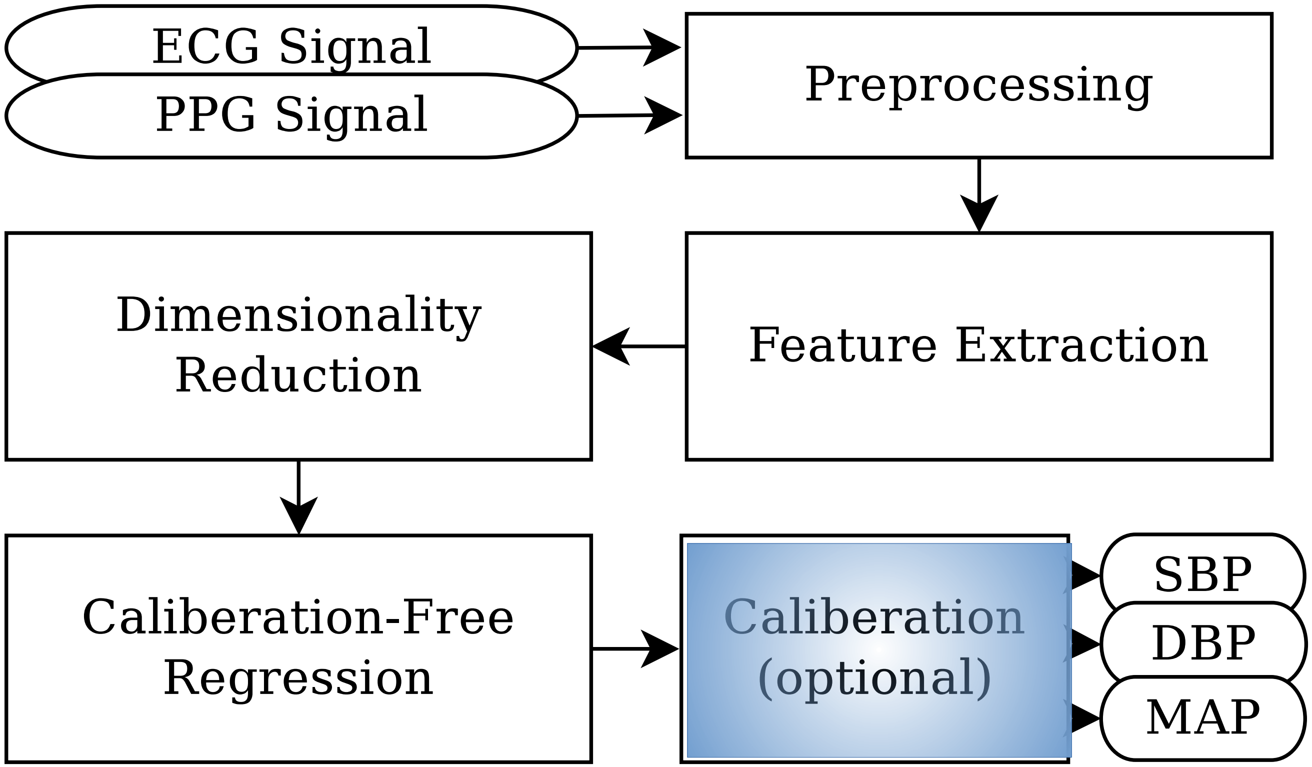


Figure courtesy of [21]

Calibration-free regression: Machine Learning

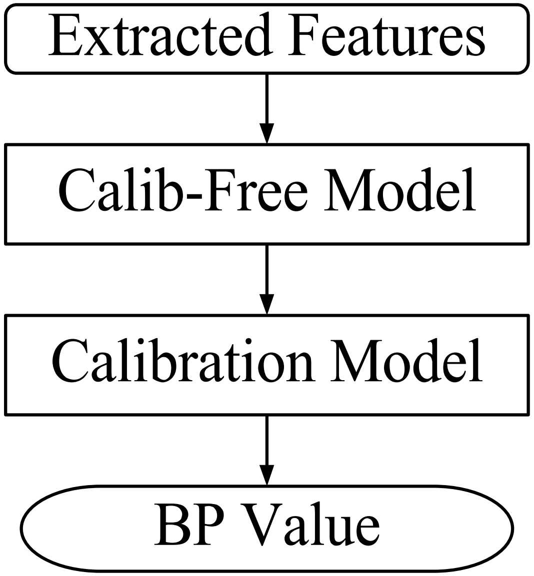
Algorithm	Properties	Pros	Cons
Linear Regression	Linear	Simple, Fast	Limited capability
Support Vector Machine	Sparse kernel machine	Powerful	Complex, Many hyper-parameters
Random Forest	Ensemble method, Bootstrap	Low bias, Fast	-
Adaptive Boosting	Ensemble method with weighting	Works out-of-the-box, Focus on harder samples	Slow

Proposed Methodology: Calibration



Calibration

- ✔ Optional
- ✔ One point
- ✔ Improves the results
- ✗ Disqualifies the method from the standards



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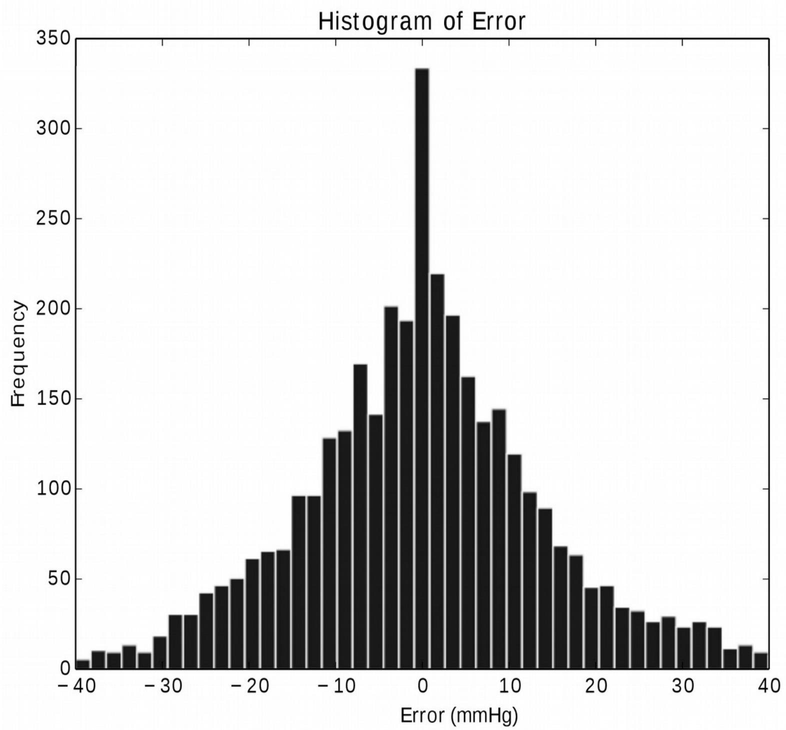
Results

Feature extraction and regression algorithm comparison:

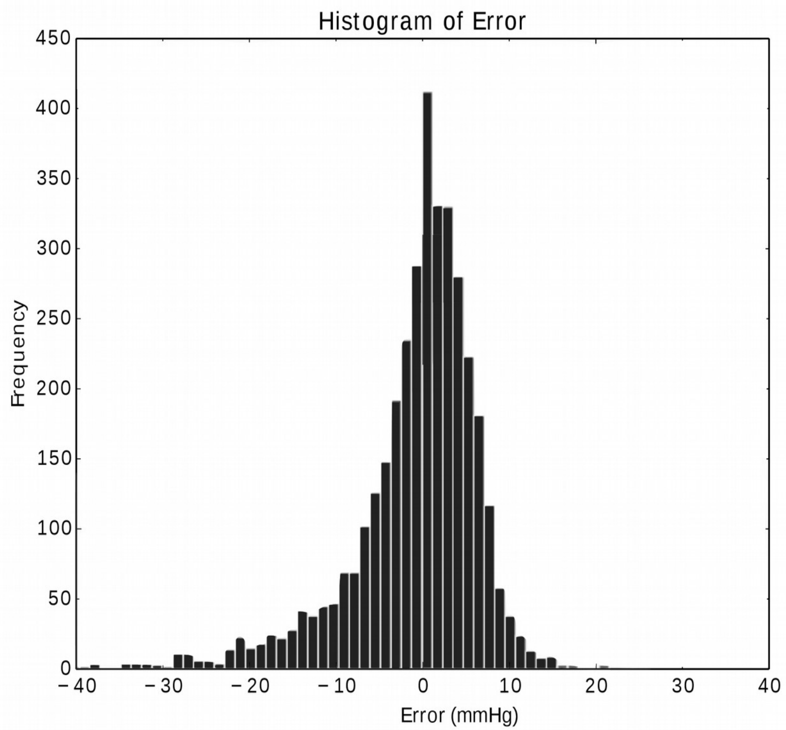
	Systolic Blood Pressure (mmHg)				Diastolic Blood Pressure (mmHg)			
Feature Set	Parameter-based		Whole-based		Parameter-based		Whole-based	
Learner / Performance	MAE	STD	MAE	STD	MAE	STD	MAE	STD
Linear Regression	14.71	10.79	14.14	10.44	6.74	6.11	6.75	6.12
Support Vector Machine	12.26	10.32	12.65	10.33	5.91	5.78	6.19	6.07
AdaBoost	**11.17**	10.09	**11.87**	10.30	**5.35**	6.14	**5.78**	6.61
Random Forest	11.80	**9.87**	12.39	**10.09**	5.83	**5.71**	6.39	**6.06**

Results

Error histogram (AdaBoost + Parameter_Based) :



(a) SBP



(b) DBP

Results

Comparison with other papers (AdaBoost + Parameter_Based) :

Work	Subjects (evaluation)	DBP STD (mmHg)	DBP MAE (mmHg)	DBP r	MAP STD (mmHg)	MAP MAE (mmHg)	MAP r	SBP STD (mmHg)	SBP MAE (mmHg)	SBP r
This Work (calib-free)	942	6.14	5.35	0.48	5.38	5.92	0.56	10.09	11.17	0.59
This Work (calib-based)	57	3.52	4.31	0.57	-	-	-	5.45	8.21	0.54
ECG_IBP [67] (calib-based)	22	-	-	0.42	-	-	0.46	-	-	0.47
rPTT [68] (calib-based)	12	-	-	0.14	-	-	0.28	-	-	0.62
BPTT [69] (calib-based)	30	6.00	-	-	-	-	-	7.61	-	-

Results

Evaluation using the BHS (AdaBoost+Parameter_Based) :

		Cumulative Error Percentage		
		$\leq 5mmHg$	$\leq 10mmHg$	$\leq 15mmHg$
Our Results	DBP	62.7%	87.1%	95.7%
	MAP	54.2%	81.8%	93.1%
	SBP	34.1%	56.5%	72.7%
BHS [71]	grade A	60%	85%	95%
	grade B	50%	75%	90%
	grade C	40%	65%	85%

Results

Evaluation using the AAMI (Random Forest+Parameter_Based) :

		ME (mmHg)	STD (mmHg)	Subjects
Our Results	Diastolic	0.36 ✓	5.70 ✓	942 ✓
	Mean Pressure	0.16 ✓	5.25 ✓	942 ✓
	Systolic	-0.06 ✓	9.88	942 ✓
AAMI [72]	SBP and DBP	≤ 5	≤ 8	≥ 85

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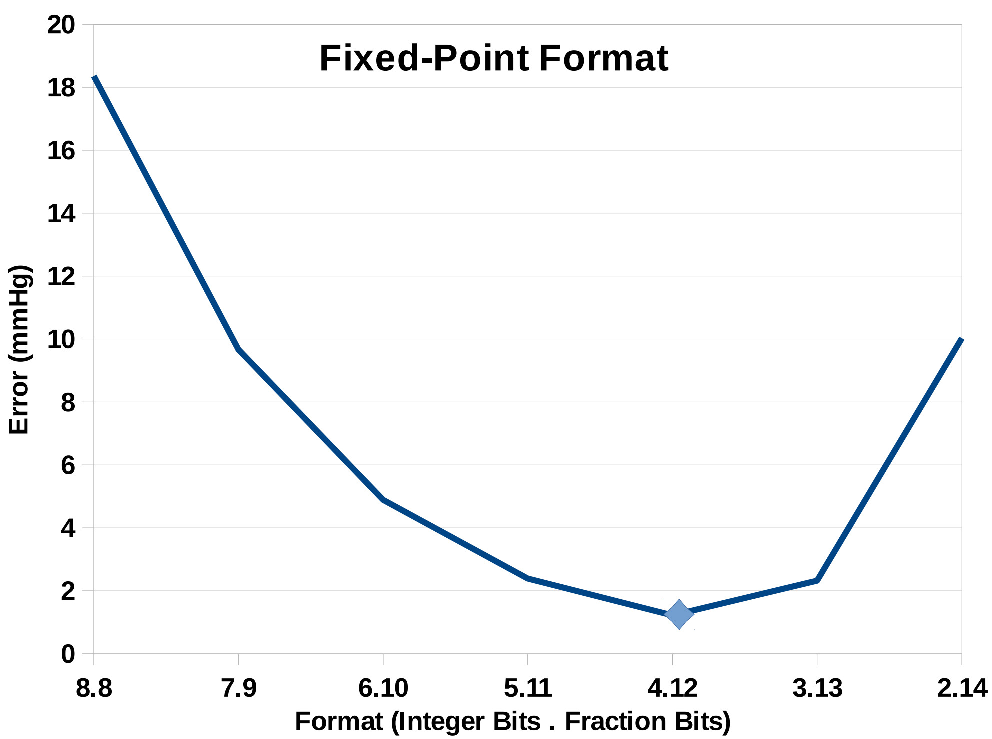
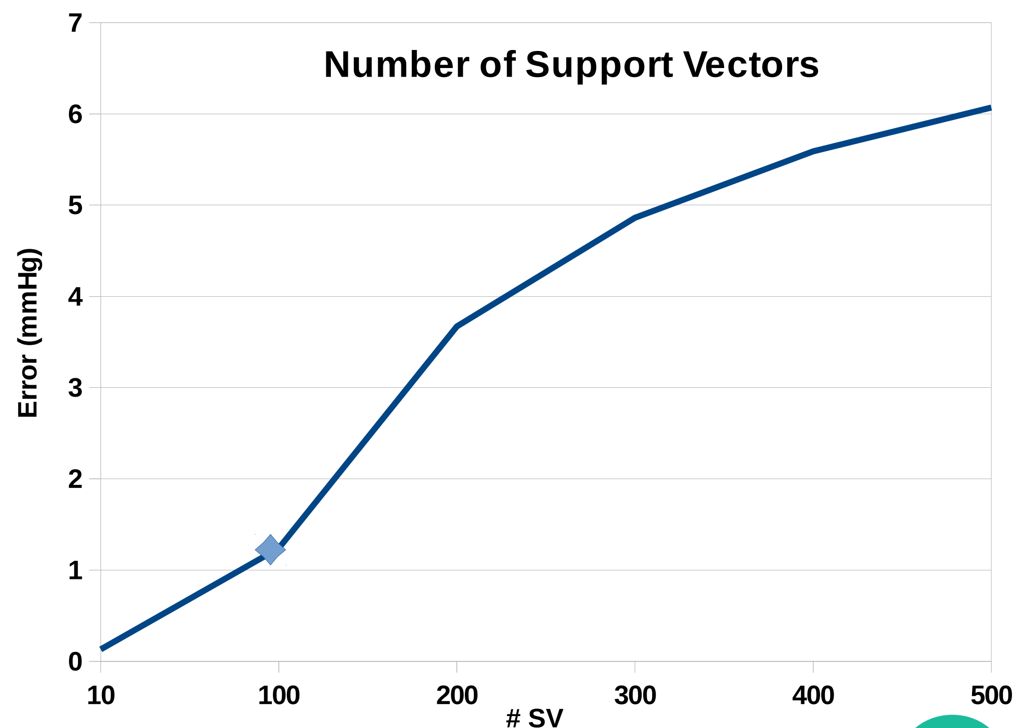
Hardware Implementation

- **Processing pipeline**
  - Preprocessing
  - Feature extraction
  - Regression
- **Regression requires hardware implementation**
- **SVM is selected for HW implementation as**
  - Its performance in BP estimation
  - Its applications in mHealth

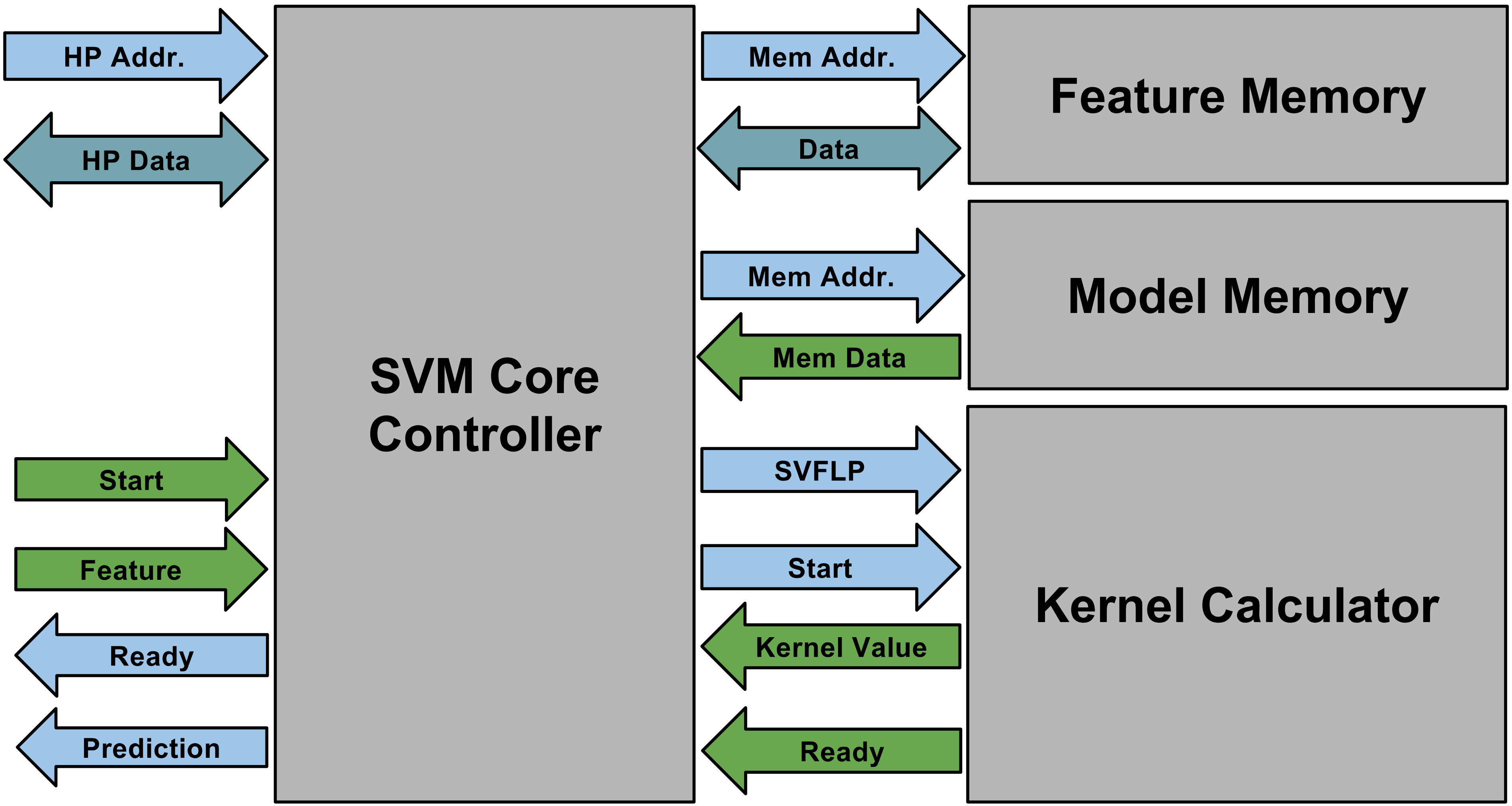
Python Simulation

- Fixed-point analysis
- Model conversion
- Test vector generation





SVM Co-processor



SVM Co-processor: Controller

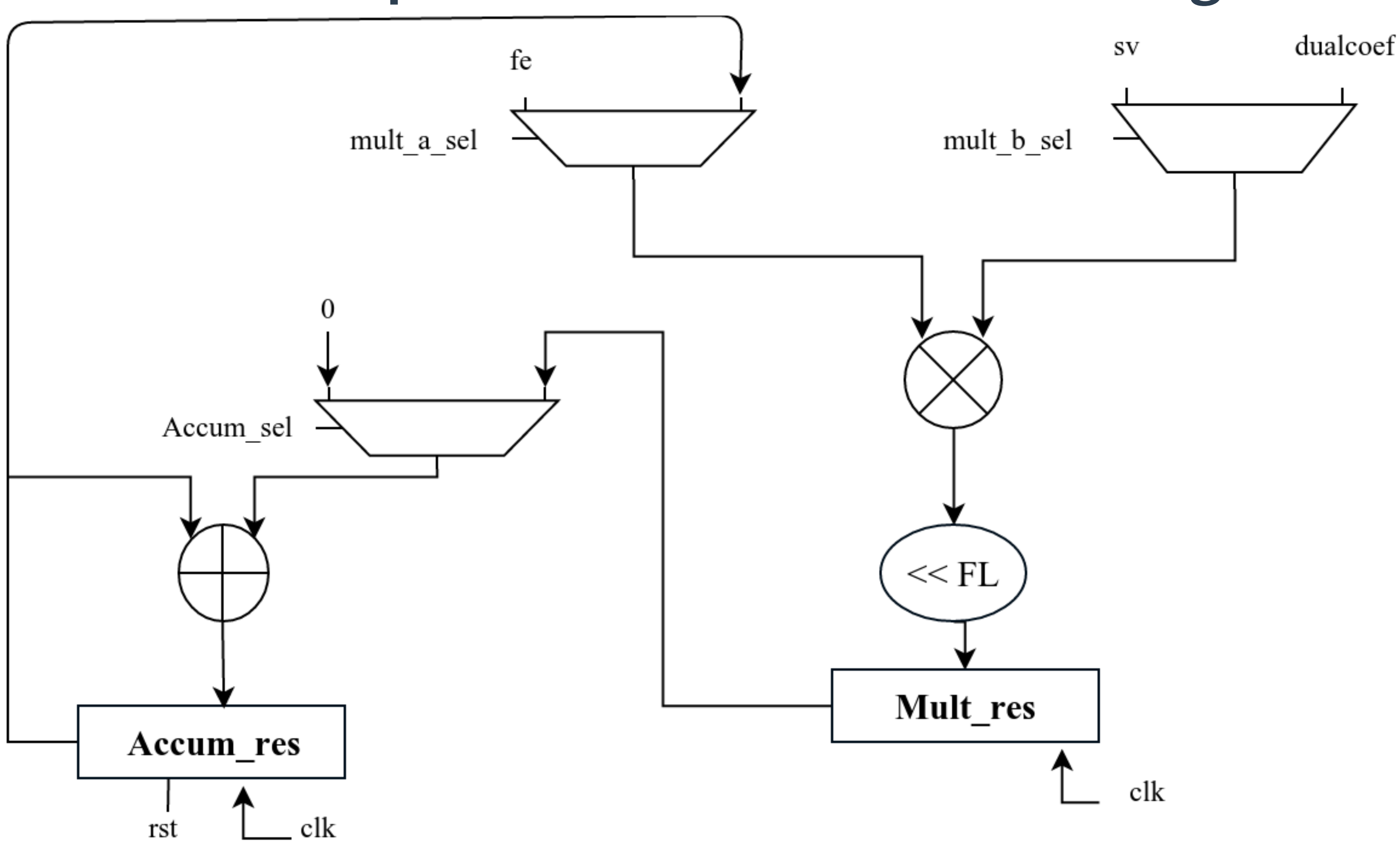
- Communicates with the host processor
- Controls the internal co-processor modules
- Consists of two 16-bit counters and a 15-state FSM

SVM Co-processor: Memory Modules

- **Features Memory**
  - Stores feature vectors
  - Flexibility in input vect. length
  - One port block RAM (1xRW)
- **Model Memory**
  - Stores the SVM model
  - Special memory layout
  - Two port block RAM (1xR+1xW)

SVM Co-processor: Kernel Calculator

- The kernel computation core
- Consists of a 16-bit counter, an execution core, a 7-state FSM
- Efficient data manipulation and resource sharing



SVM Co-processor: Results

- **Resource utilization (xq7z020):**

Site Type	Used	Available	Utilization
Slice LUTs	200	53200	0.38
- LUT as Logic	200	53200	0.38
- LUT as Memory	0	53200	0.00
Slice Registers	207	106400	0.19
- Register as Flip Flop	207	106400	0.19
- Register as Latch	0	106400	0.00
Block RAM Tile	32.5	140	23.21
DSP48E1	1	220	0.45

- **Timing (n_sv=200, n_fe=13, clk=100MHz):**
  - total computation time = 40.305 us (~4030 clk)
  - kernel computation time = 190 ns (~19 clk)
  - state transition, initialization, etc. = 40305ns–190ns*200 = 2305 ns (~230 clk)

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Conclusion

- Capability of continuous BP monitoring → cuff-less method
- Indirect calculation of BP → employing powerful regression algorithms
- Subject specific parameters → using the information from the vital signals
- Evaluation using established health standards → novel calibration-free method
- mHealth design considerations → efficient SVM core

Publications

- M. Kachuee, M. M. Kiani, H. Mohammadzade, M. Shabany, Cuff-Less Blood Pressure Estimation Algorithms for Continuous Health-Care Monitoring, IEEE Transactions on Biomedical Engineering (TBME), 2016.
- M. Kachuee, M. M. Kiani, H. Mohammadzade, M. Shabany, Cuff-Less High-Accuracy Calibration-Free Blood Pressure Estimation Using Pulse Transit Time, IEEE International Symposium on Circuits and Systems (ISCAS), 2015.

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Thanks