# Non-Intrusive Load Monitoring: A Power Consumption Based Relaxation

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# Introduction

- NILM challenges
  - Training
  - Modeling large number of devices
- Power Consumption Clustered NILM (PCC-NILM)
  - Group devices by power consumption
  - Report on energy consumed by each class of devices
    - Instead of full disaggregation problem







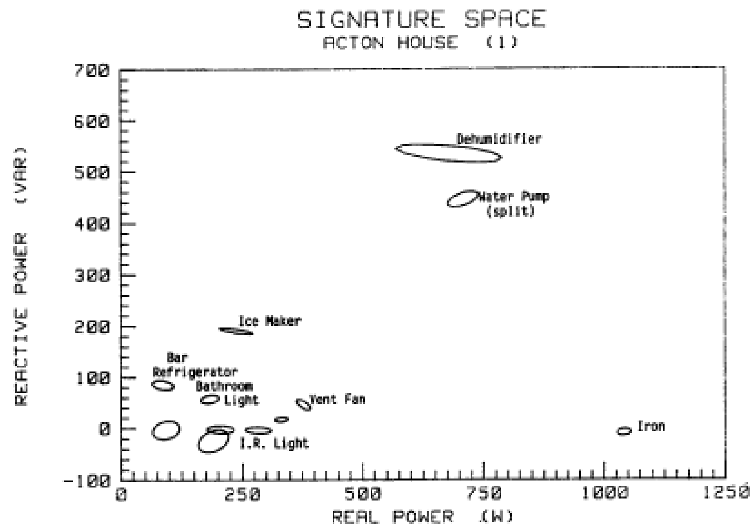







# NILM Background

- George Hart, MIT
  - First posed NILM problem in early-mid 1980’s
  - PQ-plane for clustering devices
  - Complete system for tracking energy
  - Finite State Machines (FSM) for tracking device operation
    - Could only handle on/off devices
    - Proposed methods for learning multi-state FSMs
  - Event-based framework



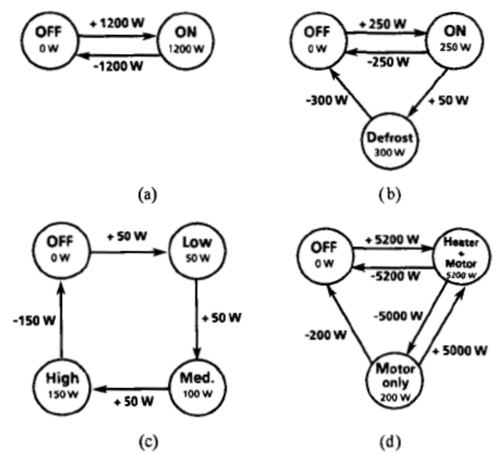




**Fig. 4.** Finite-state appliance models: (a) generic 1200 W two-state appliance, e.g., toaster; (b) refrigerator with defrost state; (c) “three-Way” lamp; (d) clothes dryer.

G. Hart, “Nonintrusive appliance load monitoring," *Proceedings of the IEEE*, vol. 80, no. 12, pp. 1870–1891, 1992.

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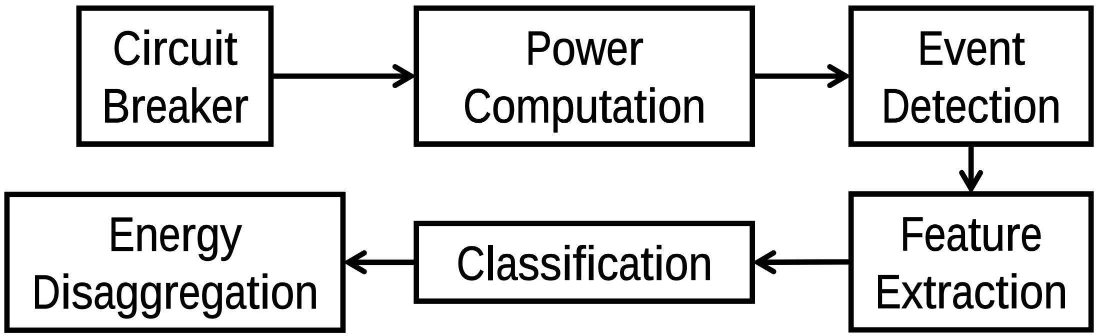
# NILM Background

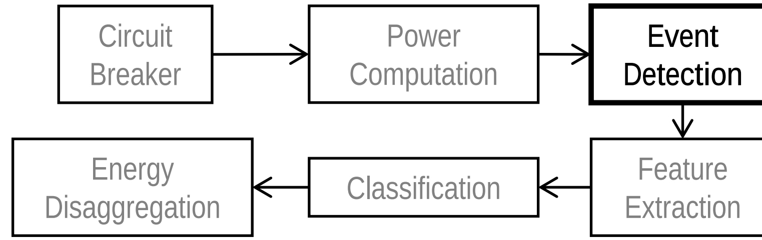
- Traditional event-based NILM framework



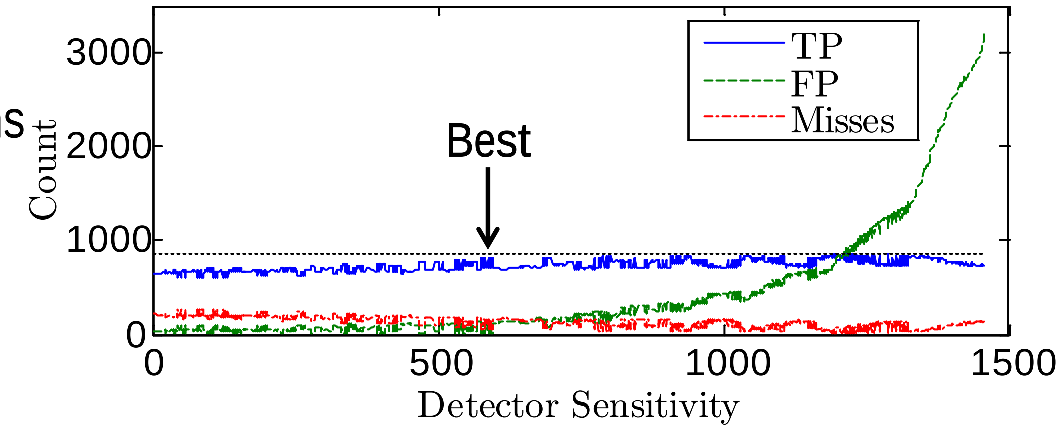

- Research after Hart, mid-1990's until 2011
  - Focus on event detection, feature extraction, and classification
  - Almost no work on **energy** disaggregation
    - Zeifman NILM review paper in 2011[1]
      - Apart from Hart, only one author mentioned energy metrics
    - Berges Ph.D. Thesis[2] proposes Energy Identification Ratio (EIR) metric

[1] M. Zeifman and K. Roth, "Nonintrusive appliance load monitoring: Review and outlook," *IEEE Transactions on Consumer Electronics*, vol. 57, no. 1, pp. 76–84, Feb. 2011.
[2] M. Berges, "A framework for enabling energy-aware facilities through minimally-intrusive approaches," Ph.D. Thesis, Carnegie Mellon University, 2010.

# Event Detection Parameter Sweep




- Log-Likelihood Ratio Event Detector
  - 3 degrees of freedom
  - 1,456 parameter combinations
  - Fast algorithm
- BLUED Dataset
  - Power sampled at 1 Hz
    - 867 phase A events
    - 1,588 phase B events
- Detector Sensitivity
  - Ordering based on total number of events detected
- Best Detector
  - Based on $\frac{TP}{E}$ vs. $\frac{FP}{E}$ [1]




| Sensitivity | Events | TP | FP | Misses |
|---|---|---|---|---|
| Least | 681 | 646 | 35 | 221 |
| Most | 3972 | 736 | 3236 | 131 |
| Most TP | 1762 | 856 | 906 | 11 |
| Least FP | 750 | 743 | 7 | 124 |
| Best | 829 | 814 | 15 | 53 |

How to track energy with so many misses and false positives?

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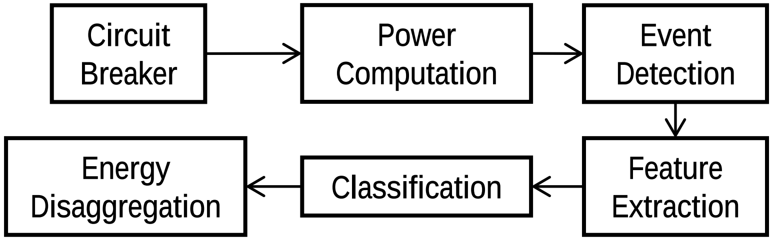
[1] K. Anderson et al., "Event detection for nonintrusive load monitoring," in Proceedings of the 38th Annual Conference on IEEE Industrial Electronics Society (IECON).Montreal, Canada: IEEE, Nov. 2012.

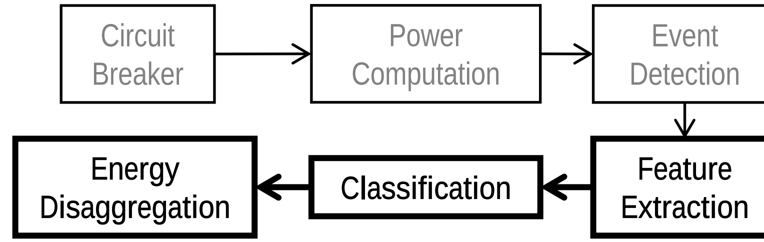
# Event-Based NILM




- Difficulties with traditional event-based approach
  - Training
  - Lack of accepted performance metrics
    - Event detection, classification, energy consumption, etc.
  - Lack of energy disaggregation
    - Work on event detection and classification but little energy tracking
    - Cascading effect of errors from event detection and classification stages

Step back and reconsider the NILM problem…

# Reconsidering the Disaggregation Problem




- Additive energy disaggregation model

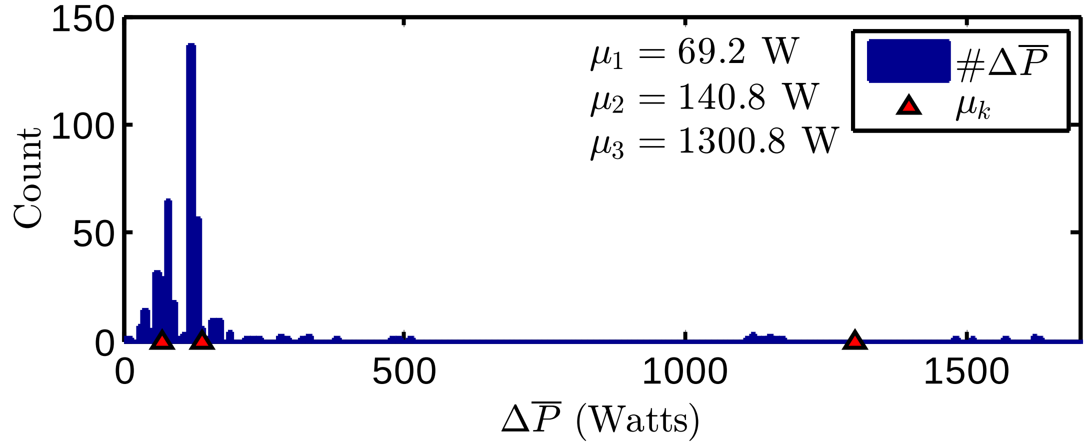
$$E = \sum_{k=1}^{K} E_k$$

  - Total energy consumed is sum of energy consumed by $K$ devices
- What if we allow K to represent something else?
  - Number of rooms
  - Activities
  - People

Need a data-driven solution…

# Power Consumption Clustering

- Histogram of ‘On’ events from phase A of the BLUED dataset



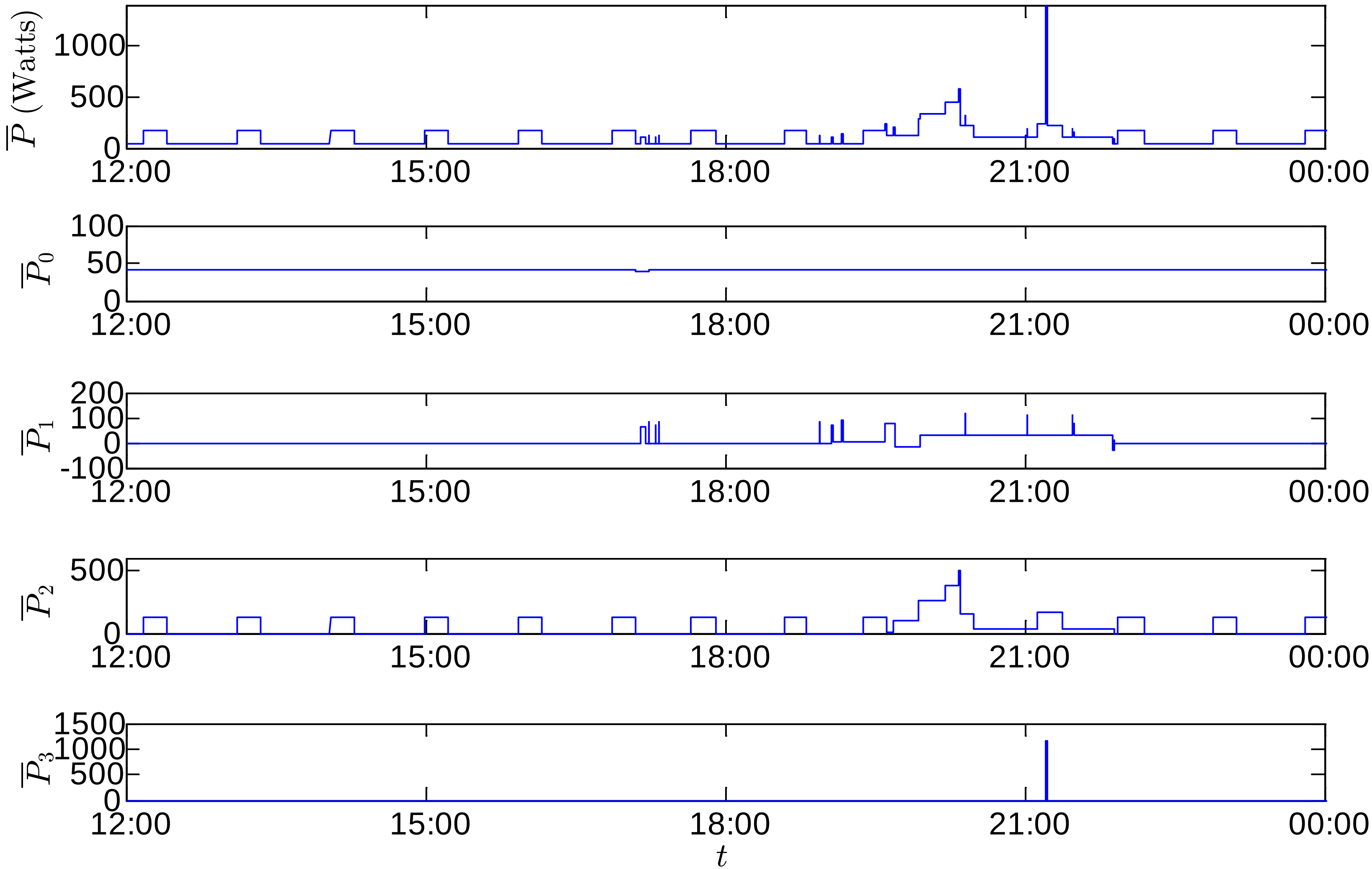

  - Cluster centroids $\mu_k$
- Track energy consumed by each class
  - Devices may be inferred from power ranges
  - Can track energy consumed by each class

$$\boxed{E = E_0 + \sum_{k=1}^{K} E_k}$$

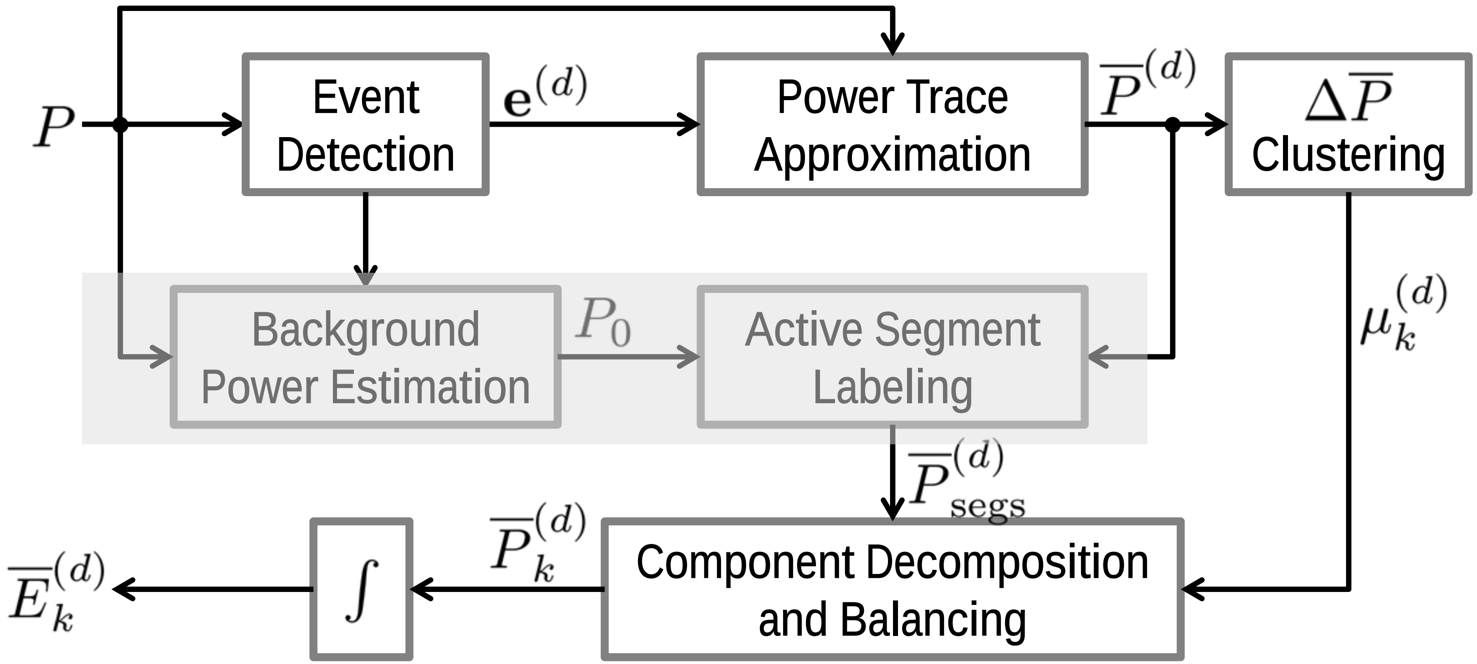
| $k$ | $\mu_k$ | Power Consumption Range |
|---|---|---|
| 0 | - | Background |
| 1 | 69.2 W | 0–105 W |
| 2 | 140.8 W | 105–720 W |
| 3 | 1300.8 W | 720+ W |

# PCC-NILM Solution Example

$$\overline{P} = \overline{P}_0 + \sum_{k=1}^{K} \overline{P}_k$$

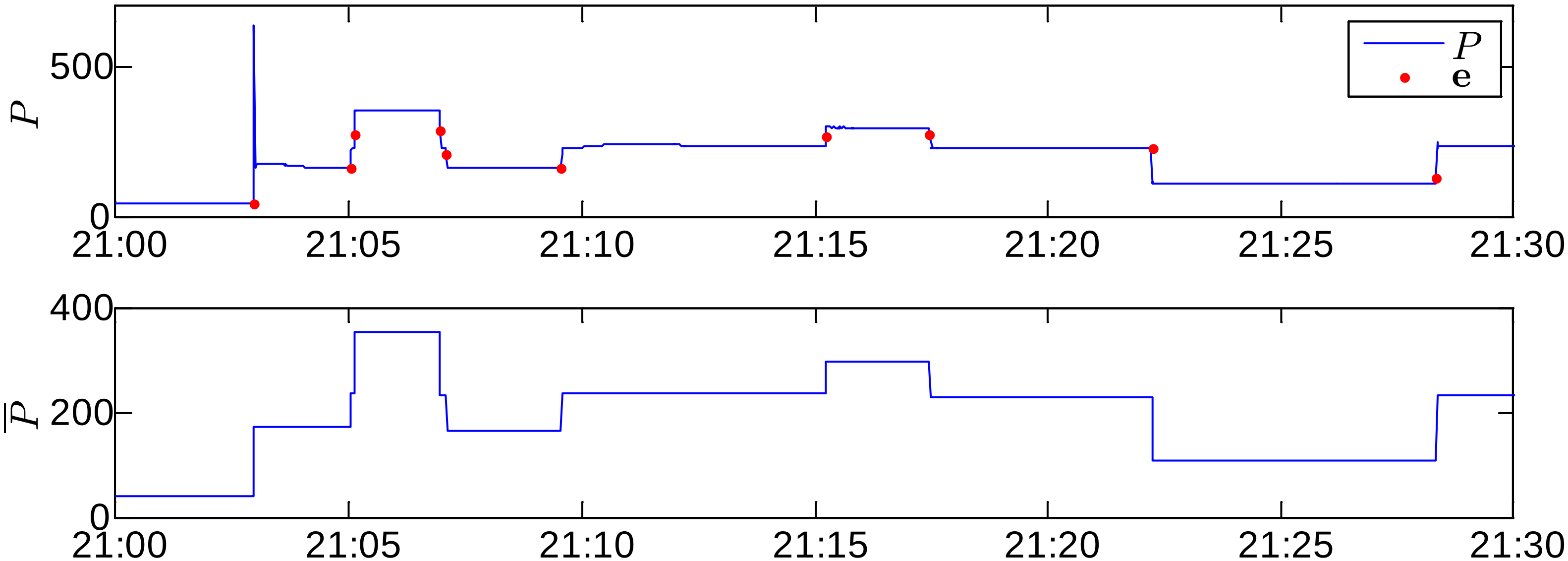


# Approximate Power Trace Decomposition Algorithm (APTDA)



# Power Trace Approximation

- Energy-preserving piecewise constant approximation, $\overline{P}$
  - Computed from original power trace, $P$, and set of edges, $\mathbf{e}$




  - $\overline{P}$ is average of each segment of $P$ $t$
    - Segments are disjoint

$$E_P = \int P\,\mathrm{d}t = \int \overline{P}\,\mathrm{d}t = E_{\overline{P}}$$

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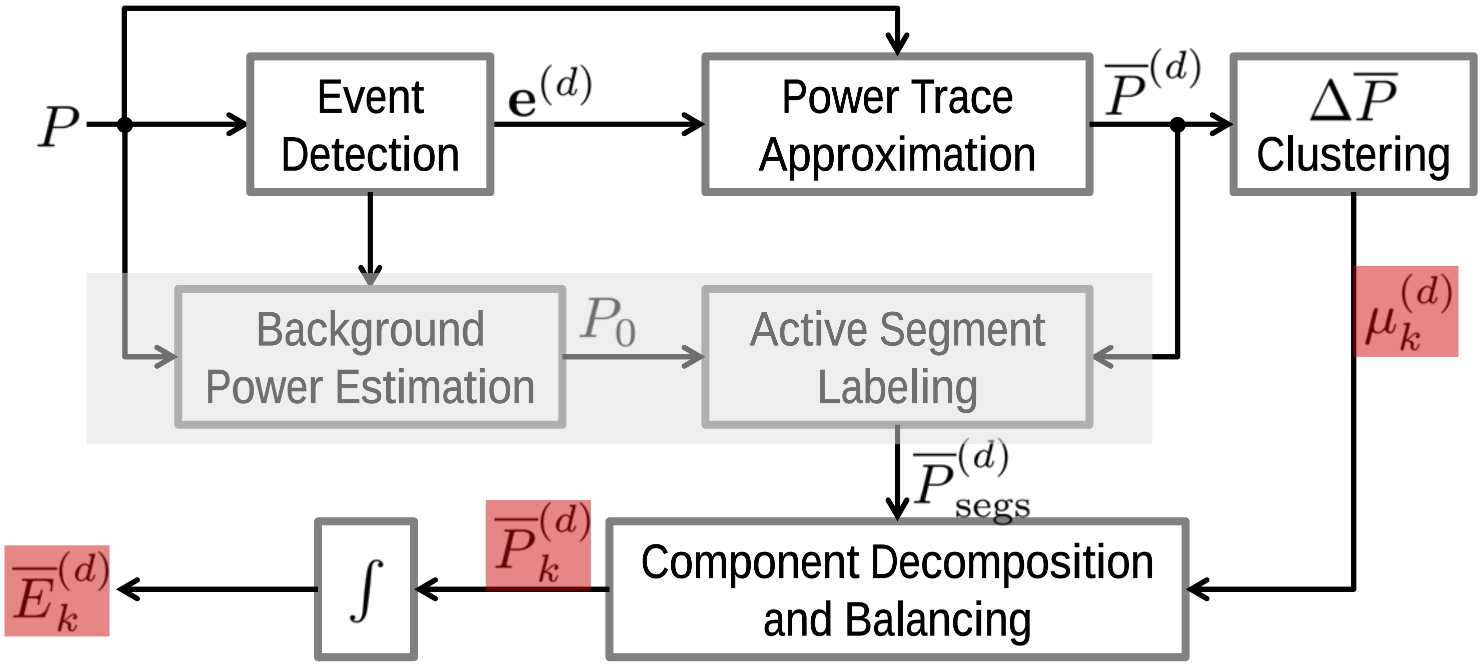
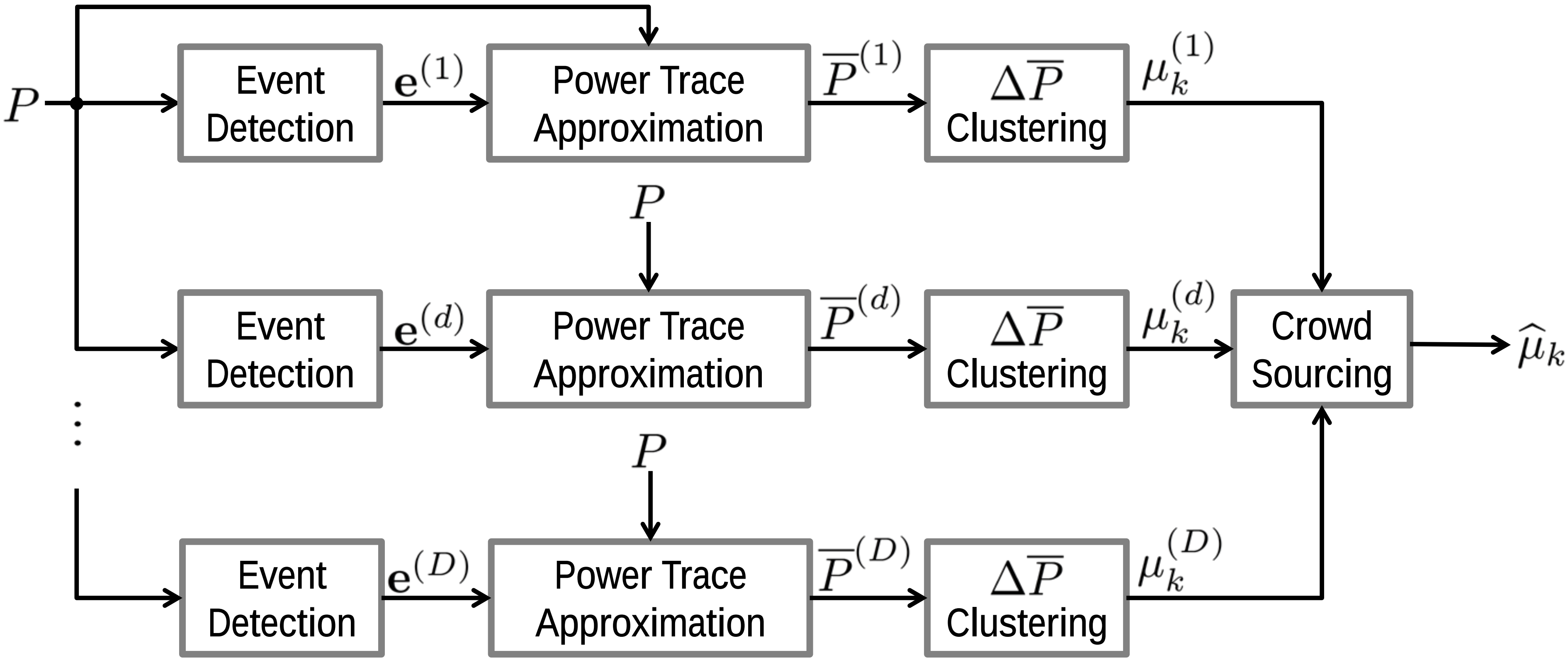



- Crowdsourcing event detectors
  - Compare results across wide range of detectors
  - Choose most stable output

# Crowdsourcing Power Ranges



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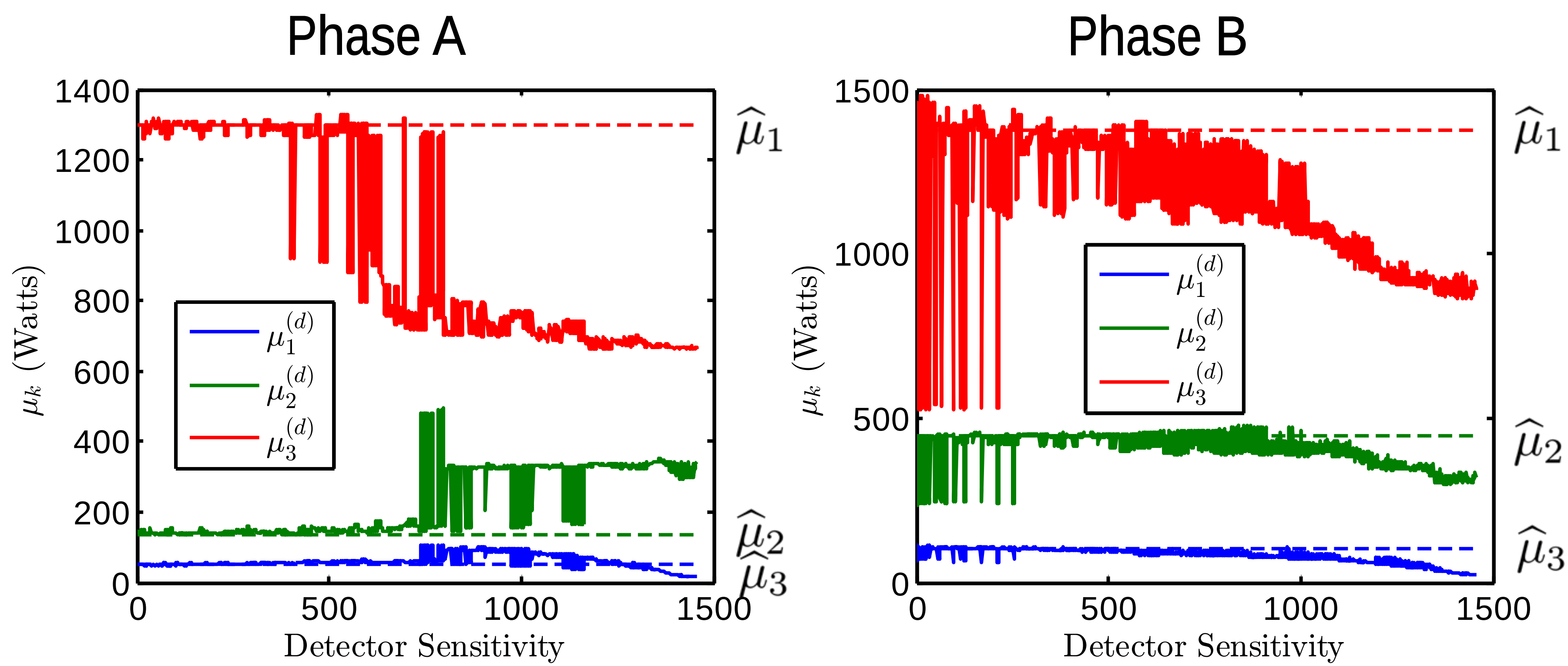
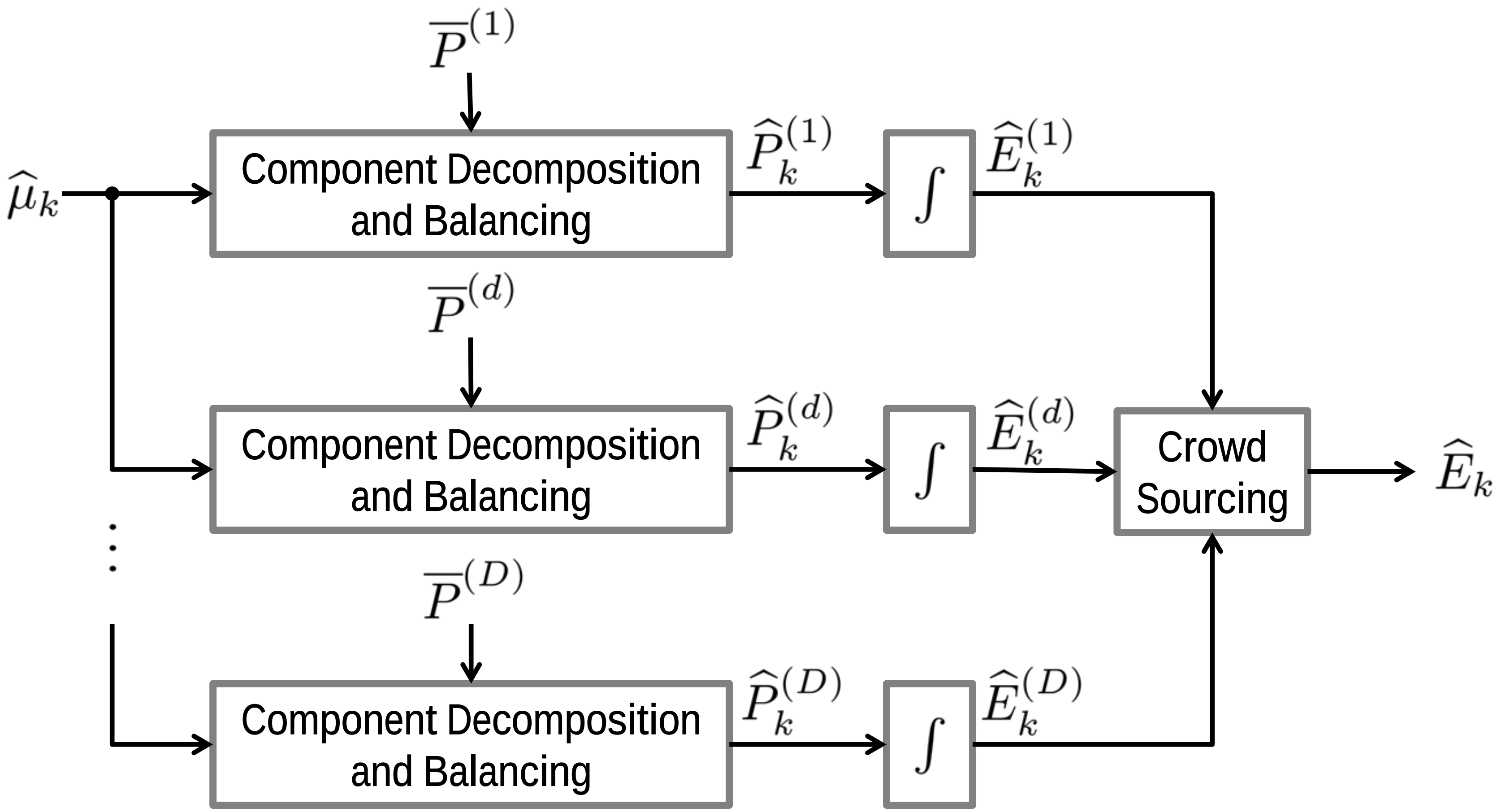
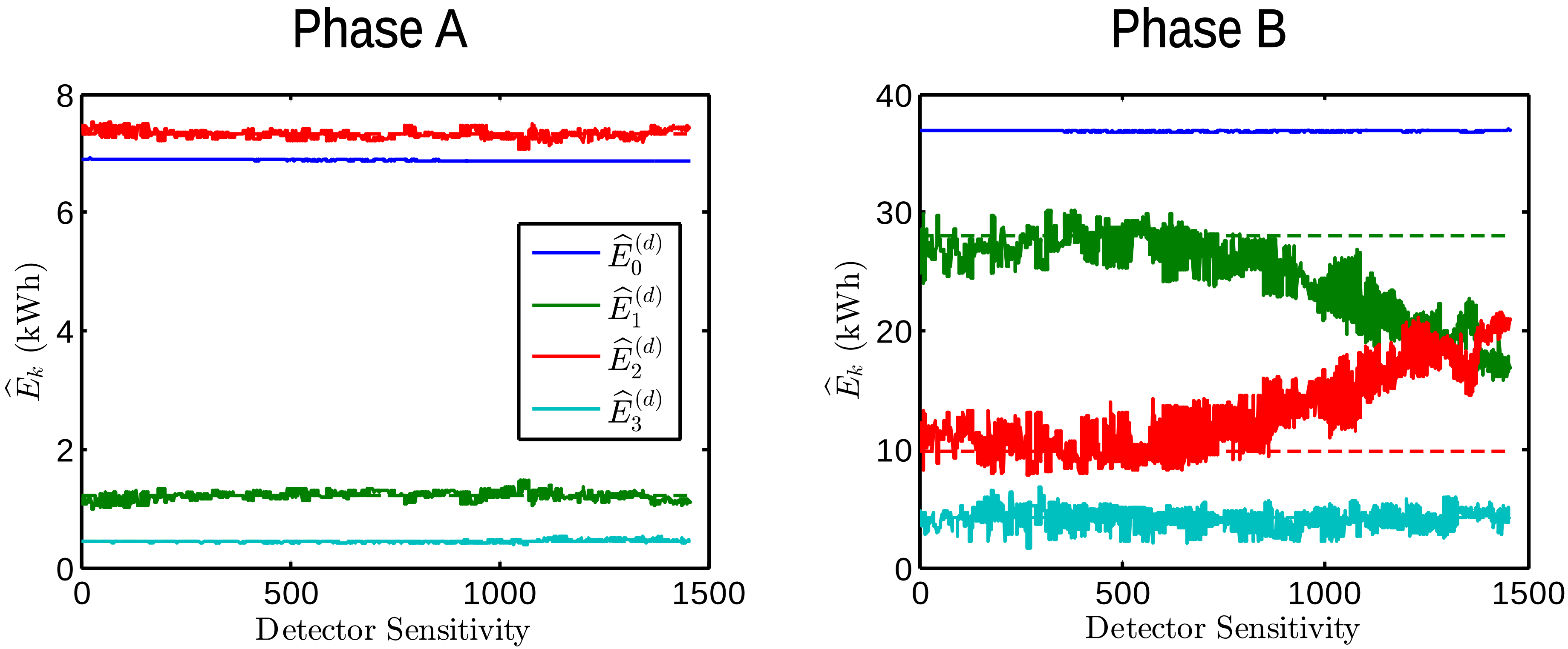



- 1,456 different power ranges
- Choose most frequent mode for each range for $\widehat{\mu}_k$

# Crowdsourcing Energy Estimates



# Crowdsourcing Energy Estimates




- 1,456 different energy estimates
- Crowdsourcing algorithm to find most stable region across all power consumption classes
- Energy estimate robust to event detection errors

# Power Consumption Clustered-NILM

- PCC-NILM
  - Relaxation of full disaggregation problem
- Disaggregate according to power consumption ranges
  - Power ranges inferred from data
- Completely Unsupervised
- Approximate $P$ and decompose into relevant components

$$P \approx \overline{P} = \overline{P}_0 + \sum_{k=1}^{K} \overline{P}_k$$

Background and Active Components

- Energy obtained by integrating components

$$\overline{E}_k = \int \overline{P}_k \, \mathrm{d}t$$

# Future Work

- Incorporate reactive power (Q)
  - 2-D APTDA
- Methods for selecting K
  - Number of classes used for clustering
- Single device classes
  - Higher consumption devices have good separation
- Sampling frequency analysis
  - Used 1 Hz power data, can we do less?
- Human computer interaction
  - Study how to report information to use
- Changing power range distributions
  - Power ranges vary with consumption changes

# Questions?