ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The Smart Thermostat

Using Occupancy Sensors to Save Energy in Homes

Distributed Systems Seminar 2011

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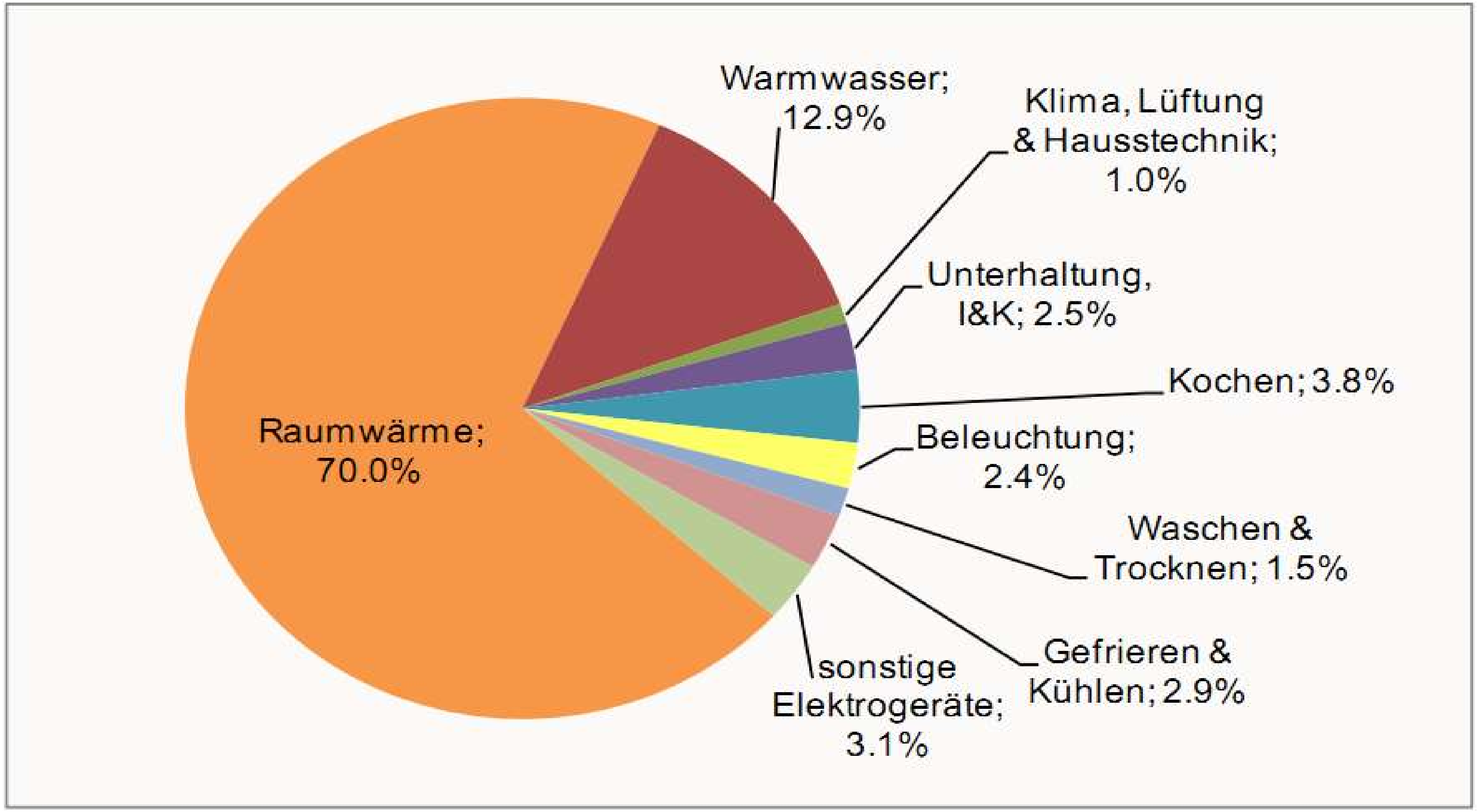
Motivation

- Save energy in order to minimize economical and ecological costs

- Approach: Reducing residental energy consumption by optimizing heating and cooling as its largest contributor

Distribution of residental energy consumption



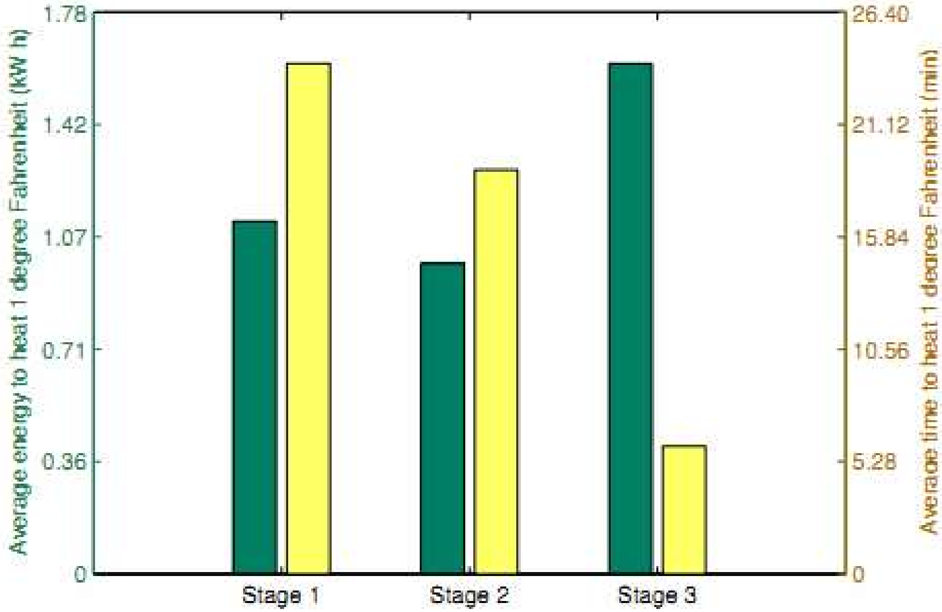
http://www.bfe.admin.ch: Analysis of Swiss Federal Office of Energy 2000 - 2009

HVAC – Heating, Ventilation and Air Conditioning

- Largest source of residental energy consumption
- Focus: Thermostat

http://www.auburn.edu/projects/sustainability/website/images/hvac.jpg

HVAC Stages



- HVAC provides stages of different efficiency
  - Stage 1: Maintain (heat pump)
  - Stage 2: Preheat (heat pump)
  - Stage 3: React (electric heater)

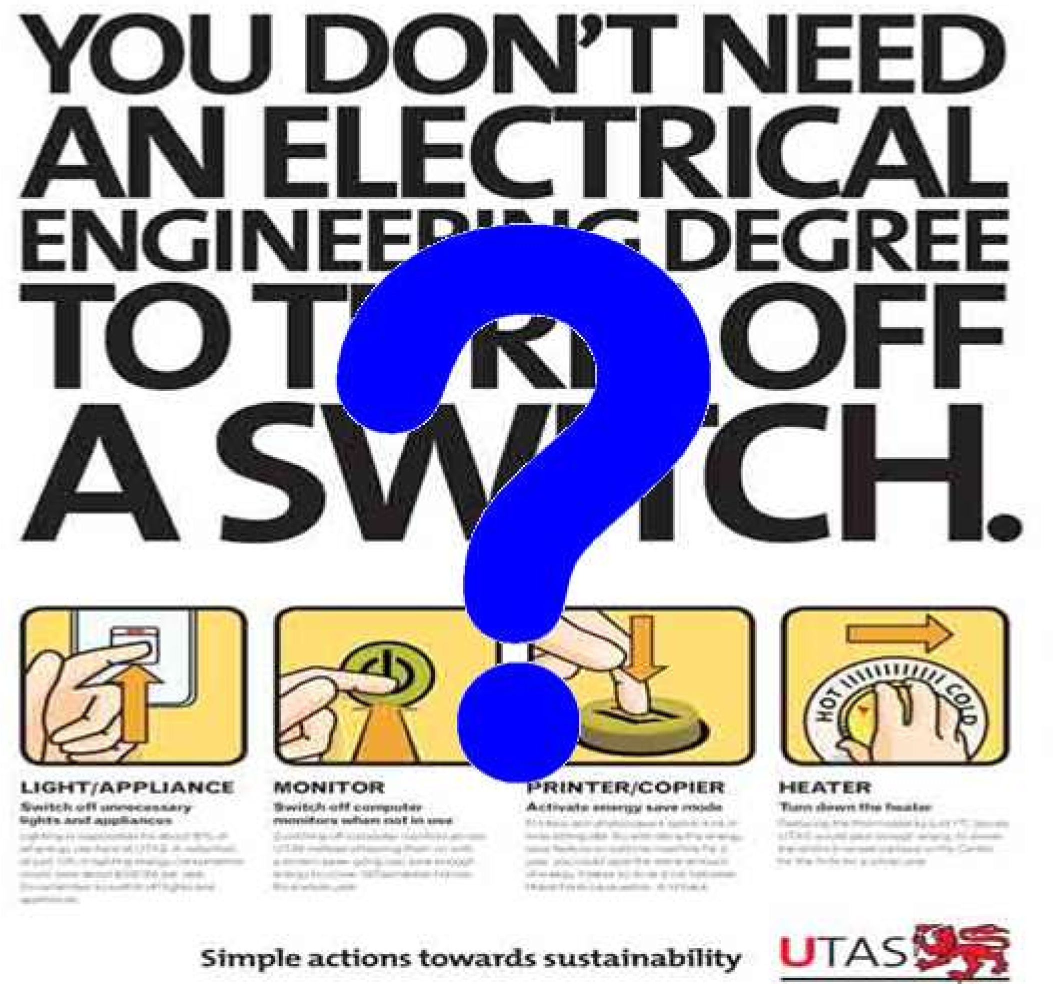
Main concern

- Tradeoff: comfort vs. energy saving
- Solution: Adjust HVAC based on occupancy
- Baseline approaches for thermostats:
  - Manual
  - Programmable
  - Reactive

Manual Thermostat

http://shop.smuk.at/shop/ProdukteBilder/613818_gr.jpg

Manual Thermostat



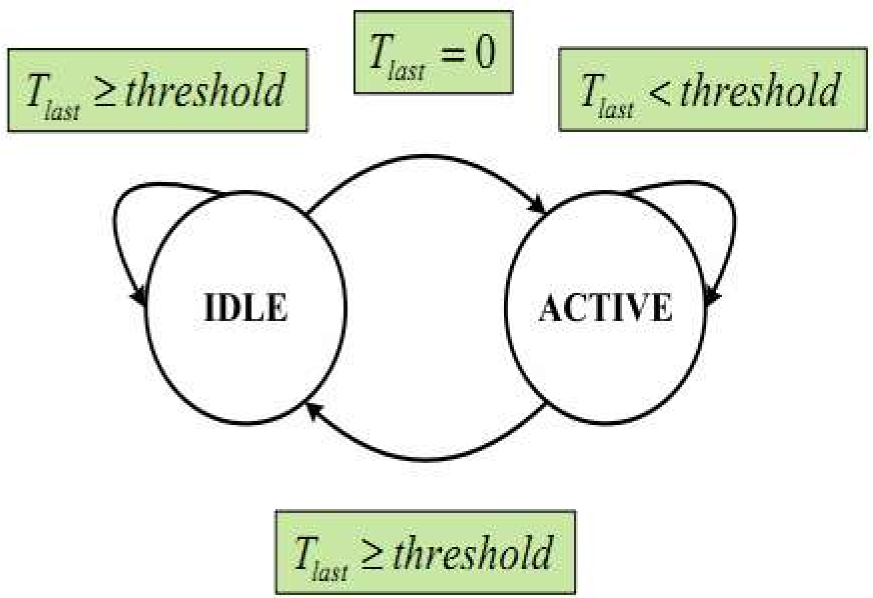
http://www.staff.utas.edu.au

Programmable Thermostat

- Based on *setback* schedule
- House is conditioned to:
  - *Setpoint* temperature if occupants at home and active
  - *Setback* temperature if occupants are away or asleep
- Schedule reflects occupant habits
- Drawback: Static schedule does not meet the dynamic occupancy patterns of most homes

Reactive Thermostat

- Uses sensors to estimate occupancy
  - ➢ Motion sensors, door sensors, …
- Drawback: Reaction on arrival and sensor interpretation



The Smart Thermostat

Idea

- Combine advantages of programmable and reactive thermostat
  - Use knowledge about historical occupancy patterns
  - Use on-line sensor data about dynamic occupancy changes

Components

X10 Motion Sensor

http://www.homeandpersonalsecurity.com

X10 Door Sensor

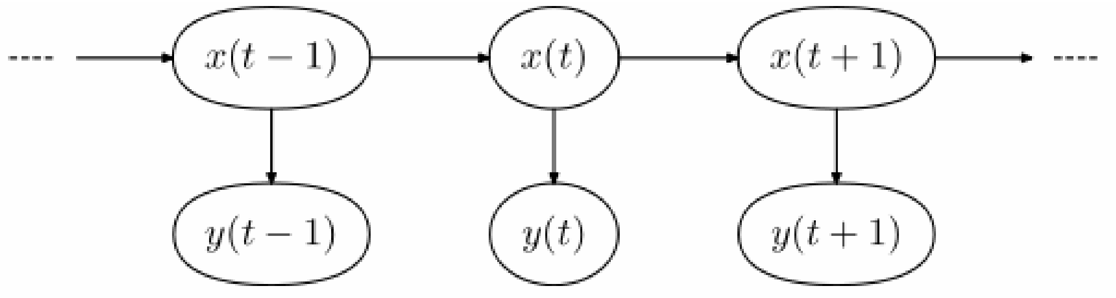
http://www.tecsol.com.au/DoorAlarm.htm

Fast reaction algorithm

- Optimal time to switch to setback temperature?
  - Too early: Occupant discomfort
  - Too late: Waste of energy

- Solution: Hidden Markov Model
  - Estimates probability of different occupancy states
  - On detection of a state transition: Adjust temperature setpoint

Fast reaction algorithm (II)



http://en.wikipedia.org/wiki/File:Hmm_temporal_bayesian_net.svg

- Hidden variable x: Distribution over states *Away*, *Active*, *Sleep*

- Observed variable y: Feature vector of sensor data
  - Time of day
  - Total number of sensor firings
  - Presence of specific sensor firings

Optimal target preheat time estimation

- Optimal time to switch HVAC on?
  - Too early: Waste of energy due to unnecessary preheating
  - Too late: Waste of energy due to inefficient heating stage

- Solution: Choose preheat time that optimizes the long-term expected energy usage

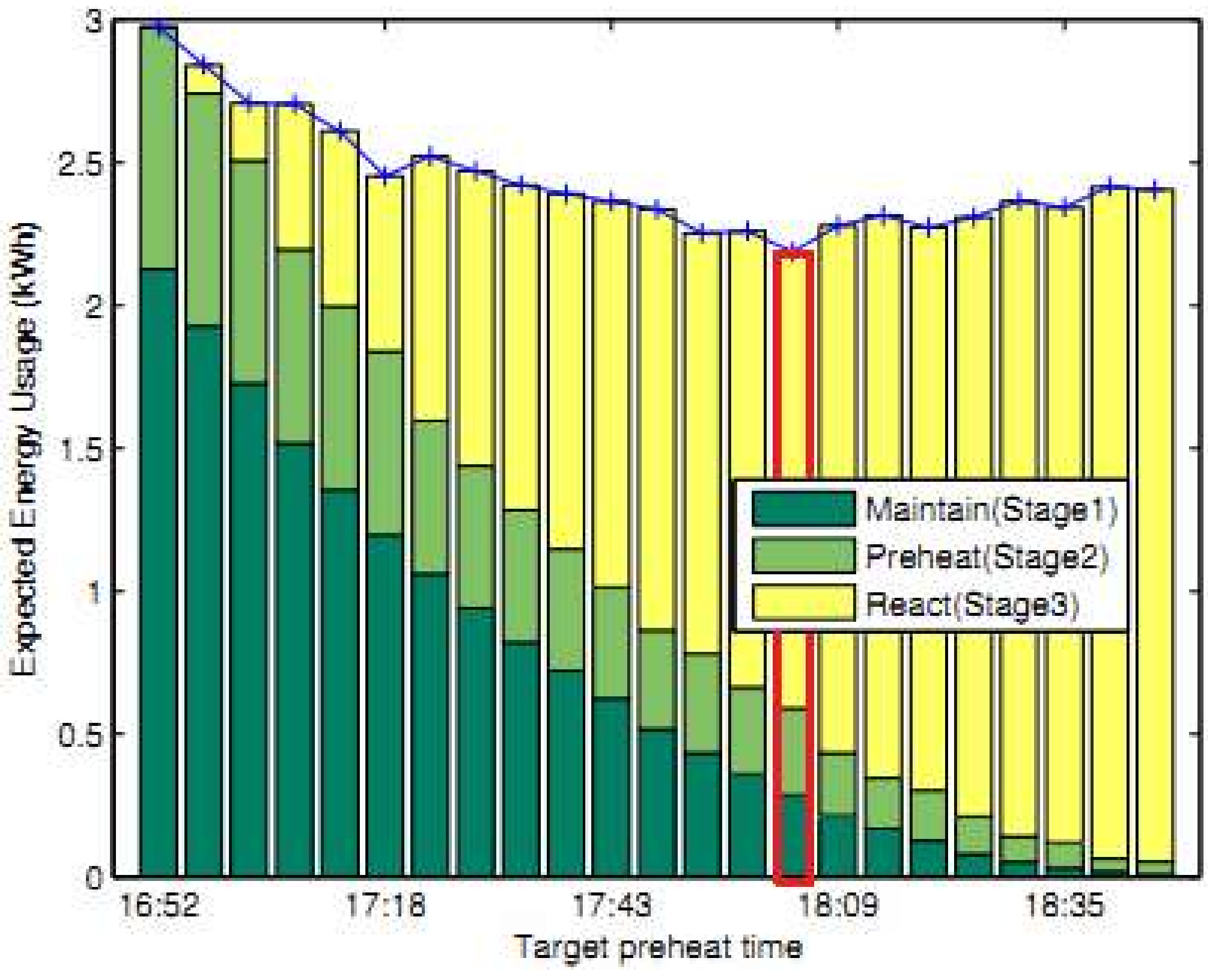
Optimal target preheat time estimation (II)

- Let **a** be the arrival time and **t** the target preheat time

- Then the resulting energy cost equals
  - The cost for preheating and maintaining for time **a** – **t**, if **t** ≤ **a**
  - The cost for reacting, if **t** > **a**

- Choose the optimal preheat time τ that minimizes the average energy cost over all observed arrival times

Optimal target preheat time estimation (III)



Evaluation

Competitors

- Reactive thermostat
  - Represents state-of-the-art

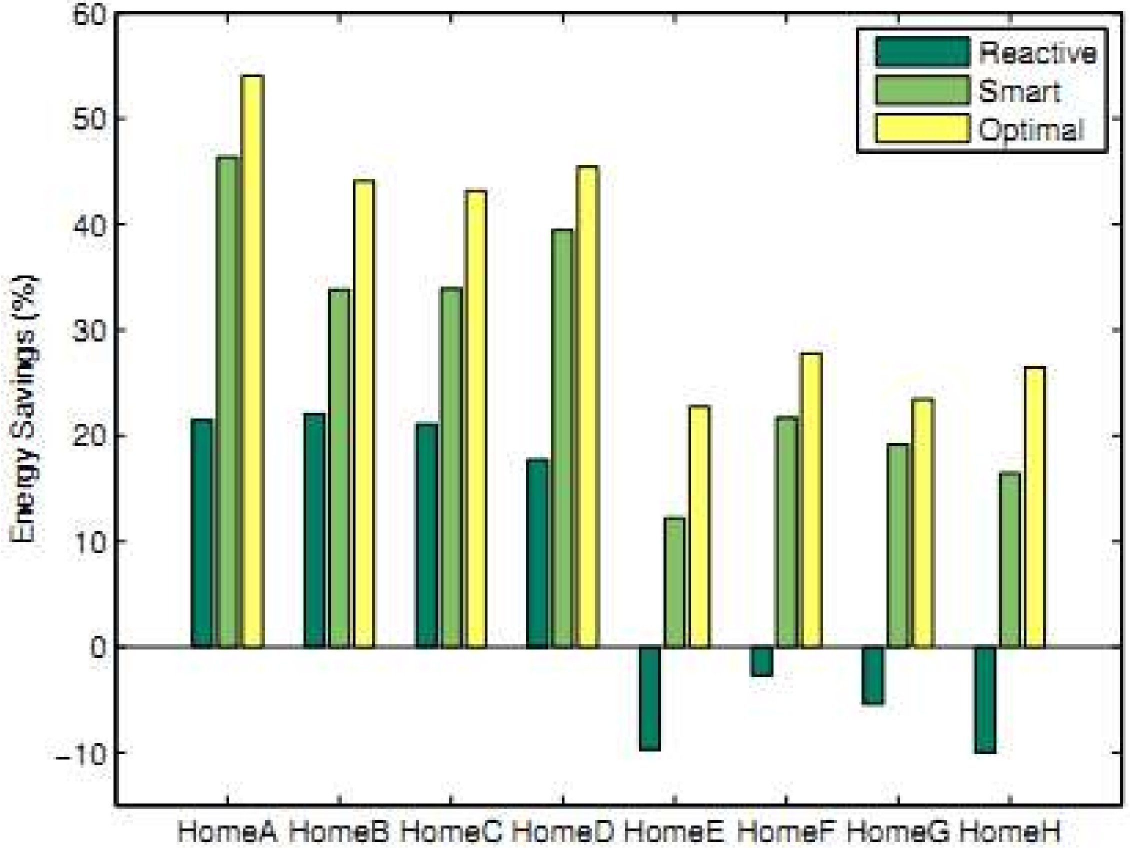
- Optimal algorithm
  - Knows exact occupancy states at any time
  - Adjusts temperature immediately after state transition

Setting

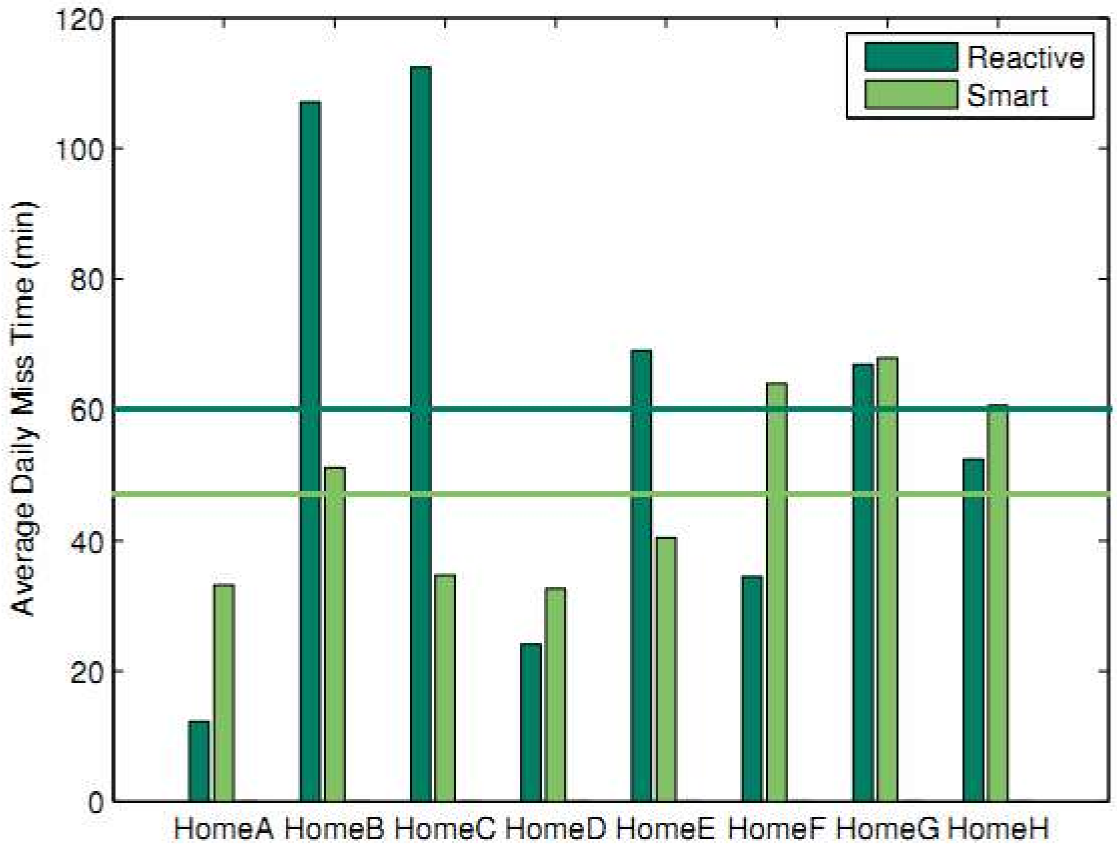
- Evaluated using EnergyPlus simulator
  - Provided by the U.S. Department of Energy
  - Uses physical description of buildings and mechanical equipment

- Simulation of 8 different home deployments
  - Evaluation periods of 14 days in both January and July

Results: Energy saving



Results: Miss time



Conclusion

Nationwide energy savings in the U.S.

- Simulation repeated over 5 climate zones

Climate Zone	Heating (billion kWh)	Cooling (billion kWh)	energy saving (%)
1	9	6	25.1919
2	24	25	25.8860
3	34	33	32.4408
4	23	31	40.2601
5	25	88	47.7498
Total	115	183	

- Results in an estimated energy saving of 38.22% nationwide for heating and cooling
  - ➢ Corresponds roughly to 4 Fukushima power plants…

Personal Opinion

- Promising approach, but still pretty vague
  - What about pets and plants?
  - When to train HMM?
- Deployment cost too low
  - Authors just mention cost of the nodes
  - What about control logic? How to interface HVAC?
- Projected nationwide savings not realistic
  - $10 billion to upgrade all 130 million homes in the U.S. will not suffice

References

- **[Lu 2010]**
  Jiakang Lu, Tamim Sookoor, Vijay Srinivasan, Ge Gao, Brian Holben, John Stankovic, Eric Field, and Kamin Whitehouse.
  The Smart Thermostat: Using Occupancy Sensors to Save Energy in Homes.
  Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys 2010), Zurich, Switzerland, November 2010

- **[Swiss Federal Office of Energy]**
  Analysis of energy consumption by specific use
  http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=de&name=de_60881886.pdf

  [Wikipedia]
  X10 Wireless Technology
  http://en.wikipedia.org/w/index.php?title=X10_Wireless_Technology&oldid=426494891
  Hidden Markov Model
  http://en.wikipedia.org/w/index.php?title=Hidden_Markov_model&oldid=428995655
  Fukushima Daiichi Nuclear Power Plant
  http://en.wikipedia.org/w/index.php?title=Fukushima_Daiichi_Nuclear_Power_Plant&oldid=429438850

Backup Slides

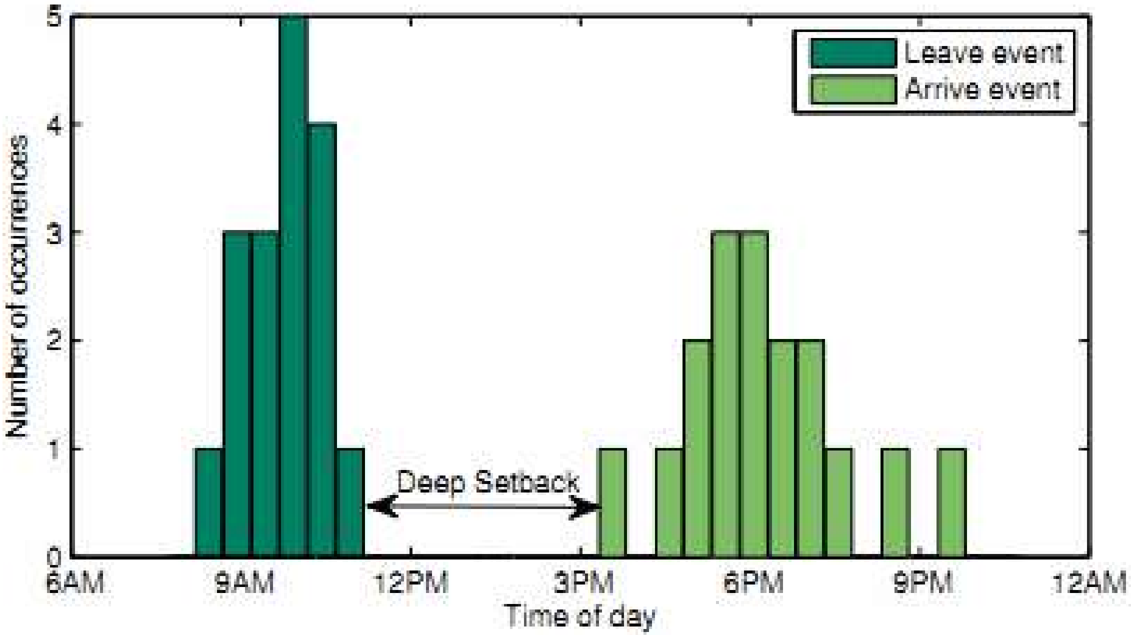
Deep setback

- Typical difference between setback and setpoint is 7° C
  - Results often in energy consumption even when house is vacant

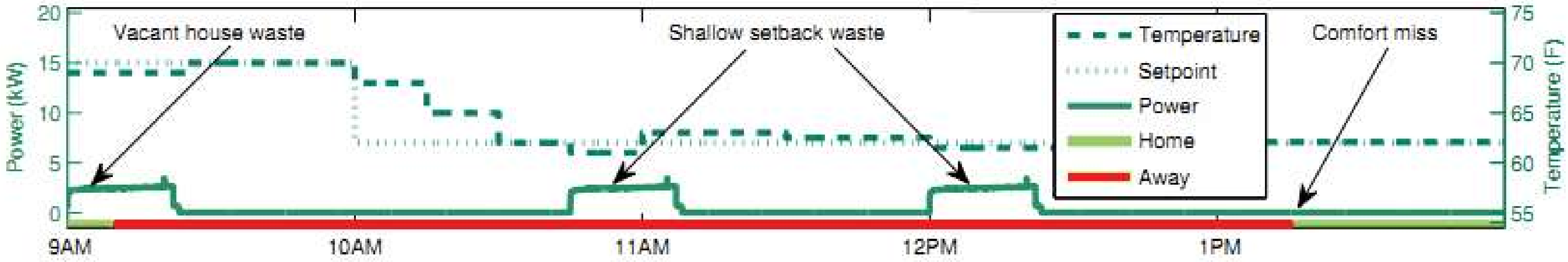
- Solution: Use deep setback as long as probability of returning occupants is negligible

Deep setback

- Use deep setback until earliest observed arrival time
- Switch to a typical shallow setback afterwards



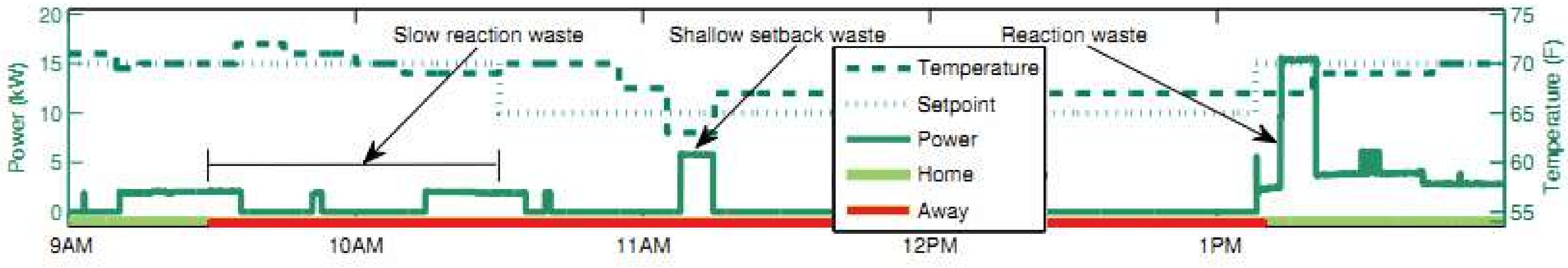
Programmable Thermostat



- Drawback: Static schedule does not meet the dynamic occupancy patterns of most homes

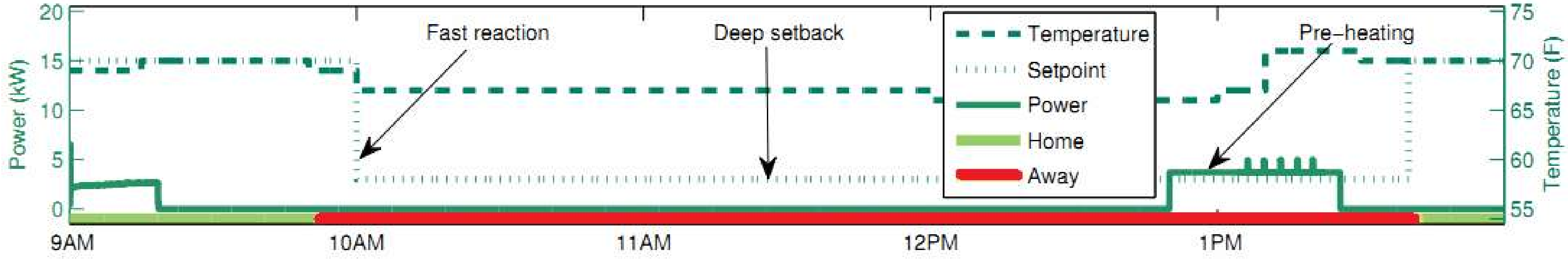
  - Vacant house vaste: Inadequate energy consumption
  - Comfort miss: Inadequate temperature
  - Shallow setback waste: Due to inadequate setback temperature

Reactive Thermostat



- Drawback: Reaction on arrival and sensor interpretation
  - Slow reaction waste: Due to timeout for recognizing absence
  - Reaction waste: Due to inability to predict occupant arrivals
  - Shallow setback waste: Due to inadequate setback temperature

Smart Thermostat



- Fast reaction: System switches to Deep setback within minutes after residents leave
- Pre-heating used to reach Setpoint at expected resident arrival time

X10 Wireless Technology

- American subsidiary of a Hong Kong-Bermuda company best known for marketing wireless video cameras
- Provides off-the-shelf wireless sensors in the low-prize segment
- Results in typical deployment costs between $25 and $100 per home

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X10 Homepage

http://www.x10.com