Passive Detection of Moving Targets with Dynamic Speed using PHY Layer Information

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Outline

- Introduction
- System Design
- Performance Evaluation
- Ongoing Work
- Conclusion

Call of Device-free Detection!

Intrusion Detection

Patience Monitoring

Search & Rescue

Limitations on current detection tech.

High Cost.

- Dedicated devices
- Small-scale deployment

Environment Constraints.

- Line-of-sight
- Enough light

Privacy Concerns.

- Personal privacy
- Sensitive Information

Wi-Fi, An alternative approach

Low Cost.

- COTS devices
- Large-scale deployment

Less Constraints.

- Non-Line-of-sight
- Work without light

Less Concerns.

- Less information
- No multimedia data

Still sensitive to motions.

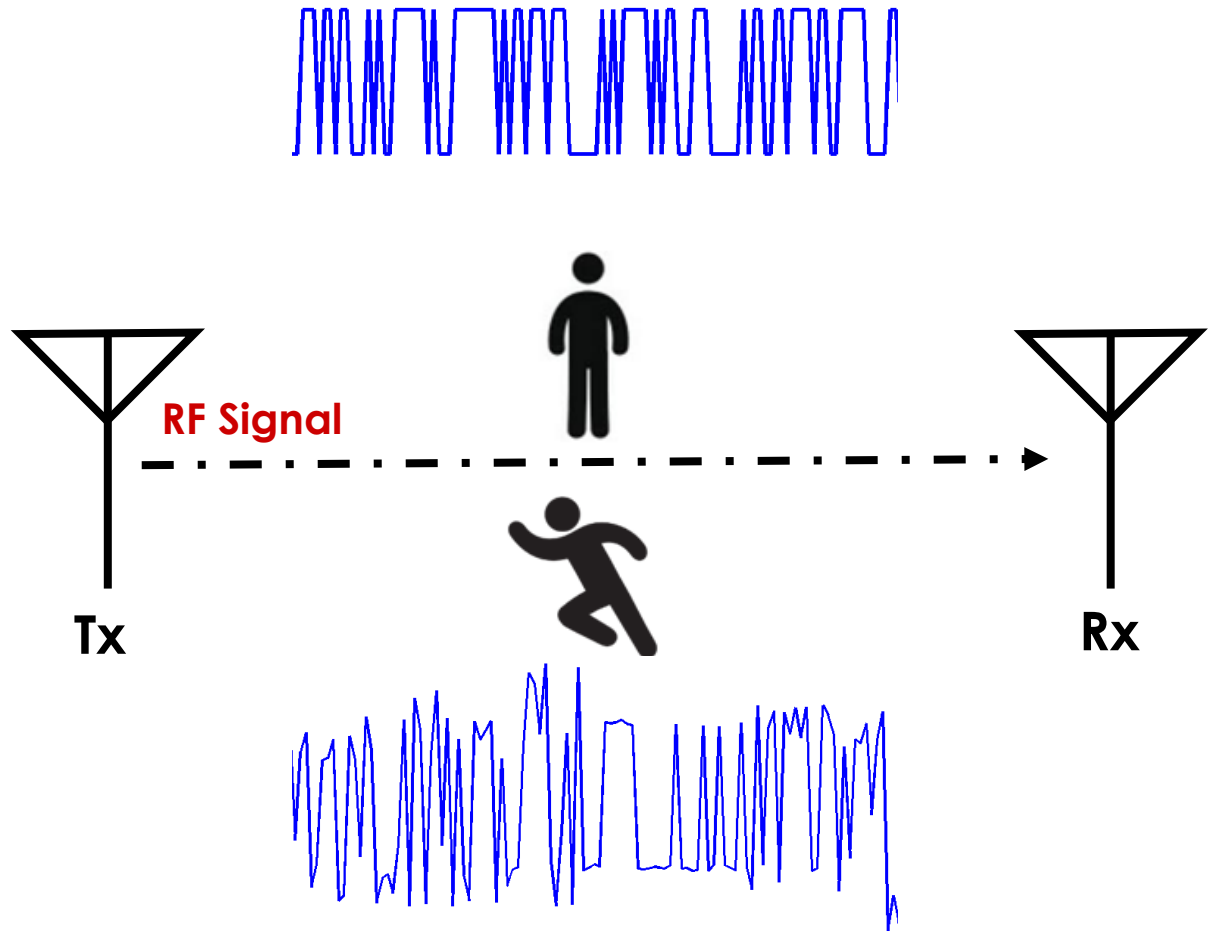
Detection towards Wi-Fi : RSSI

Principle

- Signal Strength varies significantly with environment changes.

Drawbacks

- High Variability
- High susceptibility to noise



Youssef et. al. RASID [PerCom '12]

Detection towards Wi-Fi : CSI

Principle

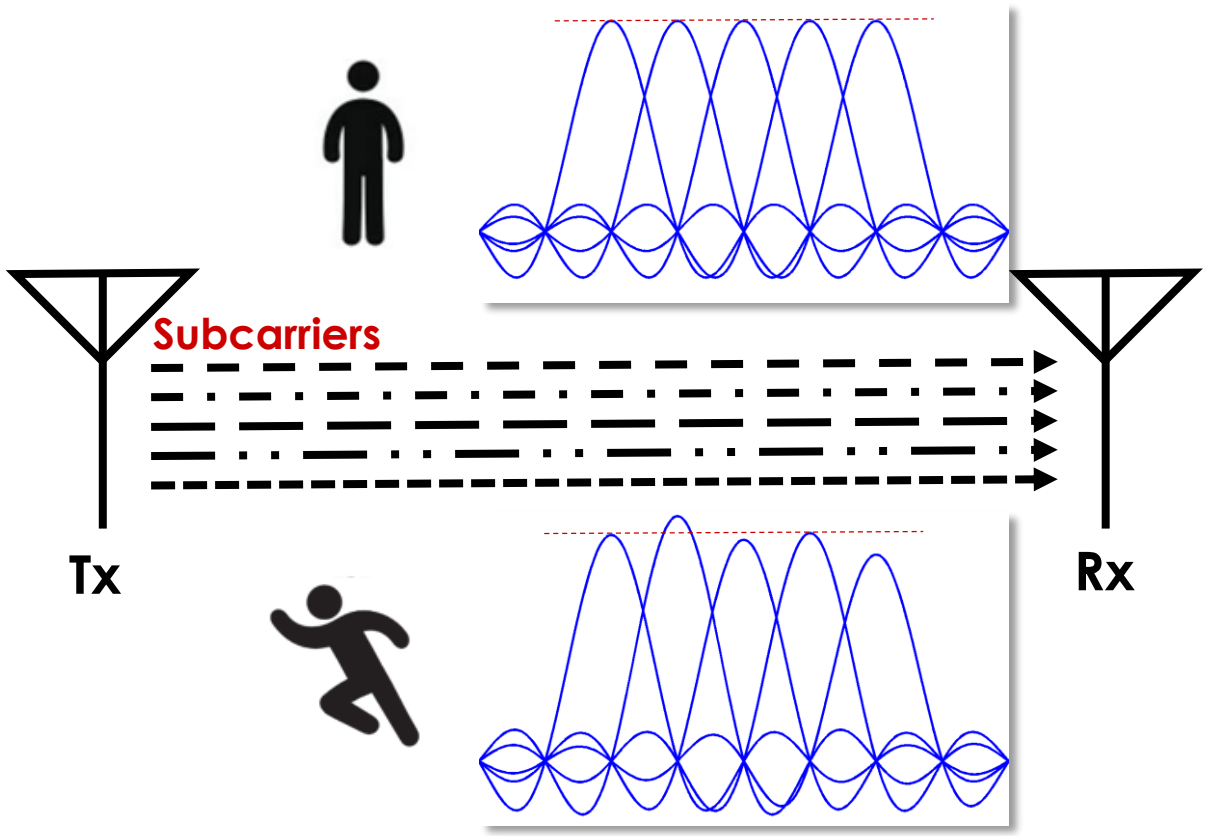
- RF Signal is composed of several individual subcarriers.
- Each subcarrier varies with environment changes.
- CSI is the combination of phases and amplitudes of all subcarriers.

$$\boldsymbol{H} = [\boldsymbol{H}(\boldsymbol{f_1}), \boldsymbol{H}(\boldsymbol{f_2}), \ldots, \boldsymbol{H}(\boldsymbol{f_N})]$$

$$\boldsymbol{H}(\boldsymbol{f_k}) = \|\boldsymbol{H}(\boldsymbol{f_k})\| e^{\angle \boldsymbol{H}(\boldsymbol{f_k})}$$

Drawbacks

- Only amplitude information is used.



Xiao et. al. FIMD [ICPADS '12]

Challenges against fully using CSI

Noise and Interference distort measurements

CSI phase is unusable

Identify motion event using feature properly

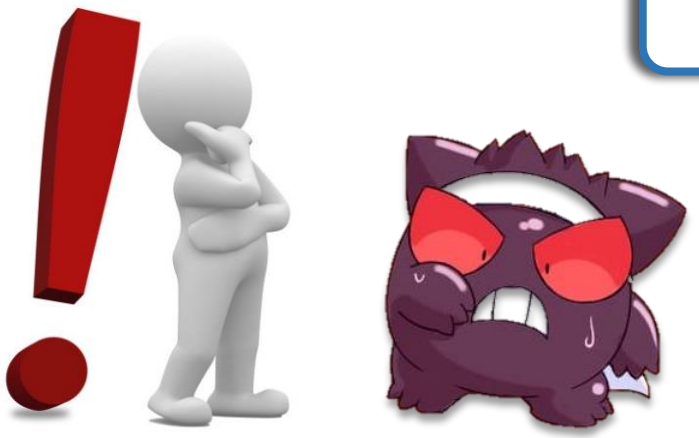
Slow motions may be missed due to low sensitivity…

Contribution to Extending Detection Range

Extracting robust feature from CSI

Fully exploiting CSI, both frequency & space

Carefully selecting learning algorithm



PADS

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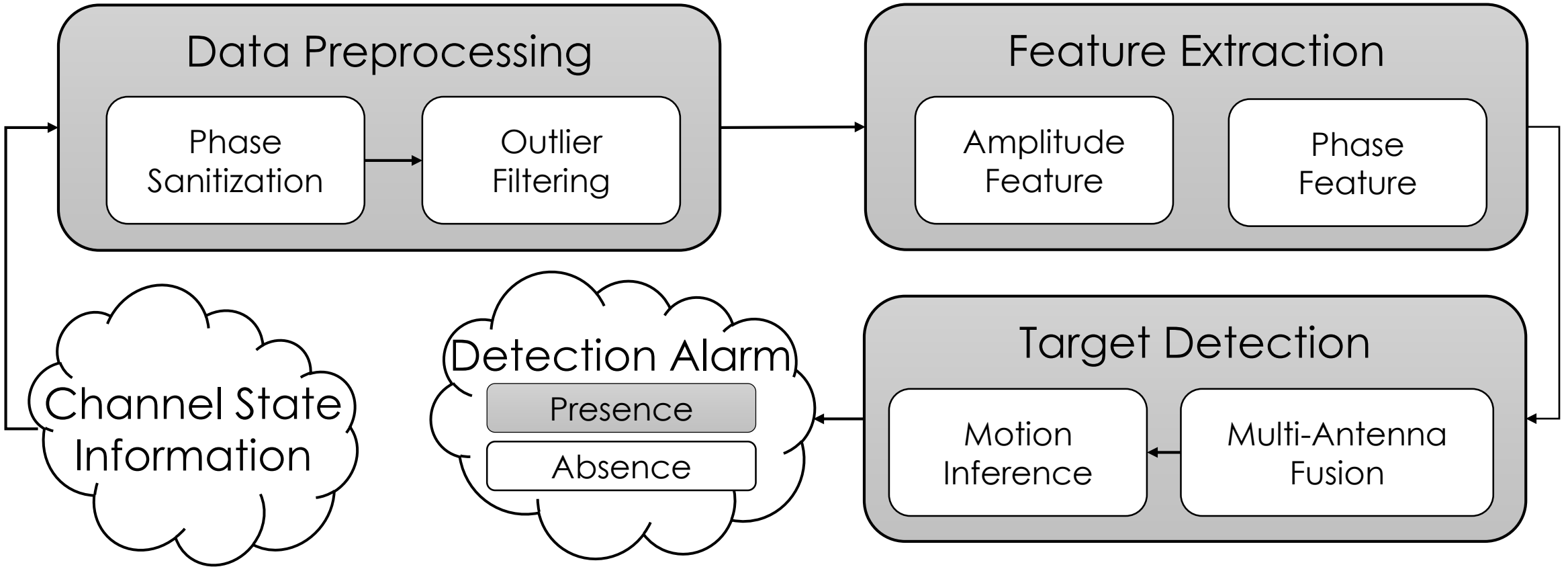
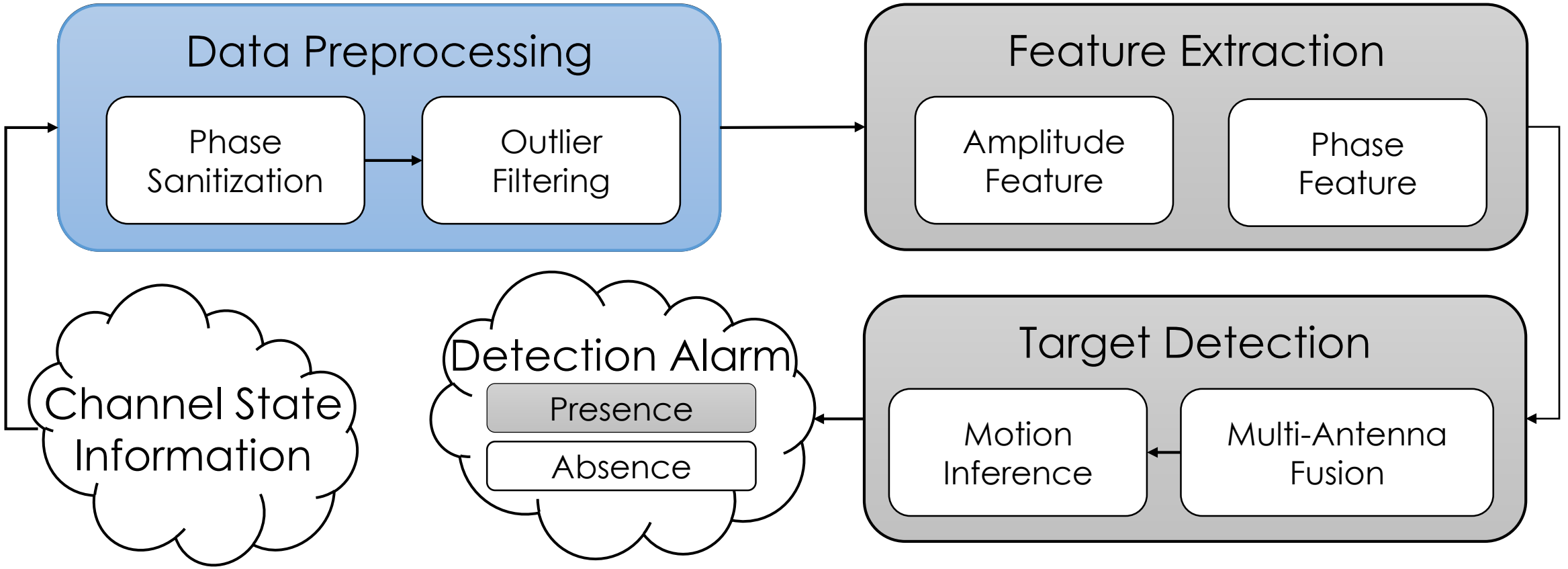
Architecture overview of PADS



Architecture overview of PADS



Phase Sanitization

Unsynchronized Tx/Rx Pair leads to polluted CSI phase.

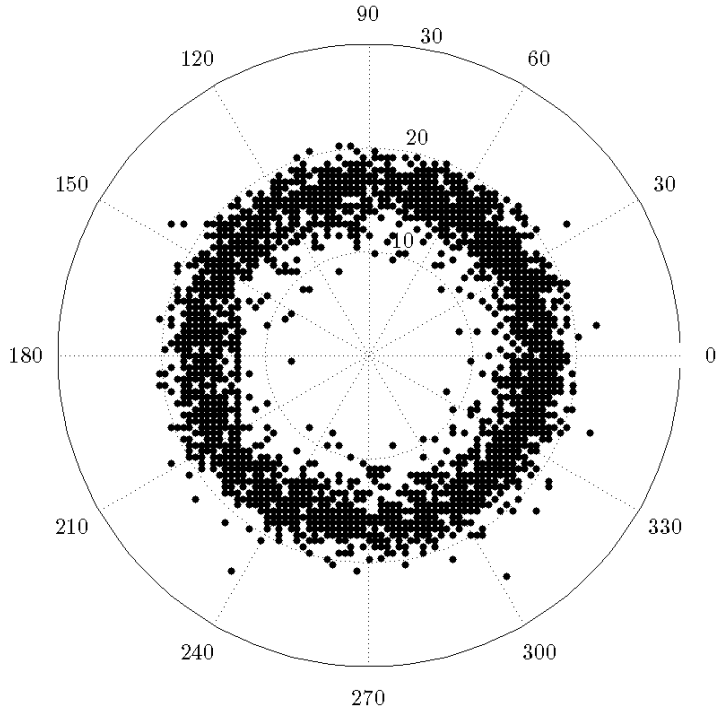
Measured Phase

$$\hat{\phi}_i = \phi_i - 2\pi \frac{k_i}{N} \delta + \beta + Z$$

Real Phase

Phase Shift

Phase relation for ith subcarrier



Raw phase distribution of ith subcarrier

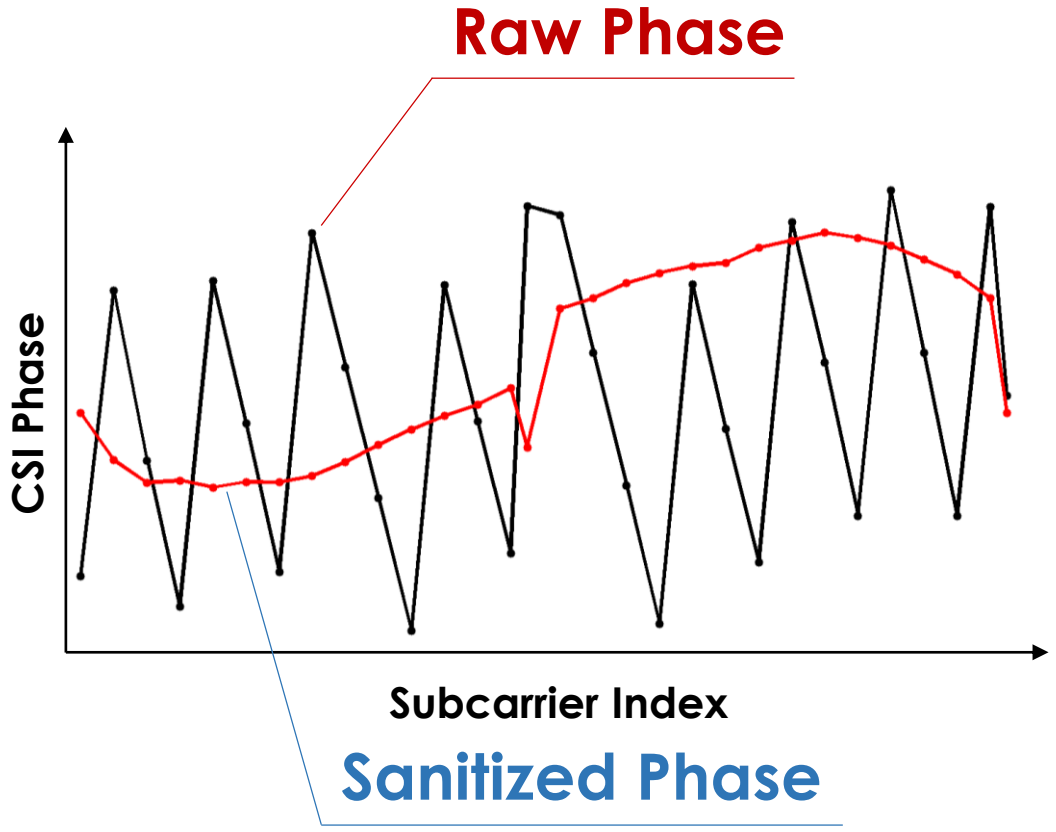
Using linear transformation

$2\pi \frac{k_i}{N} \delta + \beta + Z$ can be sanitized by linear transformation

$$a = \frac{\hat{\phi}_n - \hat{\phi}_1}{k_n - k_1} = \frac{\phi_n - \phi_1}{k_n - k_1} - \frac{2\pi}{N}\delta$$

$$b = \frac{1}{n}\sum_{j=1}^{n} \hat{\phi}_j = \frac{1}{n}\sum_{j=1}^{n} \phi_j - \frac{2\pi\delta}{nN}\sum_{j=1}^{n} k_j + \beta$$

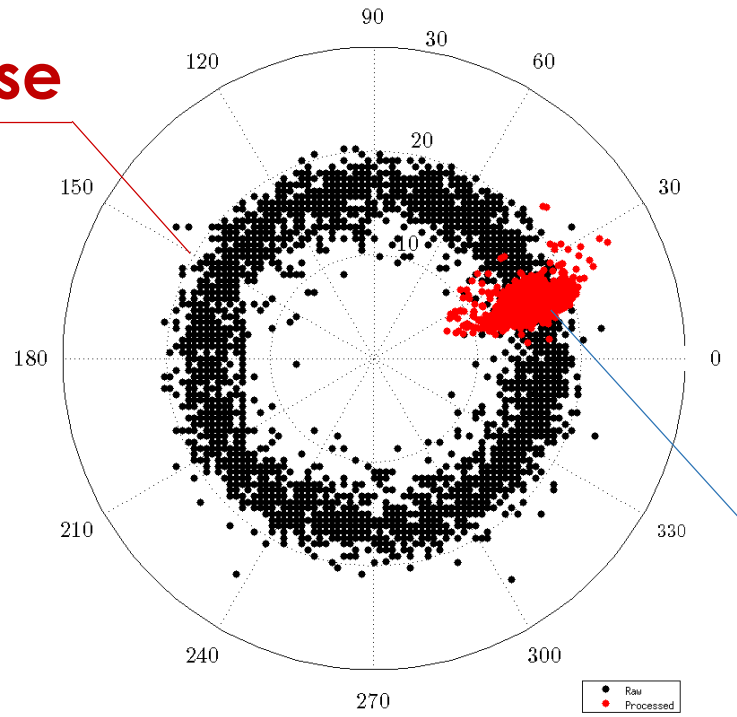
$$\tilde{\phi}_i = \hat{\phi}_i - a k_i - b$$



Sanitization Result

$$\tilde{\phi}_i = \hat{\phi}_i - ak_i - b = \phi_i - \frac{\phi_n - \phi_1}{k_n - k_1} k_i - \frac{1}{n}\sum_{j=1}^{n} \phi_j$$

Raw Phase

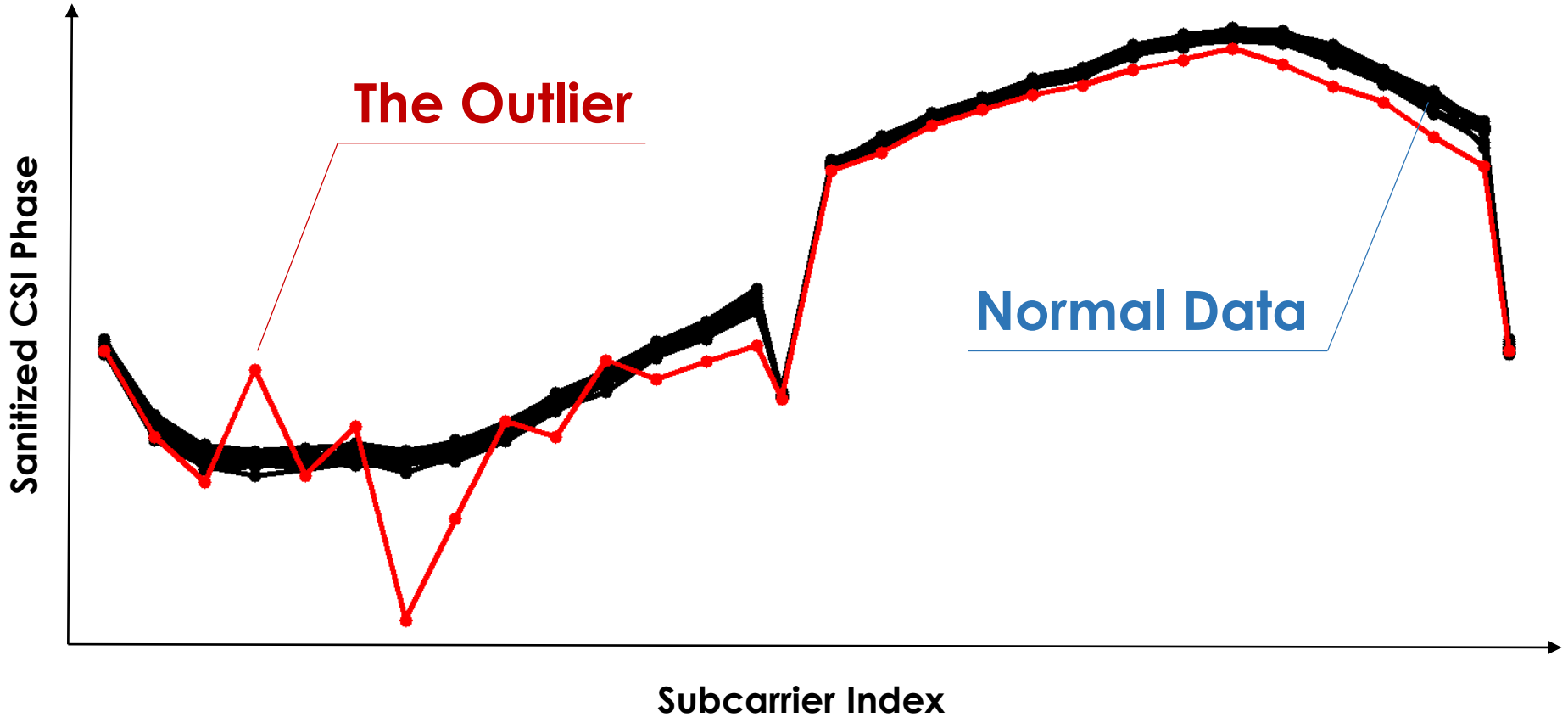


Sanitized Phase

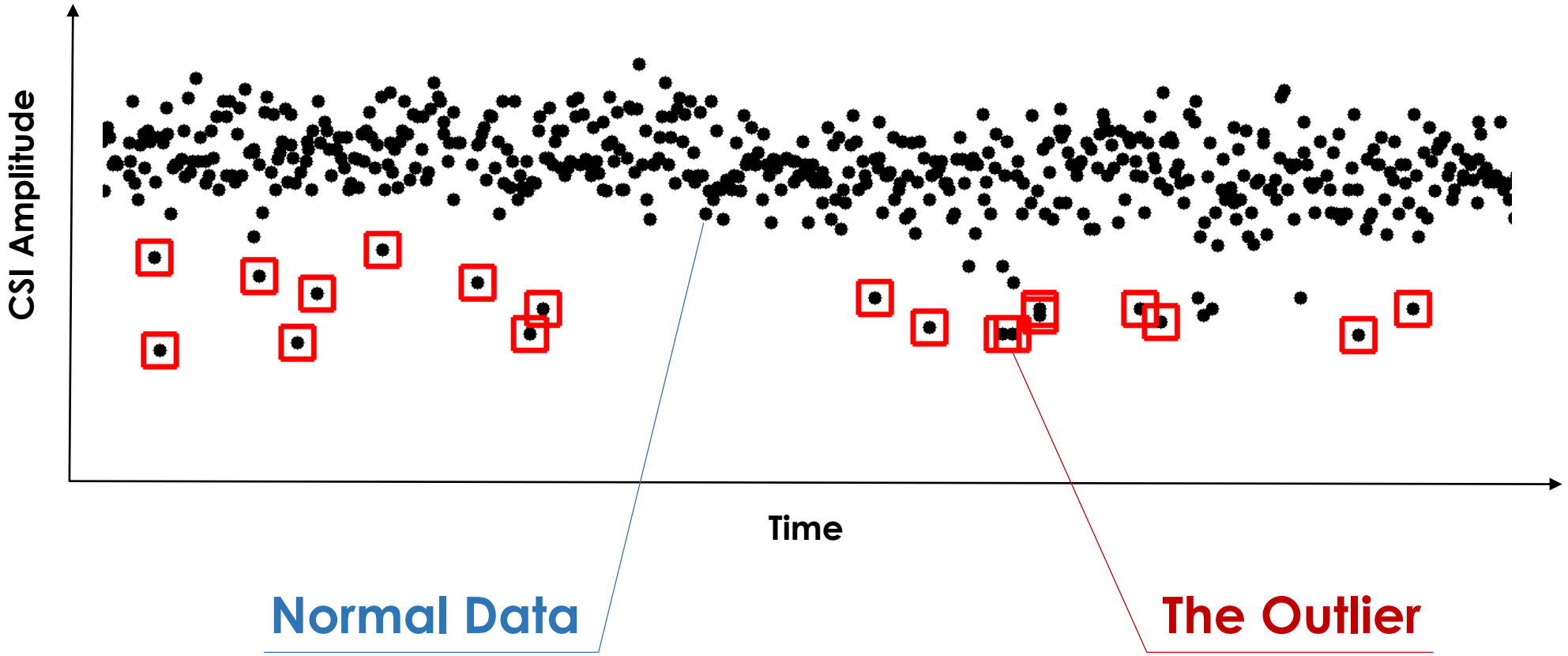
Linear combination of real phases $\{\phi_i\}_{i=1}^{n}$

- Stable
- Sufficient to use

Outlier Filtering



Using Hampel Identifier



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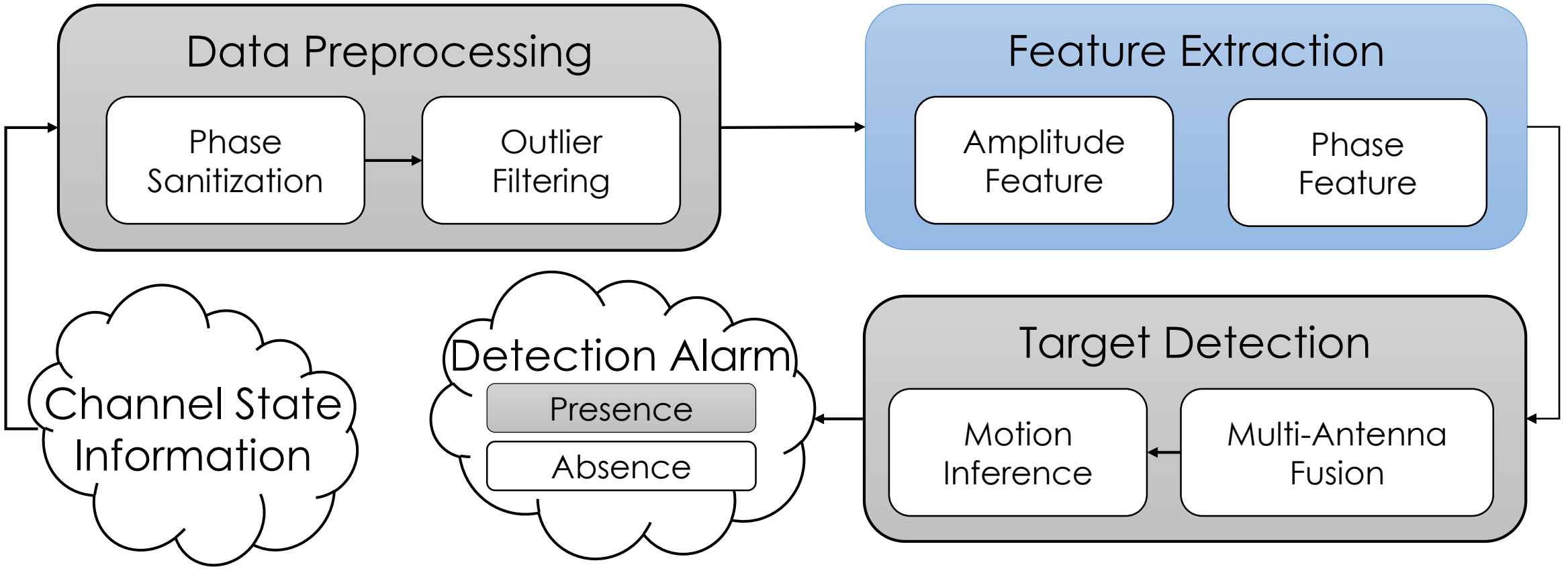
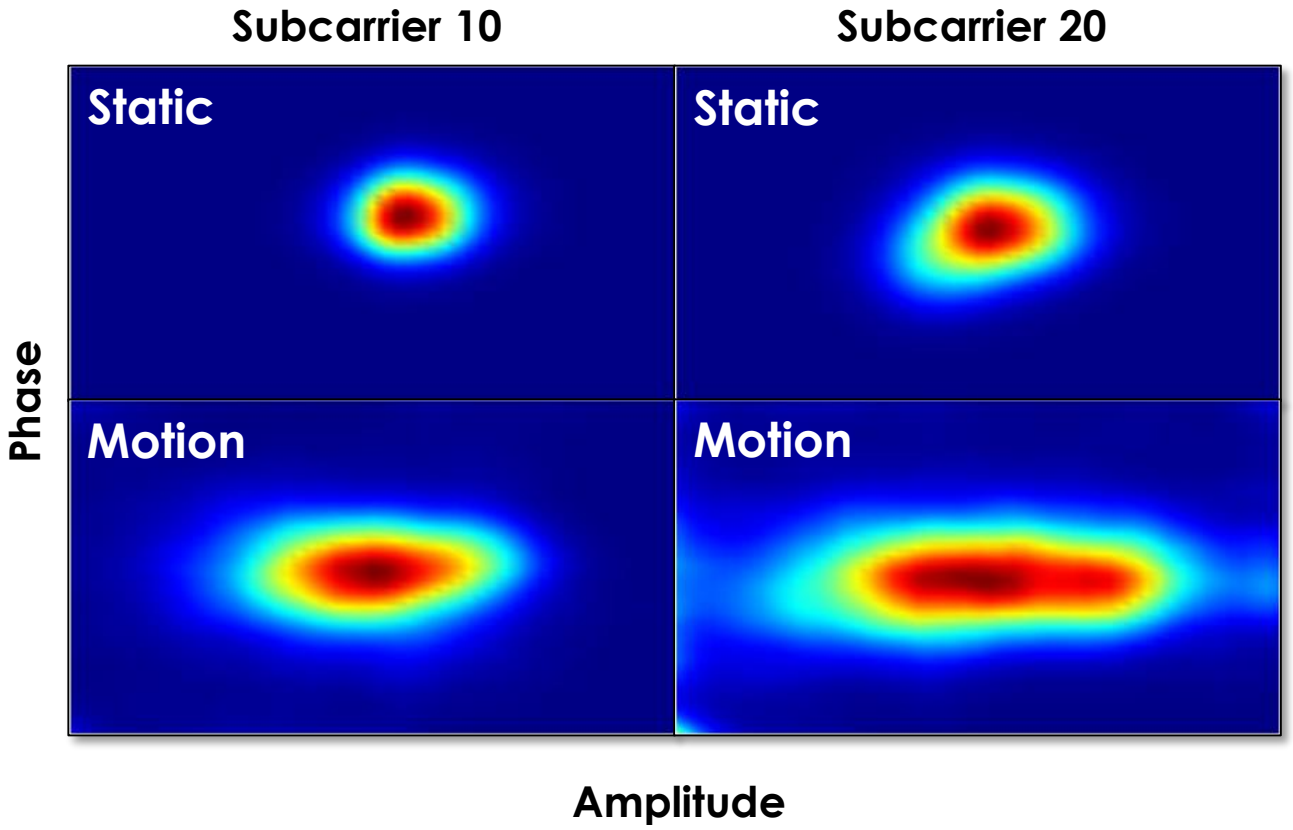


Feature Extraction



Principle

- Variance reflect changes.

Drawbacks

- Absolute signal power
- Random noise

Eliminating Absolute Signal Power

$$\boldsymbol{H} = [\boldsymbol{H}(\boldsymbol{f_1}), \boldsymbol{H}(\boldsymbol{f_2}), \ldots, \boldsymbol{H}(\boldsymbol{f_N})]$$

- **CSI with sanitized phase**

$$\bar{H} = \frac{H}{|H|}$$

- **Normalized CSI**

Mitigating Random Noise

$$\boldsymbol{H} = [\boldsymbol{H}(f_1), \boldsymbol{H}(f_2), \ldots, \boldsymbol{H}(f_N)]$$

- CSI with sanitized phase

$$\bar{\mathbb{H}} = [\bar{H}_1, \bar{H}_2, \ldots, \bar{H}_K], \quad \bar{H} = \frac{H}{|H|}$$

- Normalized CSI

$$\boldsymbol{\Sigma}(\bar{\mathbb{H}}) = \begin{bmatrix} cov(\|\bar{H}_1\|, \|\bar{H}_1\|) & \cdots & cov(\|\bar{H}_1\|, \|\bar{H}_K\|) \\ \vdots & \ddots & \vdots \\ cov(\|\bar{H}_K\|, \|\bar{H}_1\|) & \cdots & cov(\|\bar{H}_K\|, \|\bar{H}_K\|) \end{bmatrix}_{K \times K}$$

Covariance matrix of CSI amplitude

$$\boldsymbol{\Sigma}(\bar{\mathbb{H}}) = \begin{bmatrix} cov(\angle\bar{H}_1, \angle\bar{H}_1) & \cdots & cov(\angle\bar{H}_1, \angle\bar{H}_K) \\ \vdots & \ddots & \vdots \\ cov(\angle\bar{H}_K, \angle\bar{H}_1) & \cdots & cov(\angle\bar{H}_K, \angle\bar{H}_K) \end{bmatrix}_{K \times K}$$

Covariance matrix of CSI phase

Extracting Feature

$$\bar{H} = \frac{H}{|H|}$$

- Normalized CSI

$$\bar{\mathbb{H}} = [\bar{H}_1, \bar{H}_2, \dots, \bar{H}_K]$$

- Processing Normalized CSI

$$\Sigma(\bar{\mathbb{H}}) = \begin{bmatrix} cov(\|\bar{H}_1\|, \|\bar{H}_1\|) & \dots & cov(\|\bar{H}_1\|, \|\bar{H}_K\|) \\ \vdots & \ddots & \vdots \\ cov(\|\bar{H}_K\|, \|\bar{H}_1\|) & \dots & cov(\|\bar{H}_K\|, \|\bar{H}_K\|) \end{bmatrix}_{K \times K}$$

Covariance matrix of CSI amplitude

$$\Sigma(\bar{\mathbb{H}}) = \begin{bmatrix} cov(\angle\bar{H}_1, \angle\bar{H}_1) & \dots & cov(\angle\bar{H}_1, \angle\bar{H}_K) \\ \vdots & \ddots & \vdots \\ cov(\angle\bar{H}_K, \angle\bar{H}_1) & \dots & cov(\angle\bar{H}_K, \angle\bar{H}_K) \end{bmatrix}_{K \times K}$$

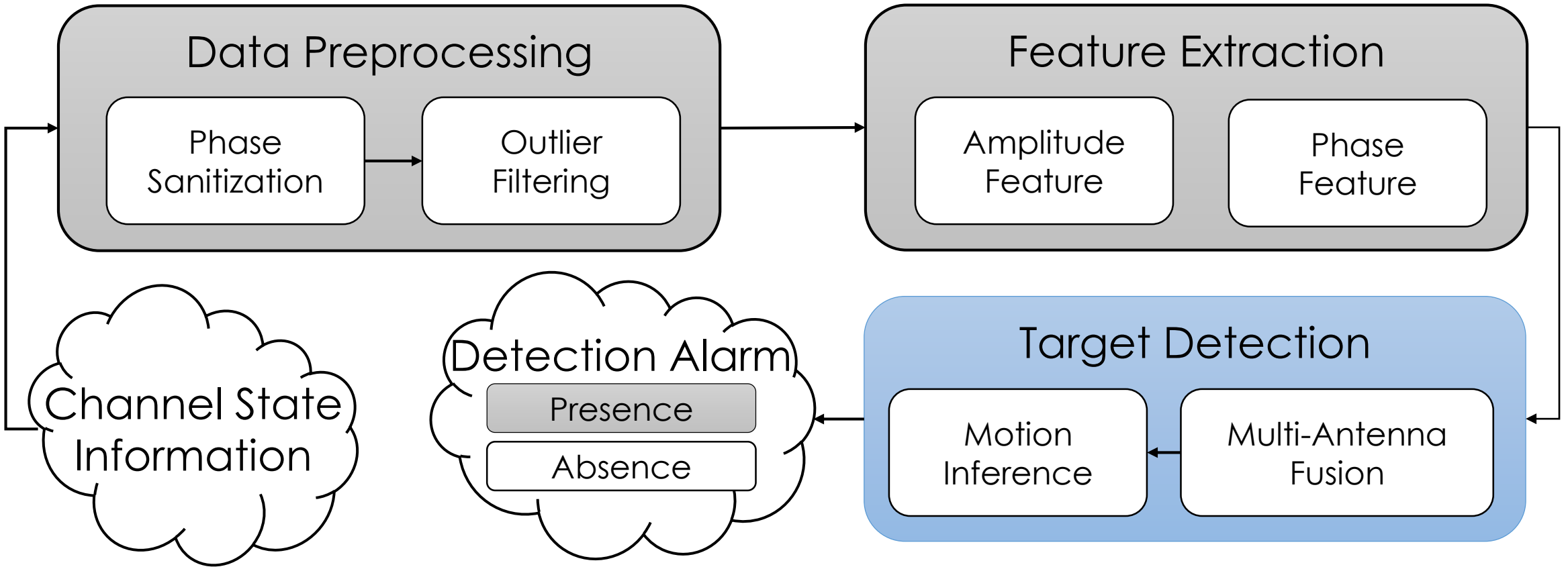
$\alpha = max(eigen(\Sigma(\bar{\mathbb{H}})))$

$\rho = max(eigen(\Sigma(\Psi)))$

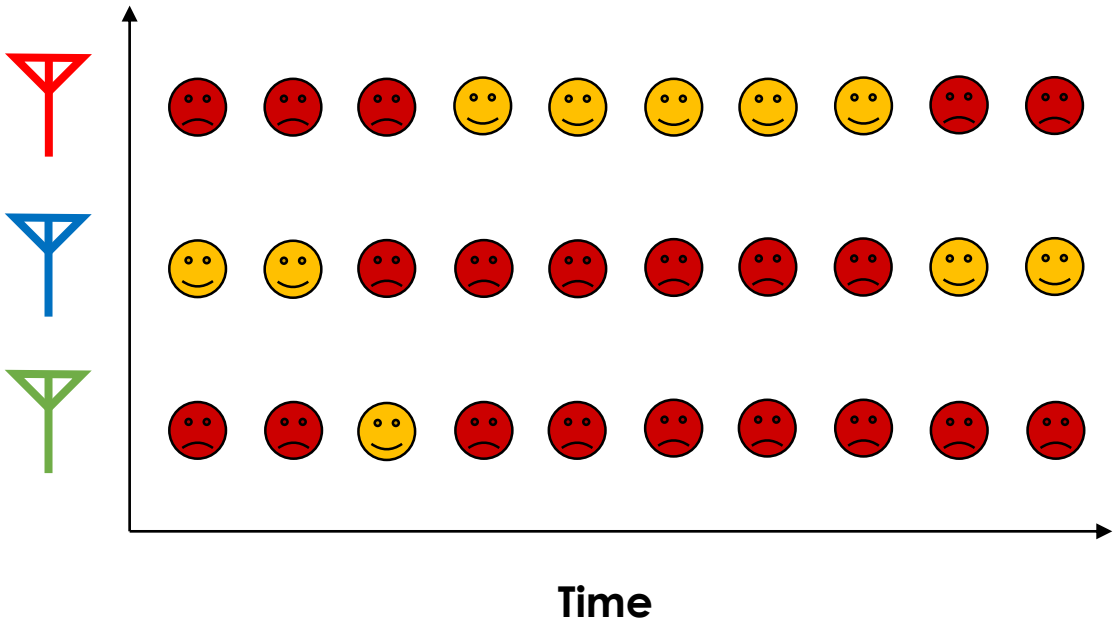
Principle Components are finally extracted

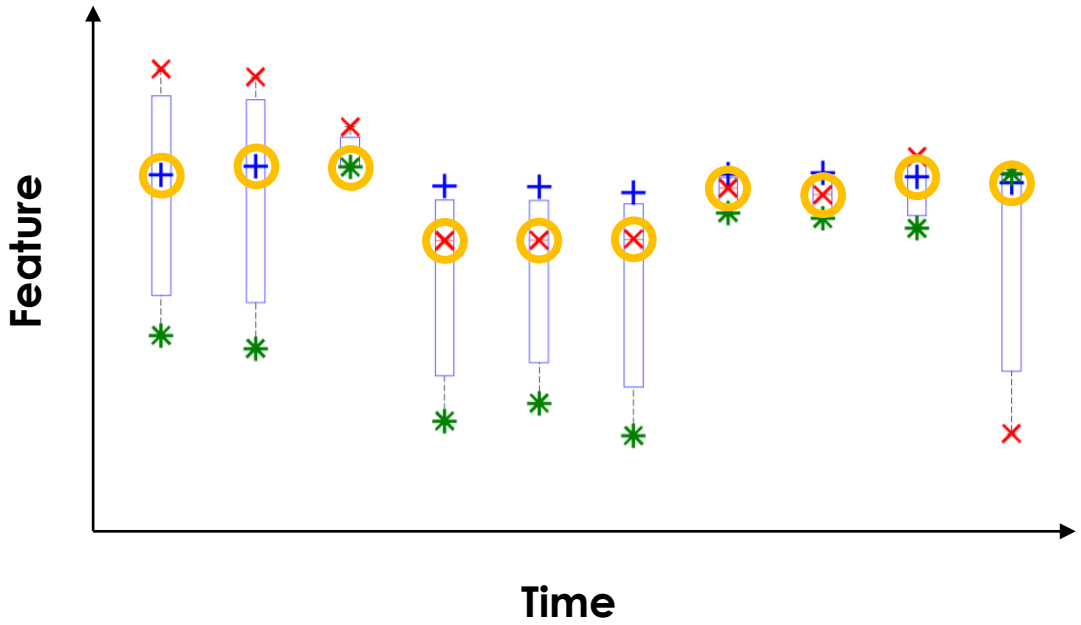
Covariance matrix of CSI phase

Architecture overview of PADS



Multi-Antenna Fusion





Median indicators keep relatively stable

Motion Inference

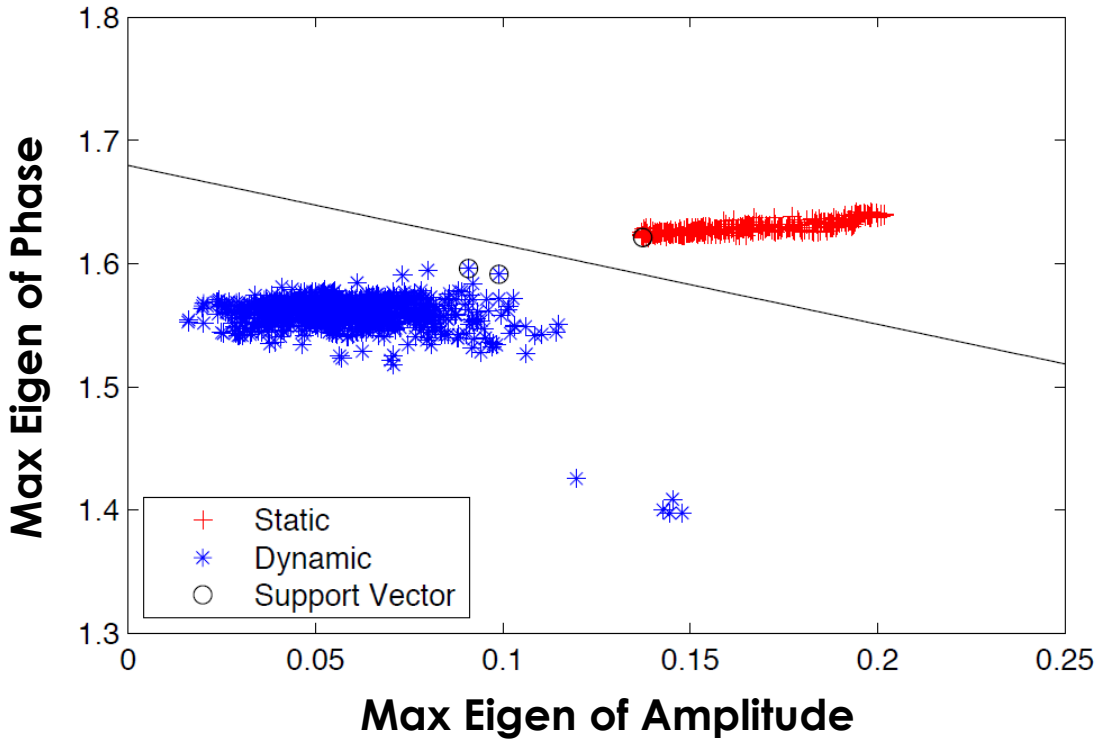
SVM Classification Algorithm

- Small training set : about 5 min
- Real time
- Effective and efficient

To get better inference result

Extending Feature set

- 2nd Max Eigen of Amplitude
- 2nd Max Eigen of Phase



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Experiment Setup : COTS Devices

Rx: Mini PC equipped with Intel 5300 NIC

Tx: 802.11n AP

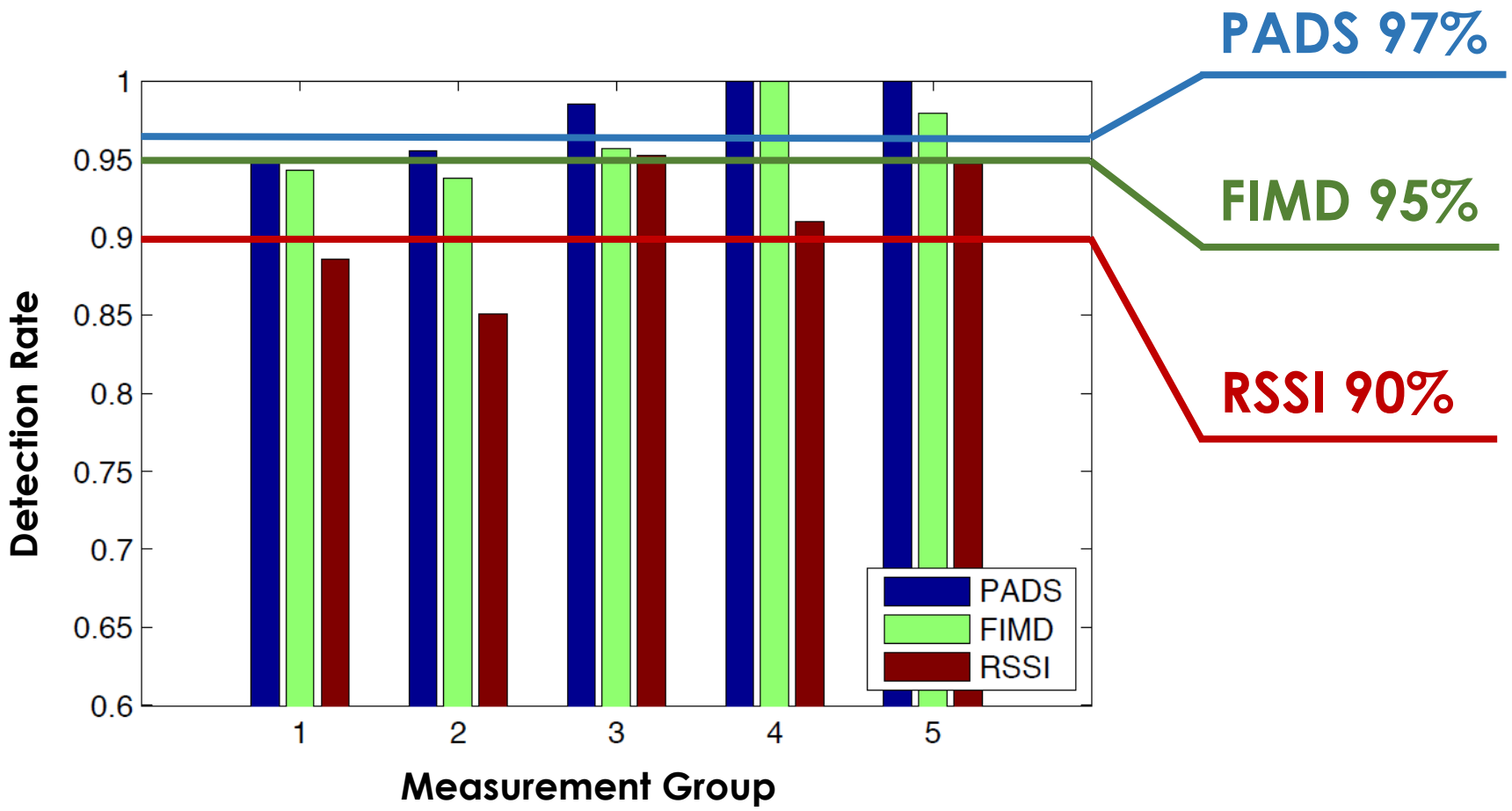
Parameter settings

- Collect data from different scenarios.
- Testers walk with different speed.
- Data of static environment is collected for training and testing.
- AP is placed at various height from 1.2m to 2m
- COTS pairs are placed at various distances from 2m to 7m
- Both LOS and NLOS conditions are involved.

Scenario of corridor

Demo

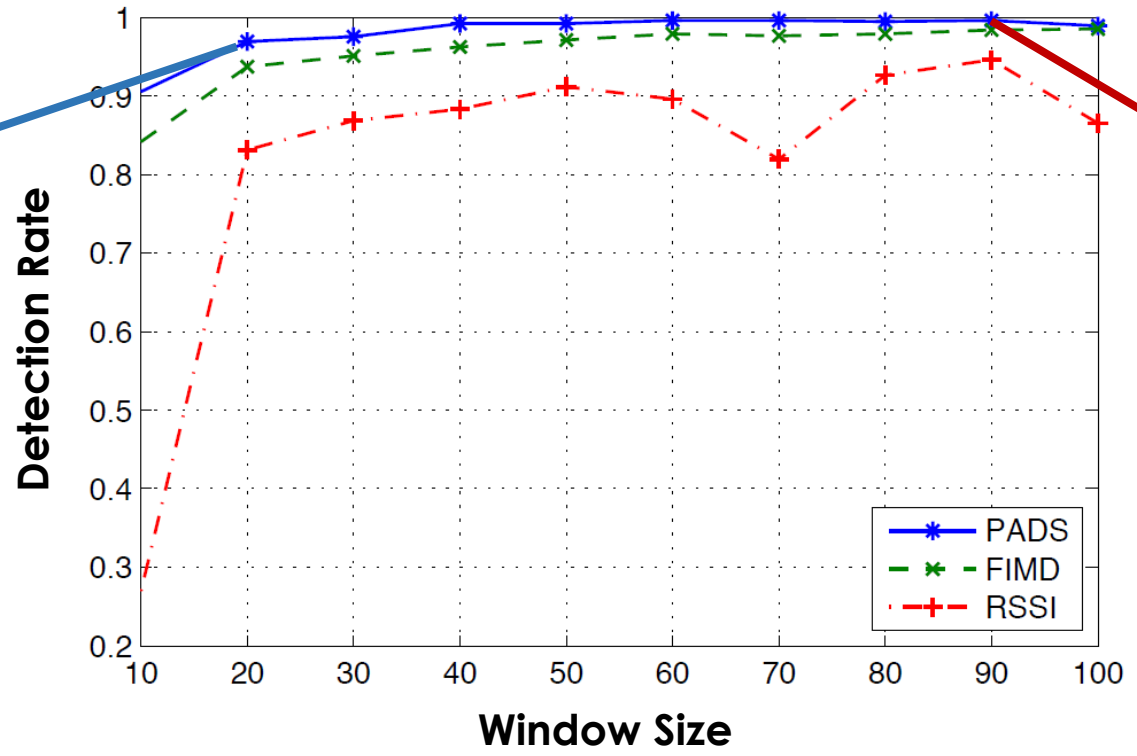
Overall Performance



Impacts of sliding window size

small window size

- Increase



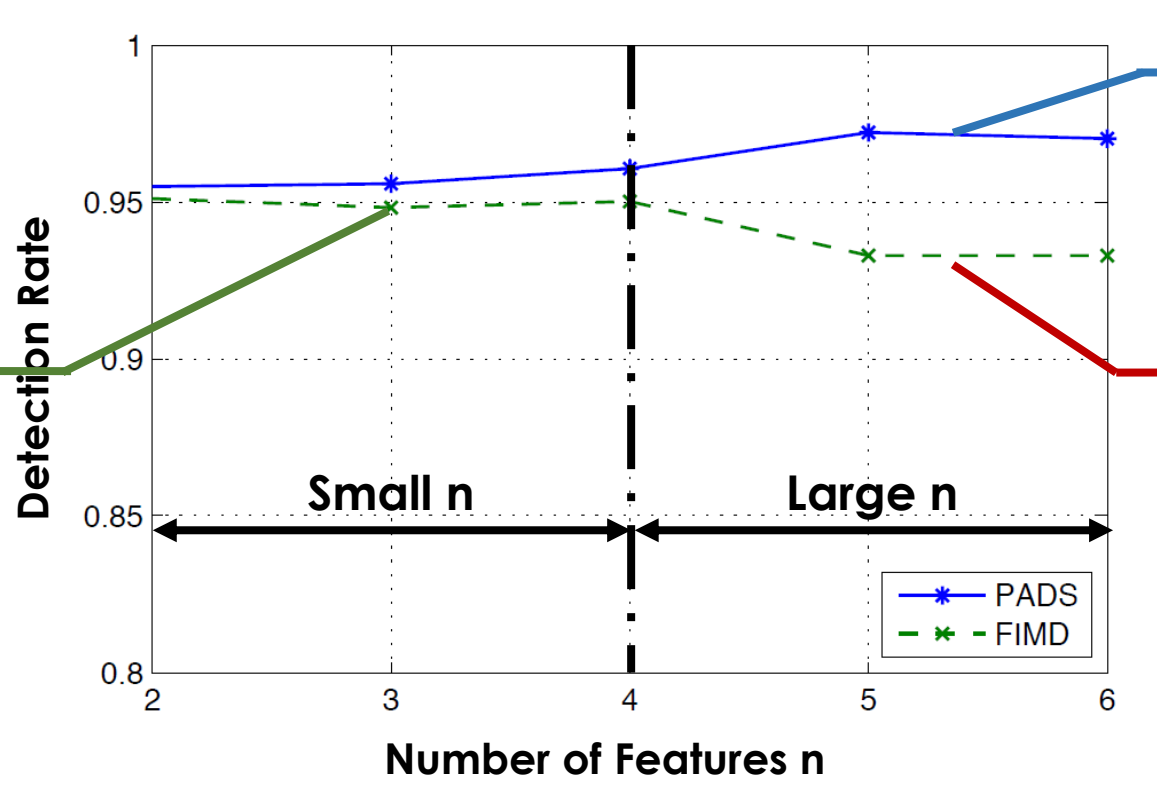
large window size

- Converge
- Decrease a bit

Impacts of number of features

BOTH

- Stable



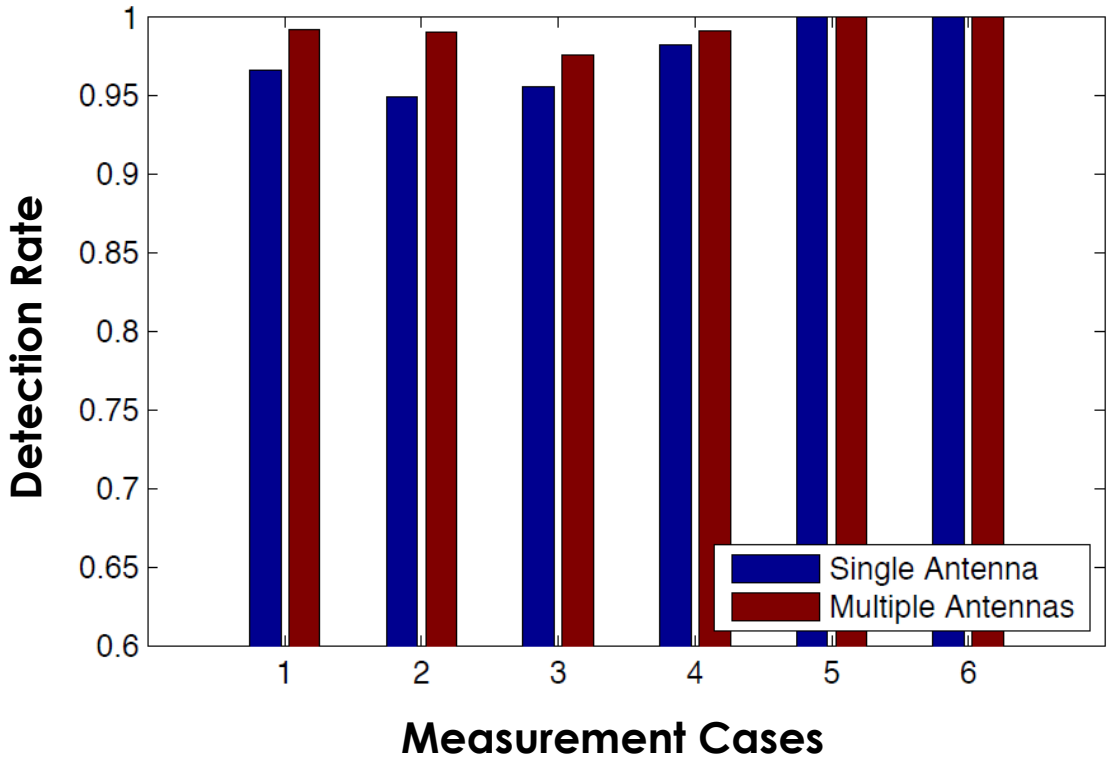
PADS

- Increases

FIMD

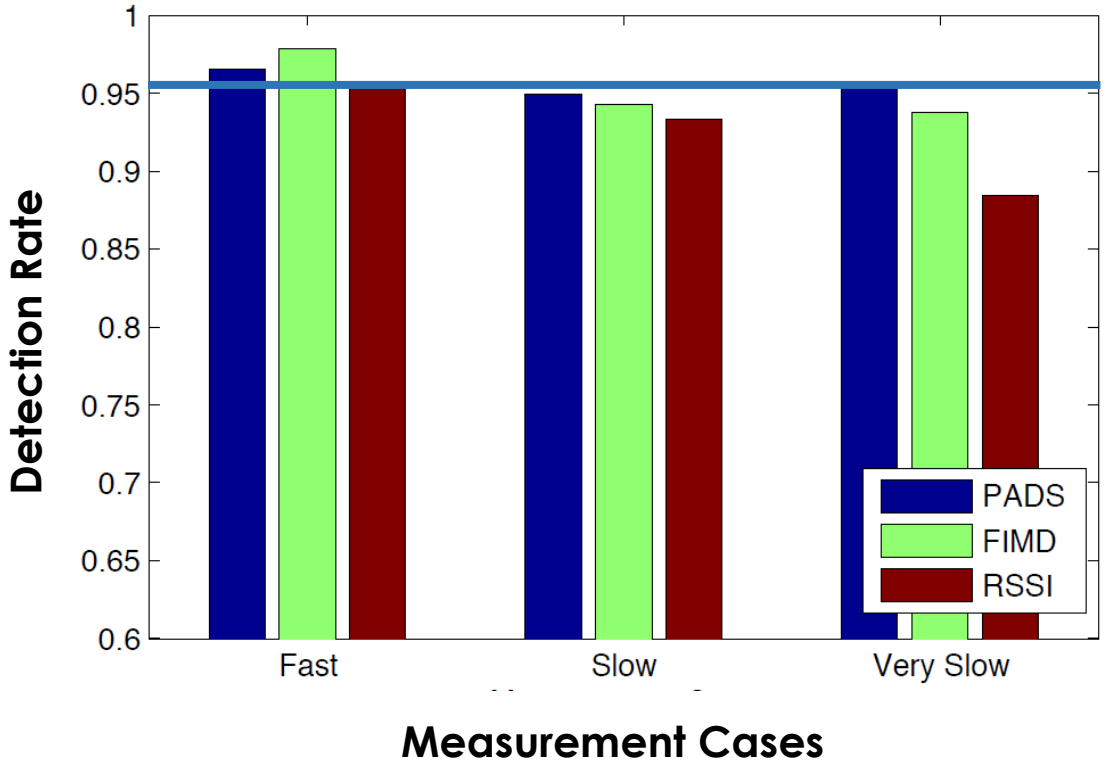
- Drops

Impacts of Number of Antennas



Probability of using "bad" antenna is reduced.

Impacts of Dynamic Speed



The performance of PADS remains almost unchanged.

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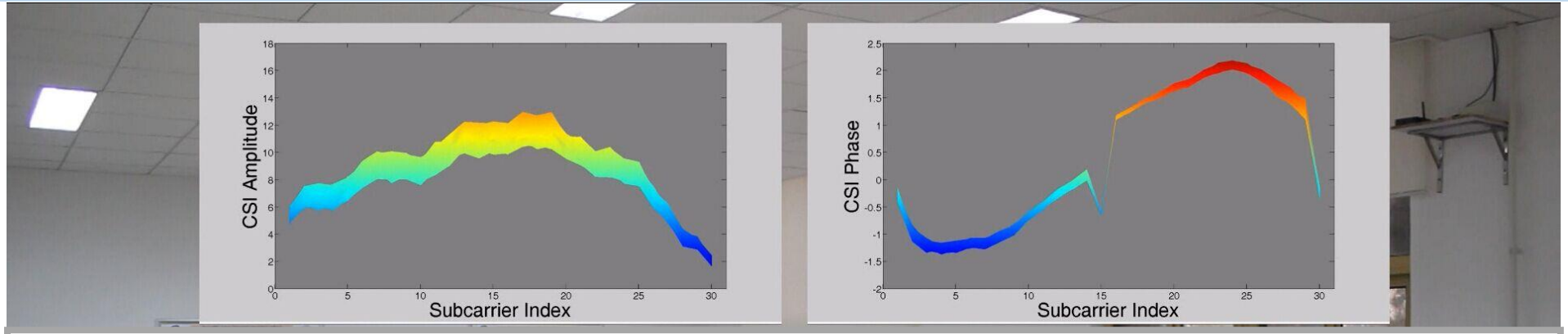
Static Human Detection



Accuracy is 95% for static human.

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Conclusion

- We propose a design for passive human detection leveraging full information of CSI.
- We propose a novel unified feature using the eigenvalue of covariance matrix of normalized CSI.
- We explore space diversity provided by multi-antennas.
- Experiment results demonstrate that PADS can achieve high performance that outperforms traditional RSS-based and CSI-based systems.

Looking forward to your comments!

Thanks
&
Questions?

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