Fraunhofer Center for Sustainable Energy Systems

Non-Intrusive Appliance Load Monitoring (NIALM): Review and Outlook*

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International Conference on Consumer Electronics

Las Vegas

10 January 2011

*Supported in part by US DOE through a subcontract with Lawrence Berkley National Laboratory (LBNL). We are grateful to Rich Brown of LBNL for helpful discussions.

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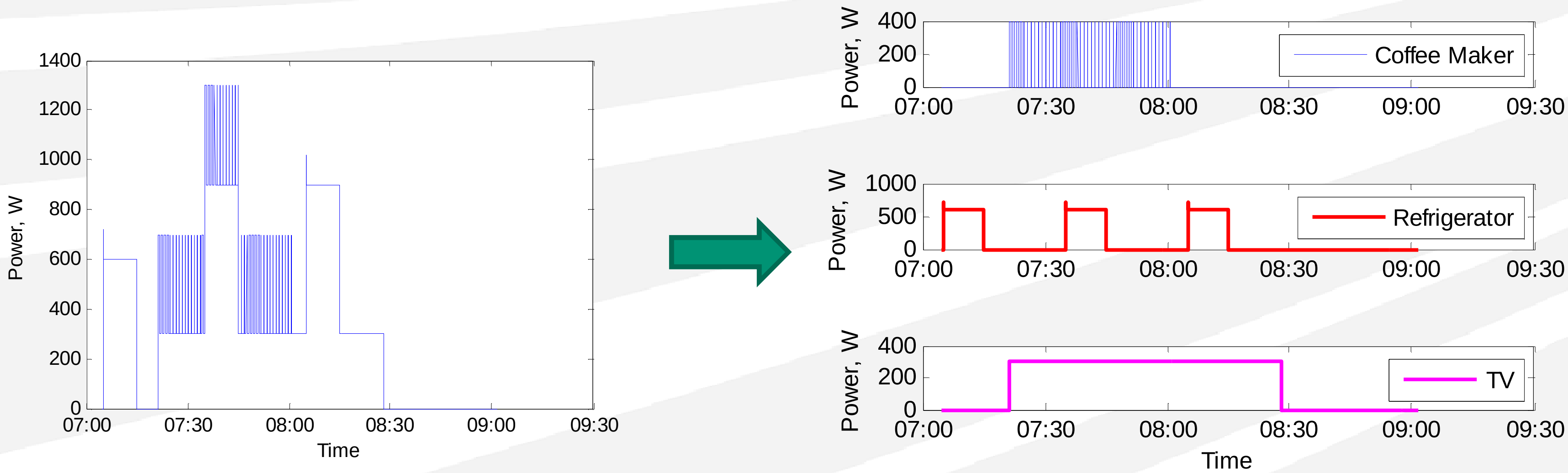
Fraunhofer: A Leading Force in Applied R&D

- **Fraunhofer Gesellschaft**: Europe's largest contract research organization – 17,000 employees
- Annual research budget: US$2.2B
- 59 institutes provide contract R&D and certification services for clients
- **Research Themes:** health, security, communication, mobility, energy, environment

- **Fraunhofer USA**: 7 Centers, >200 employees, Annual research budget >$50M
- Fraunhofer CSE is located in Cambridge, MA
- Three focus areas:
  - Building Energy Efficiency
  - PV Modules
  - Smart Grid

What Is NIALM?

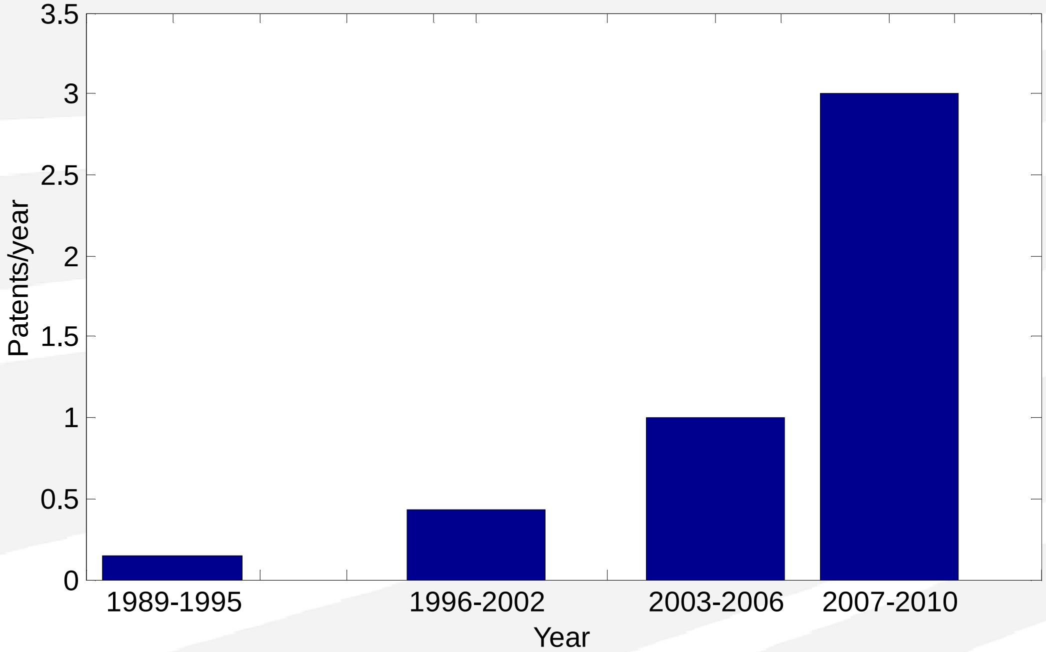
- Non-Intrusive Appliance Load Monitoring
  - A.k.a. Non-Intrusive Load Monitoring



- Main breaker/circuit level
- Data acquisition (hardware) and disaggregation algorithms (software)

NIALM: Interest

- Number of US granted patents – exponential growth

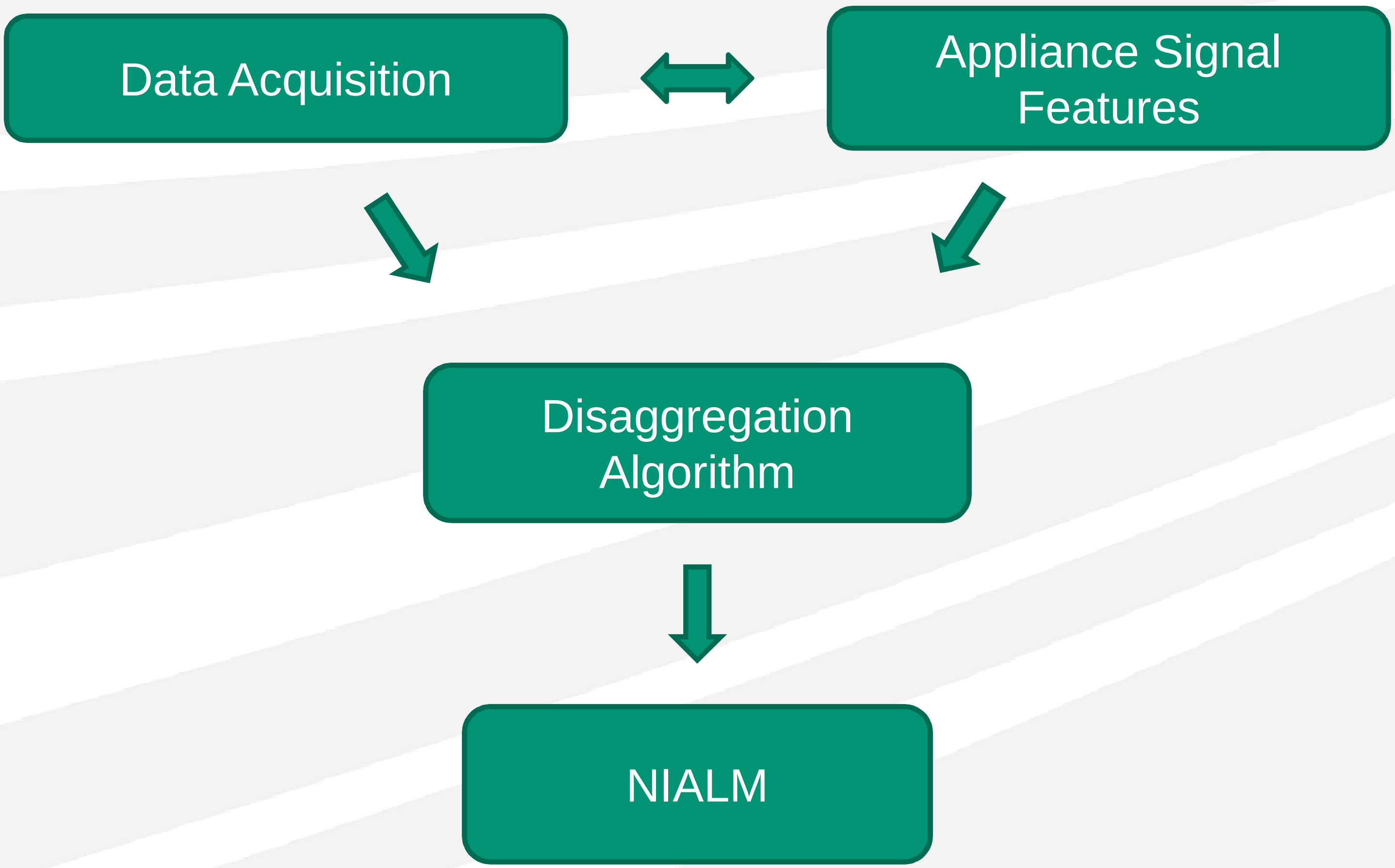


- Both large (Belkin, GE, IBM, Intel,) and small (4home, Emme, Enetics, Navetas) companies

NIALM: Motivation

- Energy saving potential
  - Residential buildings consume ~ 20% of primary energy in USA
  - Electricity constitutes ~ 70% of residential energy consumption
  - Feedback on energy usage can result in 5-15% saving
- Smart Grid – unique business opportunity
  - ~ 80 M smart meters in USA are projected by 2013
  - Hardware can be used by NIALM
  - Non-intrusive "manual" alternative to home automation
- Time-of-use electricity pricing
  - Transition from fixed to time-dependent pricing in Europe and North America
  - More people are concerned with energy monitoring and management

How Does NIALM Work?



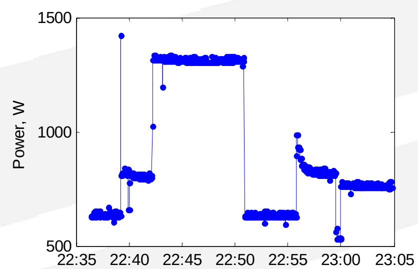
Data for NIALM: Sampling Rate

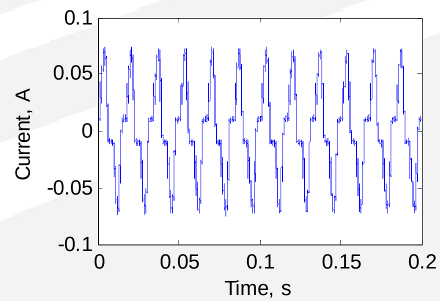
Typical daily number of switching events in a household: up to ~ 10^3-10^4 [Baranski, 2004]

0.1 Hz – minimum sampling rate

Inexpensive hardware: 1 Hz

More expensive hardware: > 5 kHz





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NIALM: Types of Appliances

- ❑ Permanent

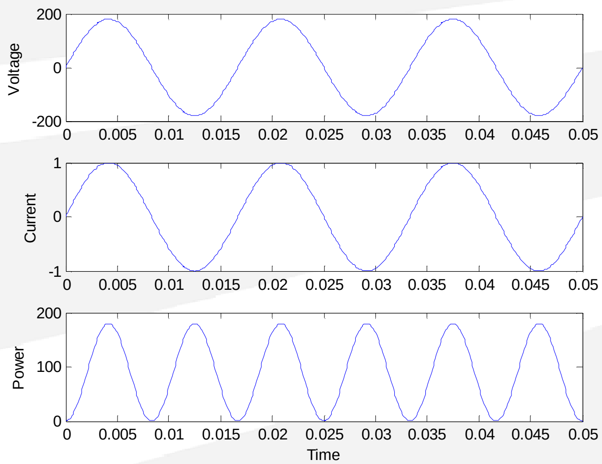
- ❑ On/off

- ❑ Multi State

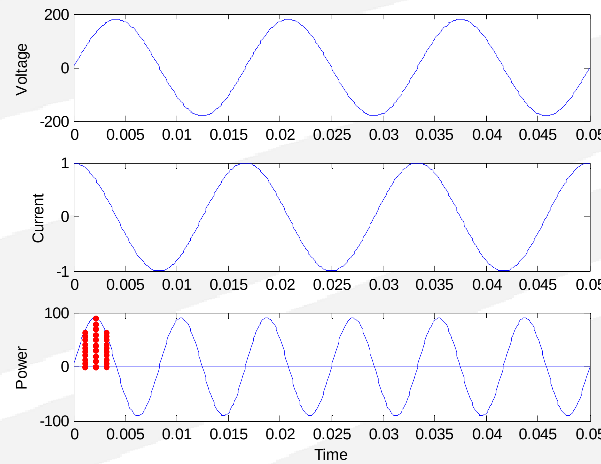
- ❑ Variable

I. Low Sampling Rate, Features: Power Change

Real Power



Reactive Power



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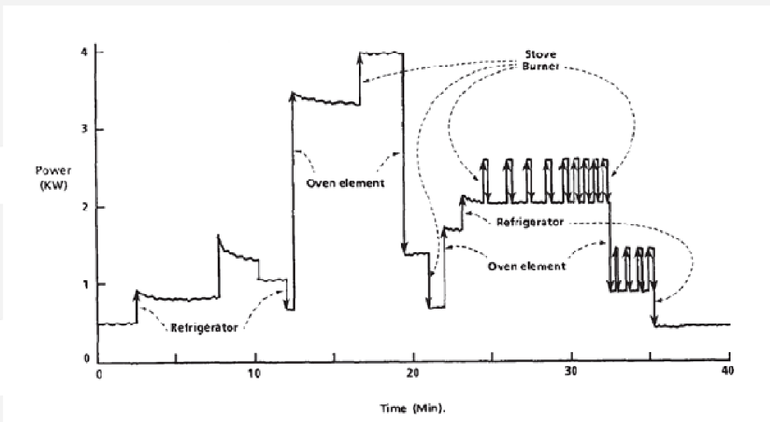
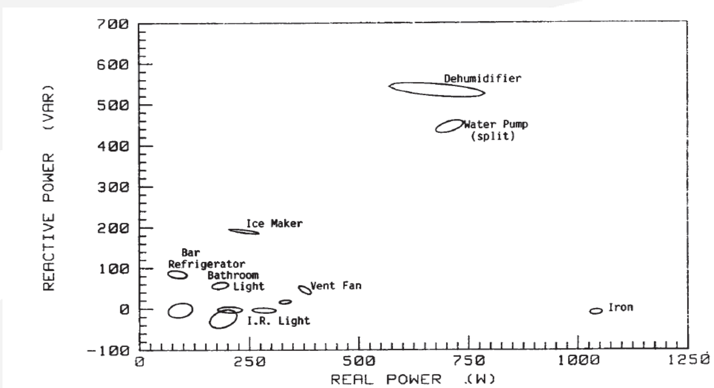
I. Power Change: Basic Method

Hart, 1992 (MIT method)





Accuracy: ~80%

On/off appliances

Multi State

Variable Load

Permanent Load

Same-Load Appliances

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I. Change of Real Power Only

Baranski and Voss, 2003-2004

- ❑ Hart's Method:
single **-ΔP** ←→ single **+ΔP**

- ❑ Baranski's Method:
multiple **-ΔP_i** ←→ multiple **+ΔP_i**

- ❑ Baranski's algorithm – error term minimization (optimization by genetic algorithm)

On/off appliances

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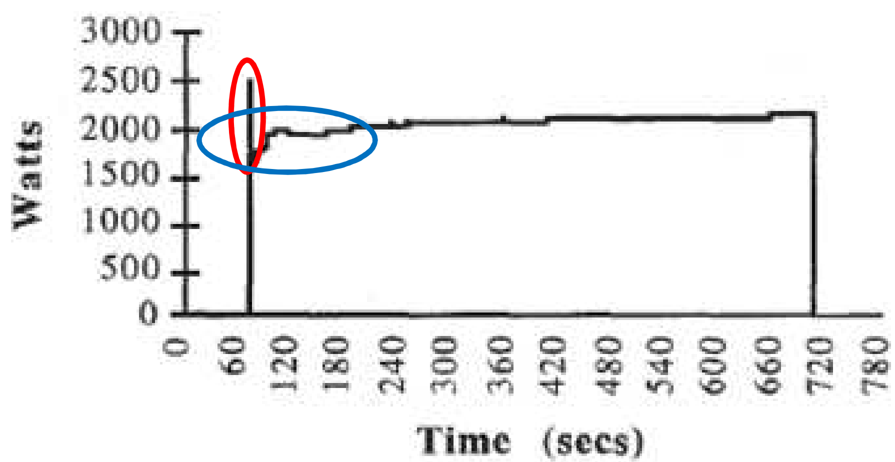
Same-Load Appliances

Accuracy: ~85%

I. Change of Power + Additional Features

Albicki and Cole, 1998

Edges and slopes as additional features



On/off appliances

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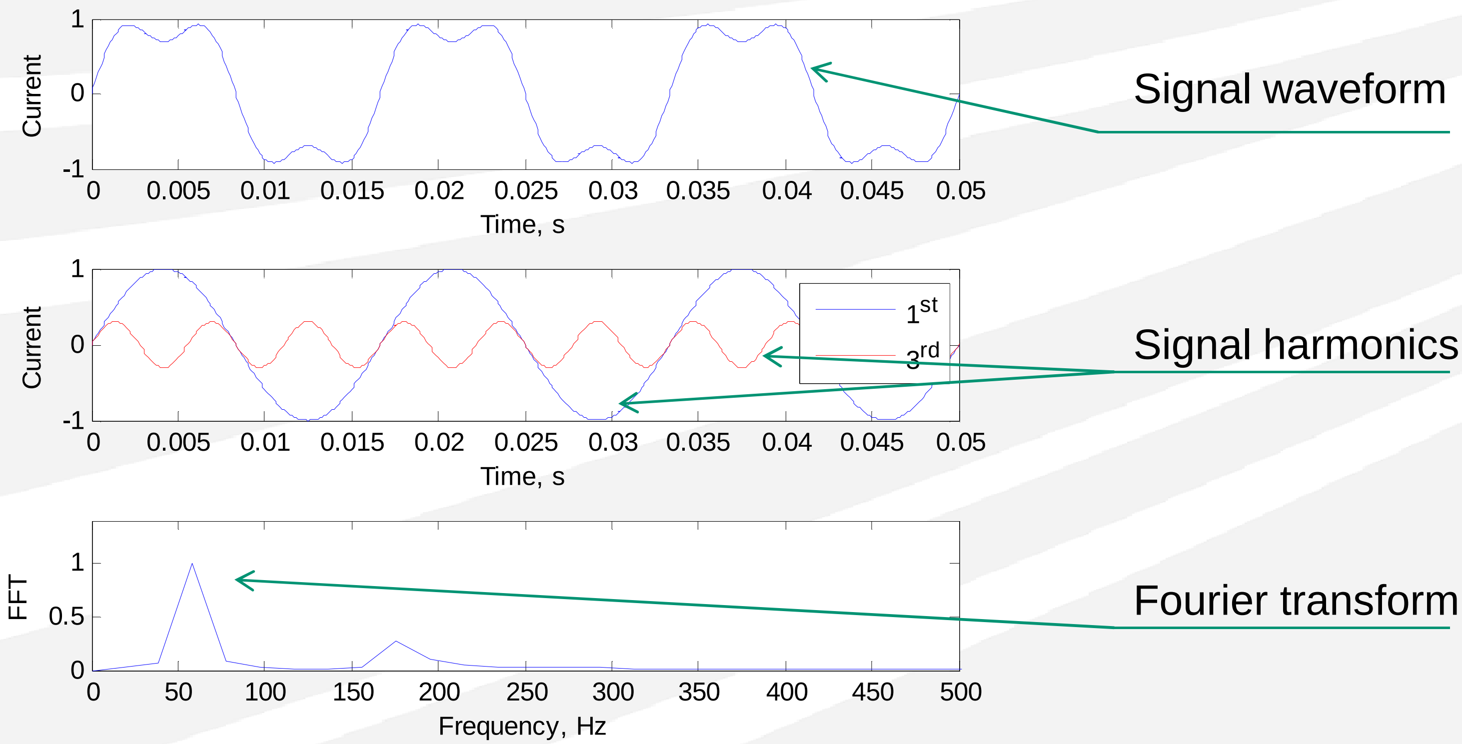
Same-Load Appliances

Accuracy: ~N/A

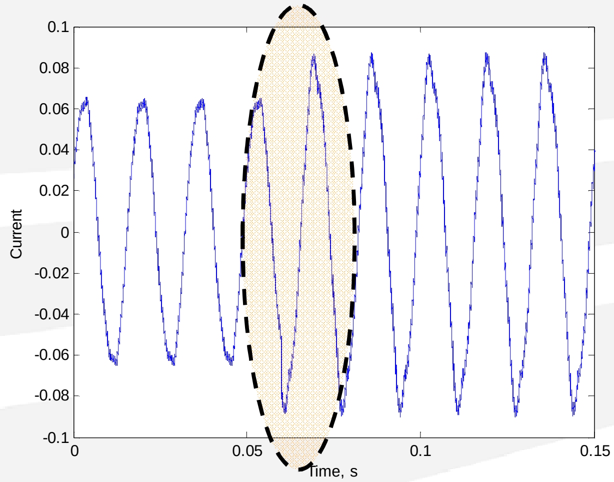
II. High Sampling Rate, Harmonics as Features

Basic Idea: Fourier Transform



II. Features: Harmonics for Transients (1/2)

Laughman *et al.*, 2003 (MIT)



1) Detect transients
2) Subtract pre-transient from post-transient
3) Take Fourier transform and compare with template
4) Set of harmonics = "power envelope"

Accuracy: ~N/A

- On/off appliances
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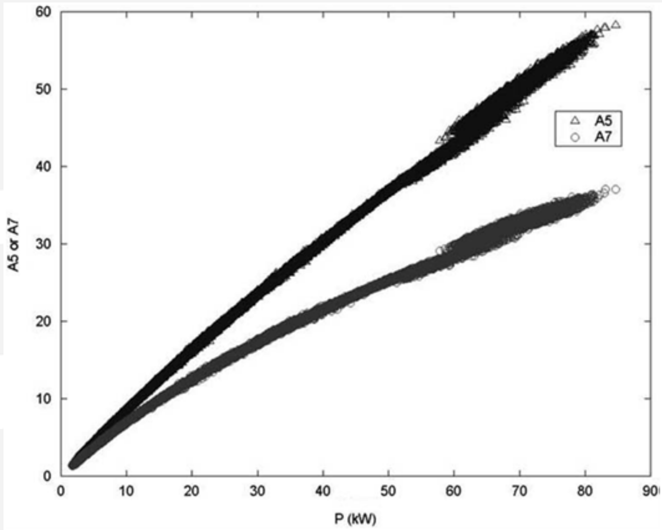
II. Features: Harmonics for Transients (2/2)

Lee *et al.*, 2005 (MIT)



1) Strong correlation between harmonics and power draw
2) Estimate harmonics then estimate load

Accuracy: ~N/A

On/off appliances

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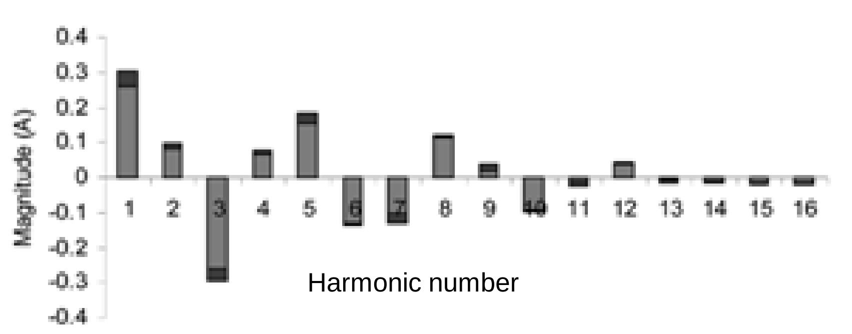
Same-Load Appliances

II. Features: Harmonics for Steady and Transients

Srinivasan *et al.*, 2006 (Singapore)

Basic idea: Set of harmonics for
all combinations of appliances

1) Obtain Fourier transform continuously
2) Compare with templates



On/off appliances

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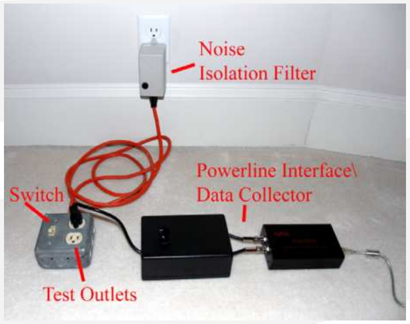
Same-Load Appliances

Accuracy: 77% (phone charger) – 99% (PC)

II. Features: Fourier Transform of Noise (1/2)

Patel *et al.*, 2007 (Ga. Tech.)

Basic idea: appliance connected to a socket induces noise (electromagnetic interference) in another socket



1) Measure signal at high rate (500 kHz)
2) Calculate Fourier transform continuously
3) Compare with templates

Accuracy: 85-90%

- On/off appliances
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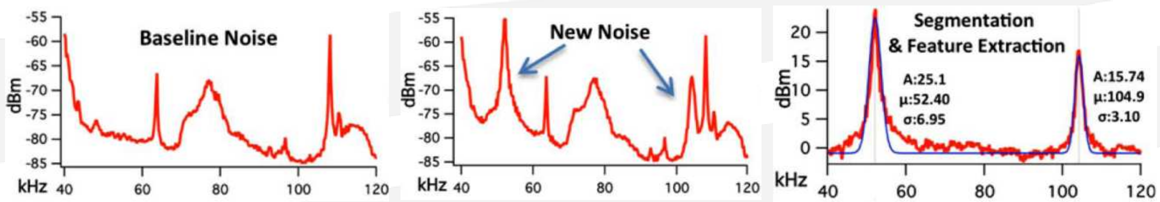
II. Features: Fourier Transform of Noise (2/2)

Patel *et al.*, 2010 (Now U. Wash.)

Basic idea: switch mode power supplies (SMPS) generate distinctive noises



- Distinctive features ("applicable across homes")
- Yet features variable enough to "differentiate between similar devices in a home"

Accuracy: up to 93.8%

On/off appliances

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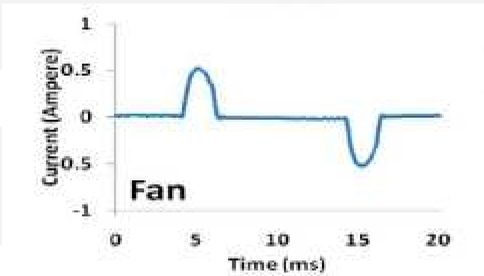
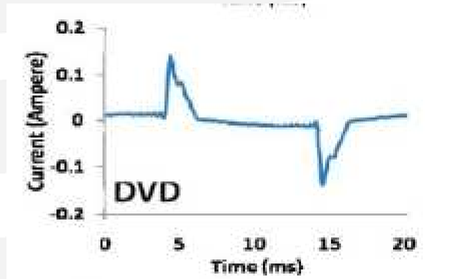
Same-Load Appliances

II. Features: Beyond Harmonics / Fourier Transform

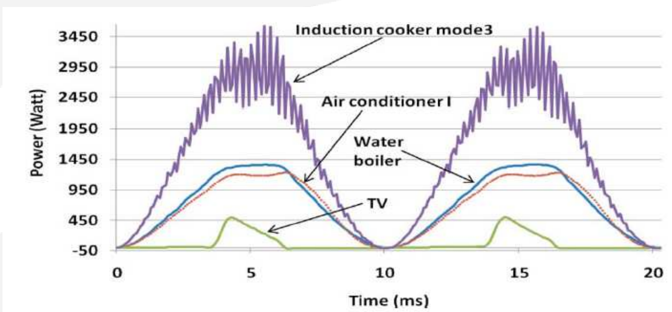
Liang *et al.*, 2010 (China Light & Power)

Waveform:





Power waveform



Accuracy: 92.7%

- On/off appliances
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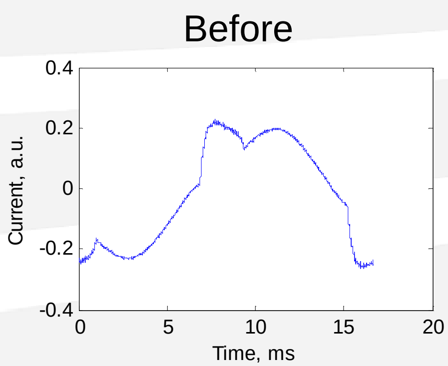
NIALM Algorithms (1/3)

Single-matching (pattern recognition)

Example: Waveform



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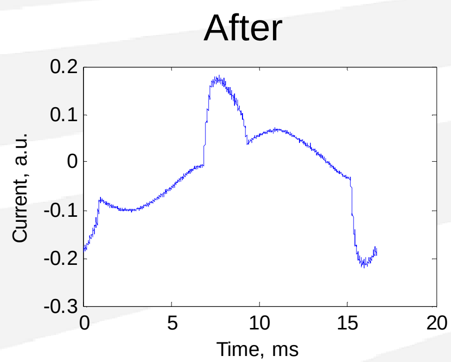

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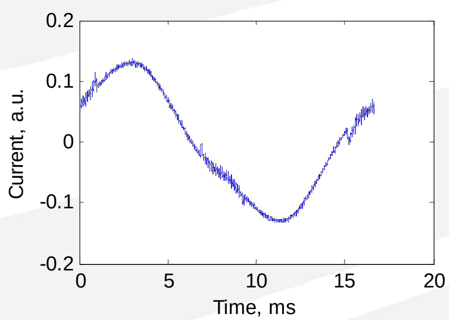

Pattern recognition methods used:

- N-nearest neighbor
- Bayes classifier
- Neural networks

On/off appliances

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Same-Load Appliances

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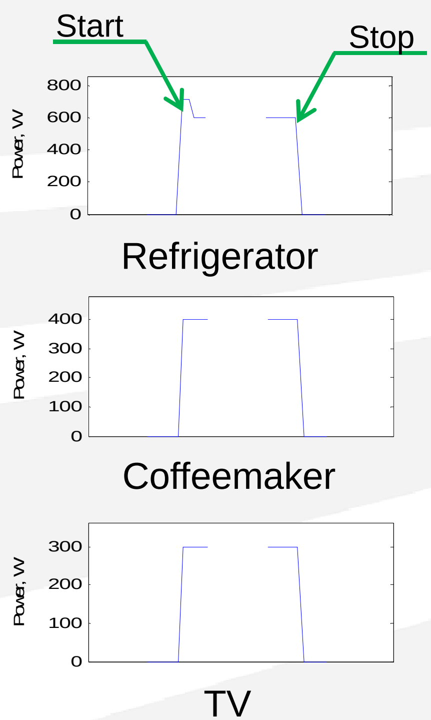
NIALM Algorithms (2/3)

Multiple-matching (Optimization)



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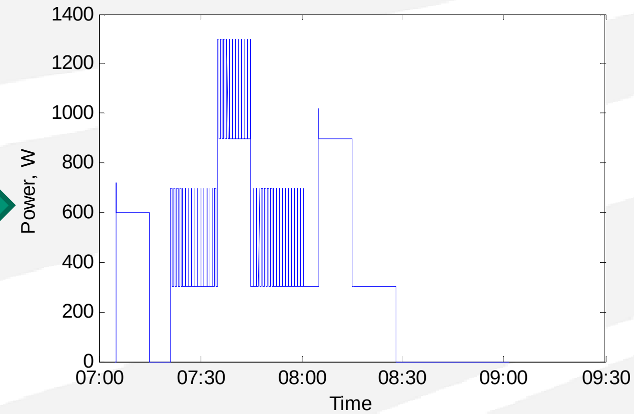

On/off appliances

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Optimization methods used:

- Least squares
- Integer programming
- Genetic algorithms

NIALM Algorithms (3/3)

True disaggregation

A.k.a. blind source separation

- Possible methods:
- Independent Component Analysis (ICA)
- Singular Value Decomposition
- Non-negative Matrix Factorization

- Yet has to be tried!

On/off appliances

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Promising Directions

- ➢ Combination of various “orthogonal” features
- ➢ Combination of “orthogonal” algorithms
  - Only one publication so far (Liang *et al.*, 2010)
- ❖ The curse of false positives
- ➢ Use of techniques known elsewhere
  - Information Fusion – Dempster-Shafer Evidence Theory

On/off appliances

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NIALM Accuracy Metrics

- Only one paper discusses: Liang *et al.*, 2010
- Can be appliance-related or overall

Example:

•Devices were turned on 80 times over monitoring period.

• 70 out of 80 – detected as “events” (no classification yet) AND also 15 false positive detections.

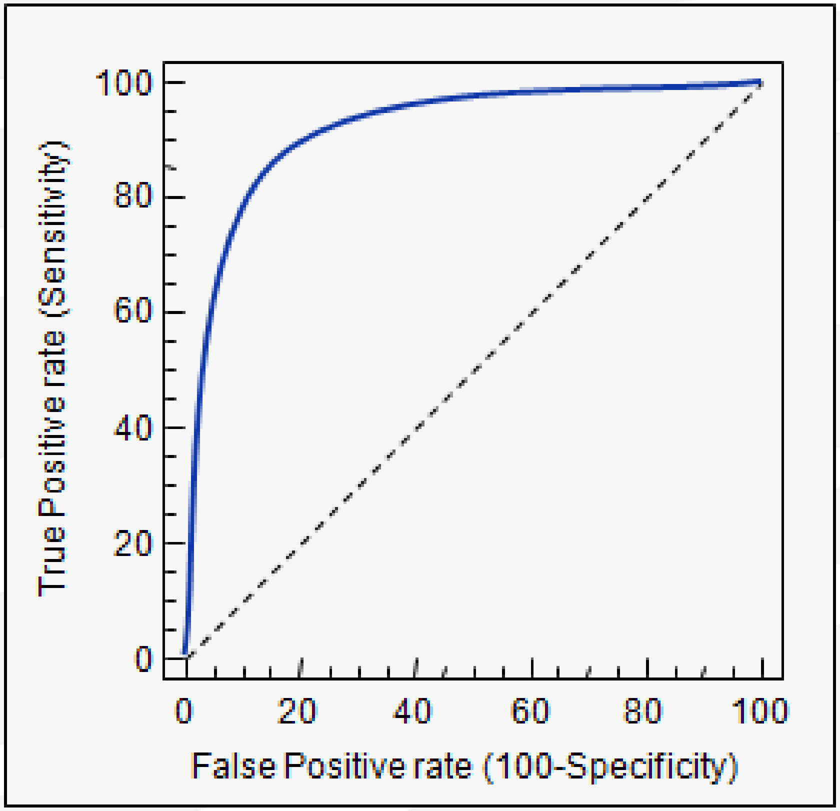
• Out of 70, 50 were correctly classified.

• What is the accuracy???

- Detection accuracy: 50/(70+15) = 58.8%
- Classification accuracy: 50/70 = 71.4%
- Overall accuracy: 50/80 = 62.5%

NIALM Accuracy Metrics – ROC

We suggest: Receiver operating characteristic (ROC)



Conclusions and Future Trends

- ❑ No complete NIALM solution is available
- ❑ No complete set of robust, widely accepted appliance features is available
- ❑Using more “orthogonal” features improves accuracy, albeit with higher false positive rates
- ❑ Using several “orthogonal” disaggregation algorithms may improve accuracy, but optimal fusion needs to be implemented
- ❑ ROC curves could be used for algorithm benchmarking rather than the ambiguous “accuracy”

Our (Fraunhofer CSE) Research Directions

- ❑ Exploration of device "signatures" to identify new orthogonal features
- ❑ Development of identification/tracking algorithms suitable for the new features
- ❑ Optimal fusion of new algorithm(s) with the algorithms available for traditional features
- ❑ Testing and benchmarking – device, whole home & branch circuit levels
- ❑ Exploration of transient event detection techniques
- ❑ Exploration of signal processing techniques for reconstruction of sources
- ❑ Results to be presented at:
  - "Viterbi Algorithm with Sparse Transitions (VAST) for Nonintrusive Load Monitoring," IEEE Symposium Series on Computational Intelligence, Paris, 2011
  - "Nonintrusive appliance load monitoring (NIALM) for energy control in residential buildings," Energy Efficiency in Domestic Appliances and Lighting Conference, Copenhagen, 2011