SmartCap:

Flattening Peak Electricity Demand in Smart Homes

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Pervasive Computing in Smart Homes

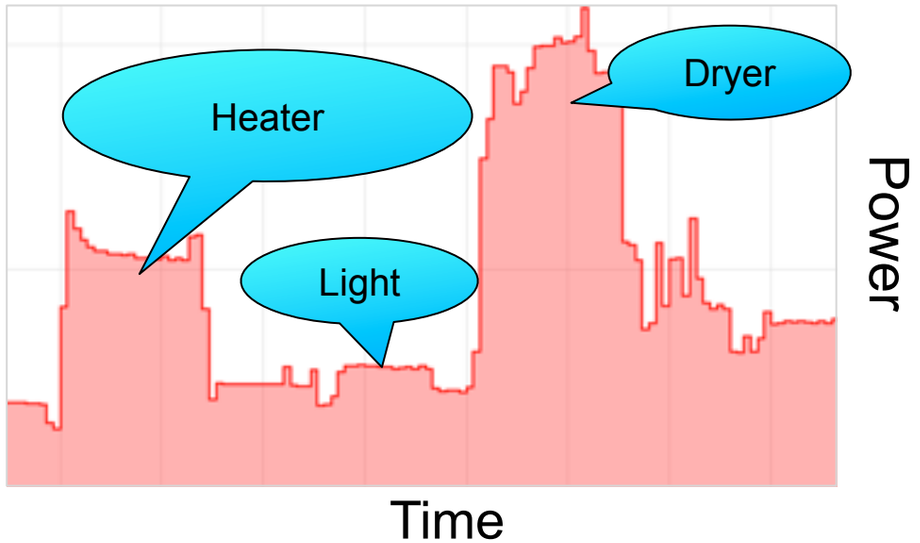
- **Smart homes**: efficiency, automation, convenience
- Enabled by pervasive computing
  - Smart meters, energy sensors, load controllers
  - Appliance integration

- Greening smart homes
  - Why? **73%** of U.S. electricity

- Economic benefits:
  - infrastructure, energy costs
- Environmental benefits:
  - carbon footprint, renewables

Demand-Side Energy Management

- Control consumer-side energy demand
  - Respond to energy availability
  - Reduce peak usage, fluctuations
- Components of DSEM
  - Monitoring (data collection)
  - Control (e.g., load shifting)



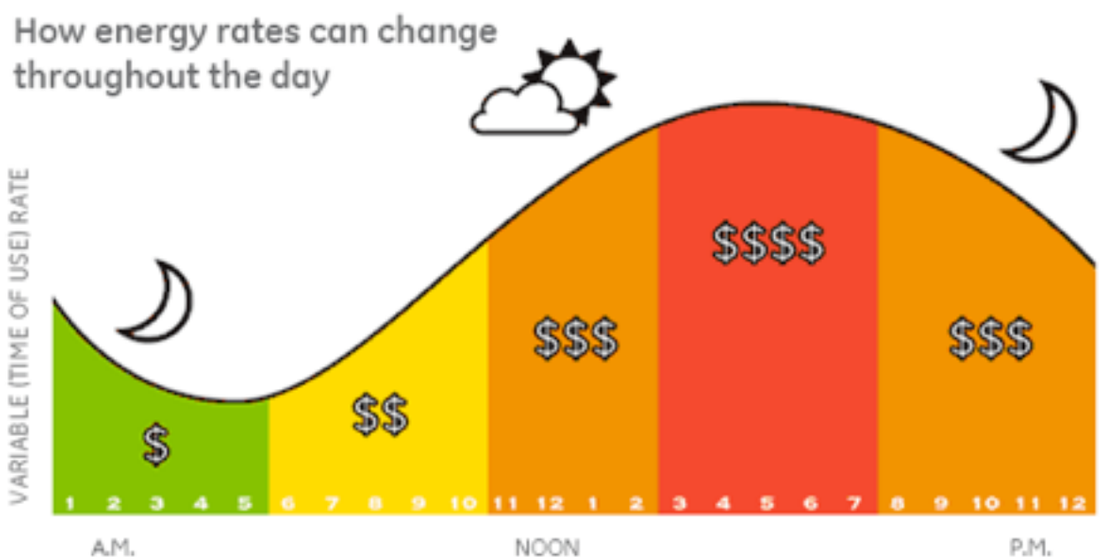
- We focus on performing **peak load reduction**

Benefits of Peak Load Reduction

- **For utilities:**
  - Lowered peak grid demand
  - Infrastructure savings
  - Transmission & distribution

$(loss \propto current^2)$

47%!



- **For consumers:**
  - Variable pricing cost savings
  - Battery efficiency
  - Assist with capping

Challenges of Peak Load Reduction

- **Change user behavior**
  - Users don't want to!
  - Maintain household routines

- Inflexible loads
  - Unacceptable: lights, TV
  - Inconvenient: dishwasher

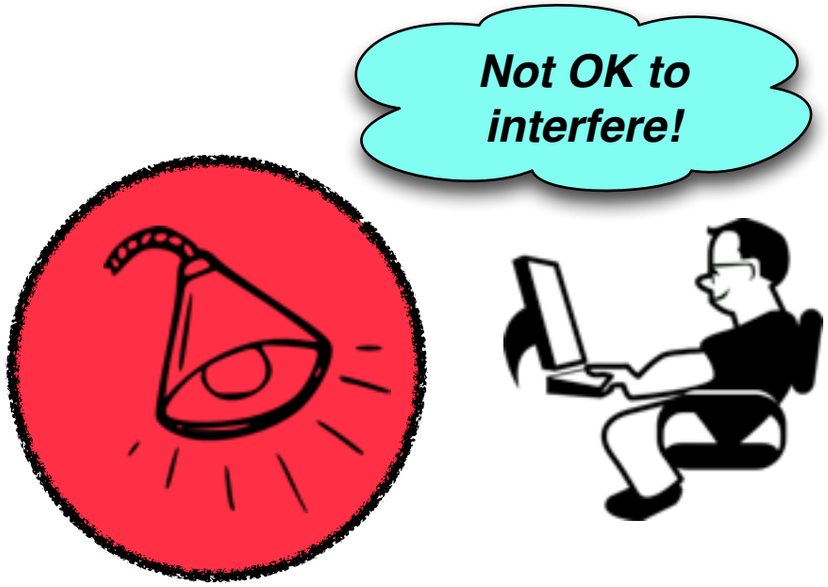
- **Goal: transparent peak reduction**
  - No user cooperation
  - No negative impact

Outline

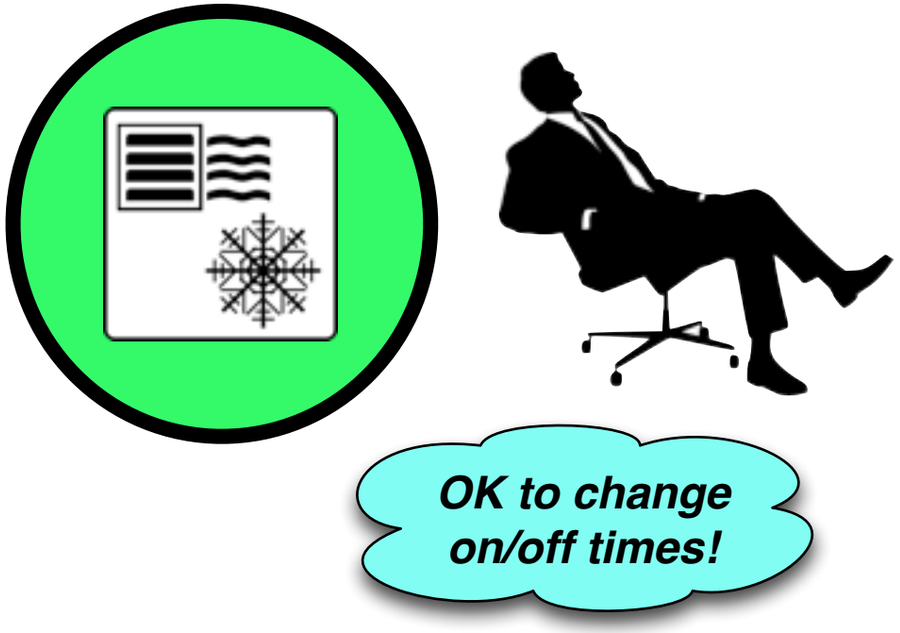
- Motivation
- Home measurement study
  - What can we schedule transparently?
- SmartCap scheduler
  - How can we perform transparent peak reduction?
- Evaluation on home data
  - How effectively does SmartCap flatten demand?
- Conclusions

Types of Loads

- **Interactive loads**
  - Controlled by users
  - TV, lights, microwave
  - Little scheduling freedom!



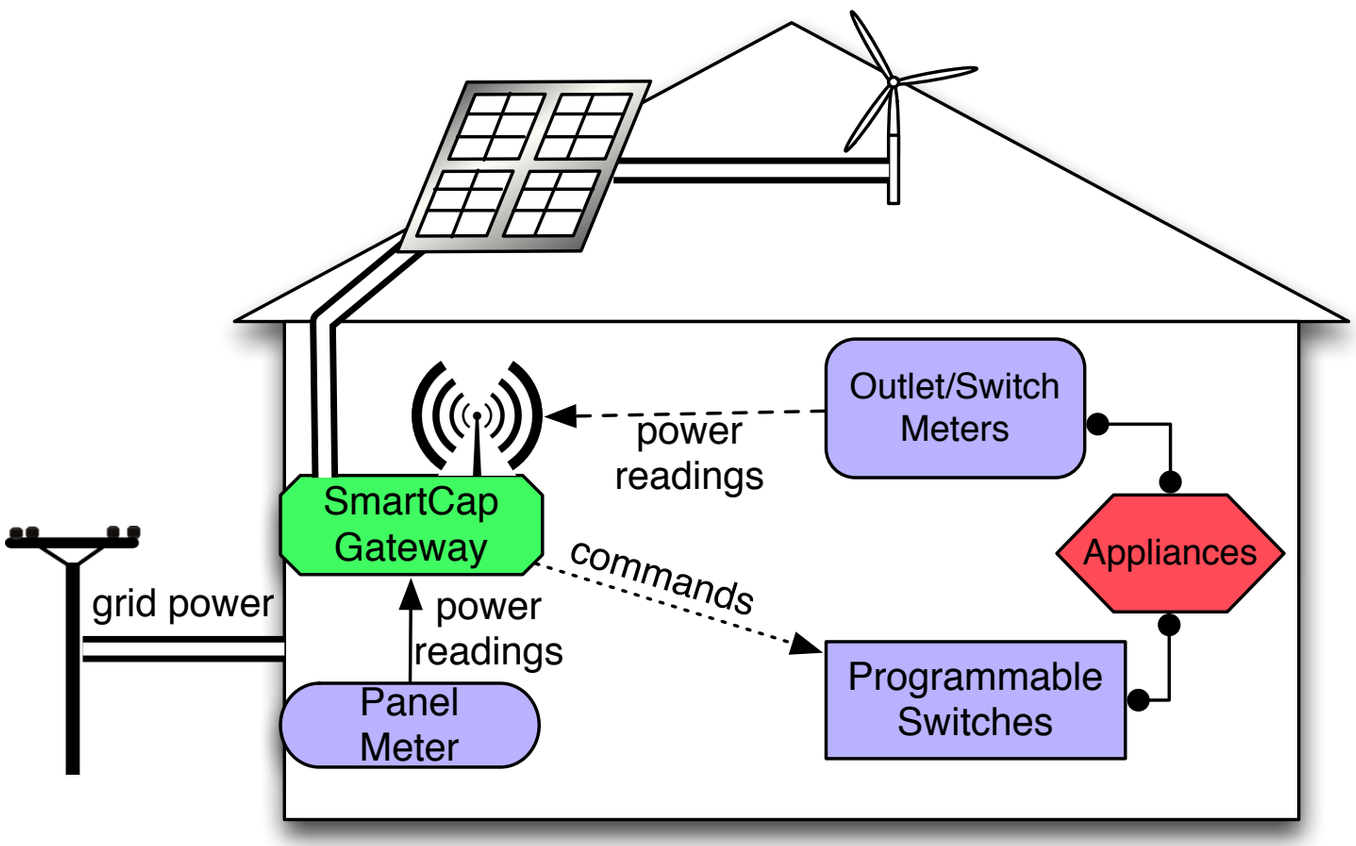
- **Background loads**
  - Not controlled by users
  - A/C, refrigerator, heater
  - Don’t care how objective is met
  - Significant scheduling freedom!



SmartCap Measurement Study

- Home monitoring deployment
  - 3 occupants, one year (so far)

- Instrumented all outlets and switches
  - Lights, TV, dishwasher, freezer, A/C, etc.



1. Background Loads are Significant

- Few major background loads
  - heat recovery ventilator
  - refrigerator
  - freezer
  - dehumidifier
  - air conditioner (x3)

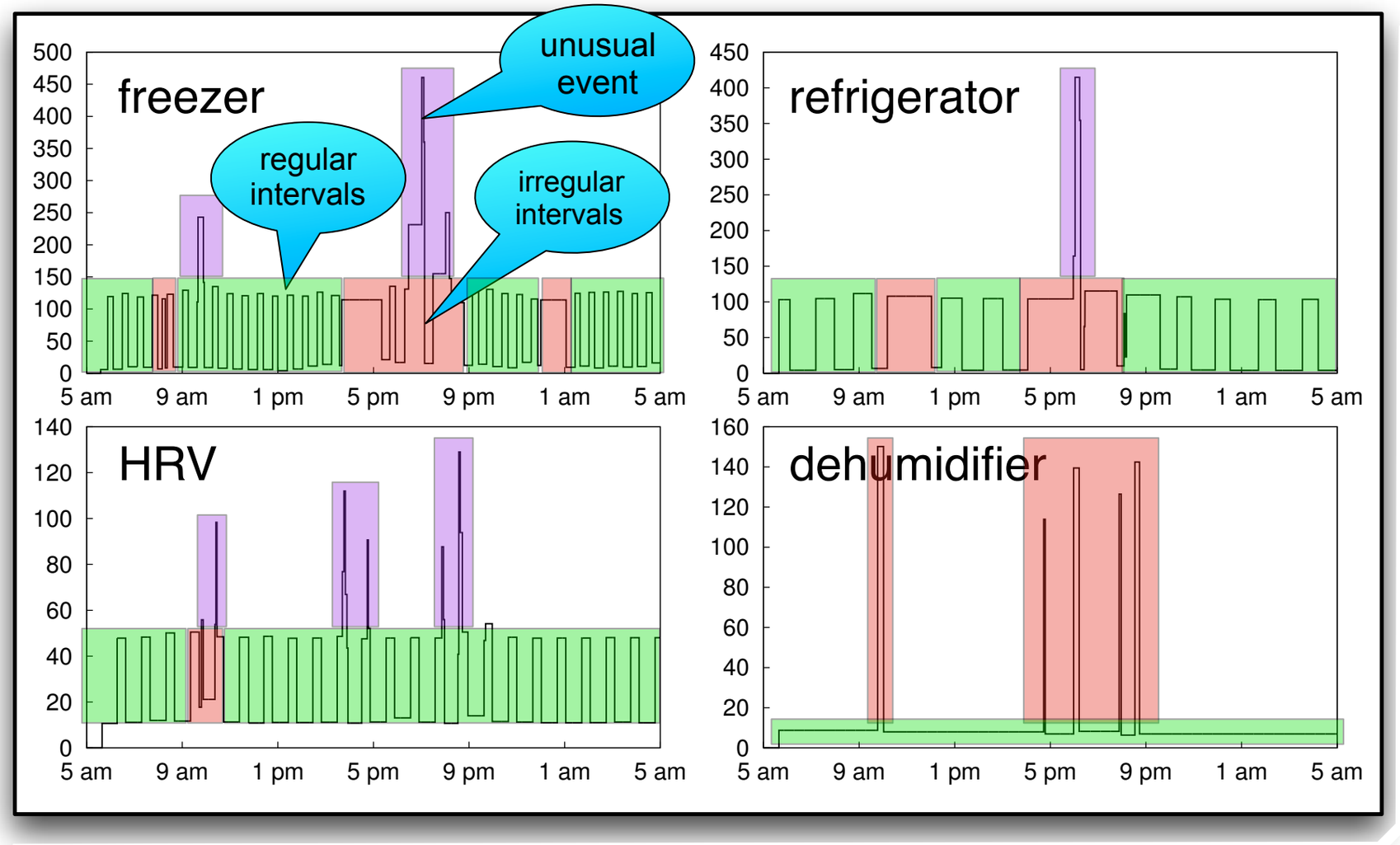
- **8%** of loads but **59%** of energy use

Load	*Peak*	*Average*	*Quantity*
Refrigerator	456W	74W	1
Freezer	437W	82W	1
HRV	1129W	24W	1
Dehumidifier	505W	371W	1
Main A/C	1046W	305W	1
Bedroom A/C 1	571W	280W	1
Bedroom A/C 2	571W	141W	1
Background	**4715W**	**1277W**	7
Interactive	**9963W**	**887W**	85

- Background loads are few but major energy users

2. Background Loads are Periodic

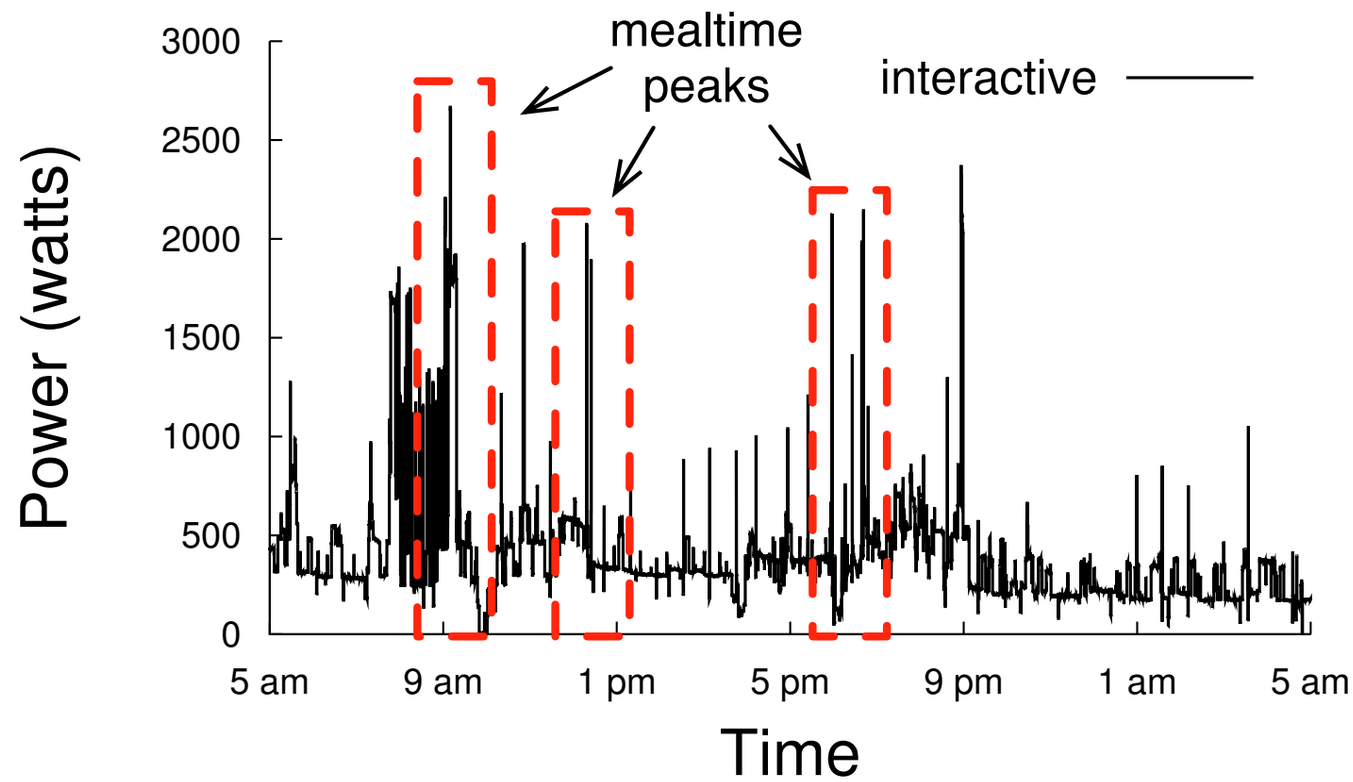
- Periodicity: regular on/off intervals
- Mostly (but not fully) independent of user behavior

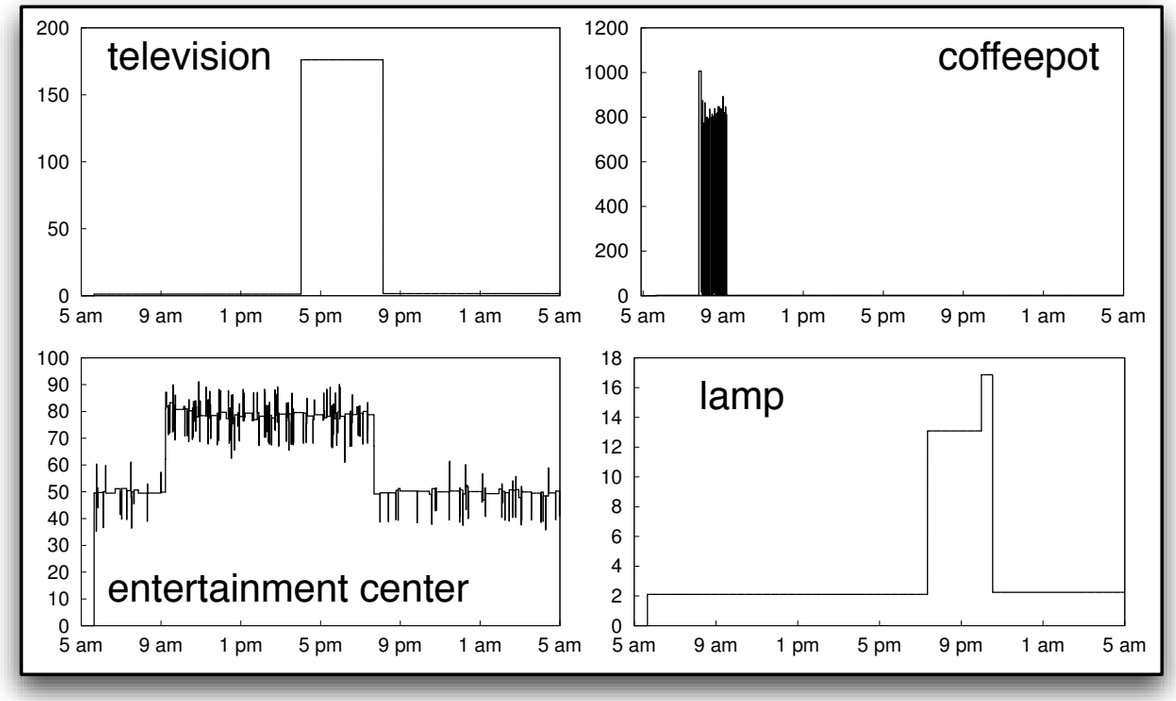


- Background loads vary but have useful periodicity

3. Interactive Loads are Unpredictable

- **"Peaky"** total load
  - Brief, high-power devices
- Many **unpredictable** individual loads
  - Human usage patterns
  - May change over time

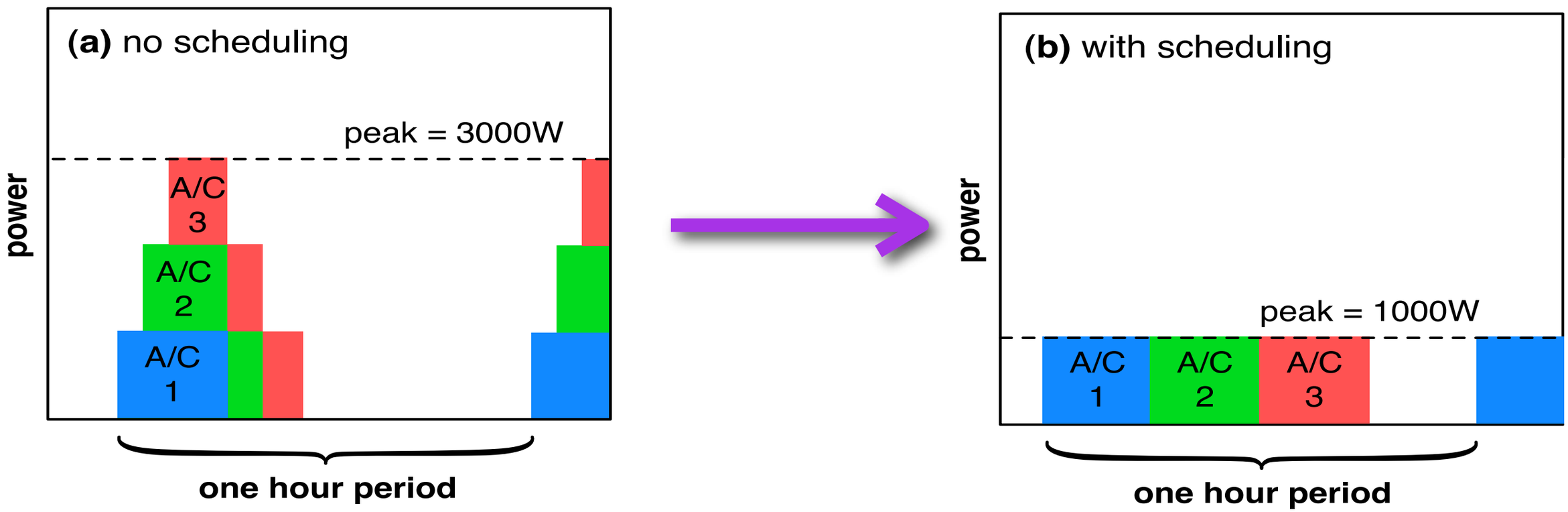




- Peak reduction must compensate for interactive loads

Flattening in SmartCap

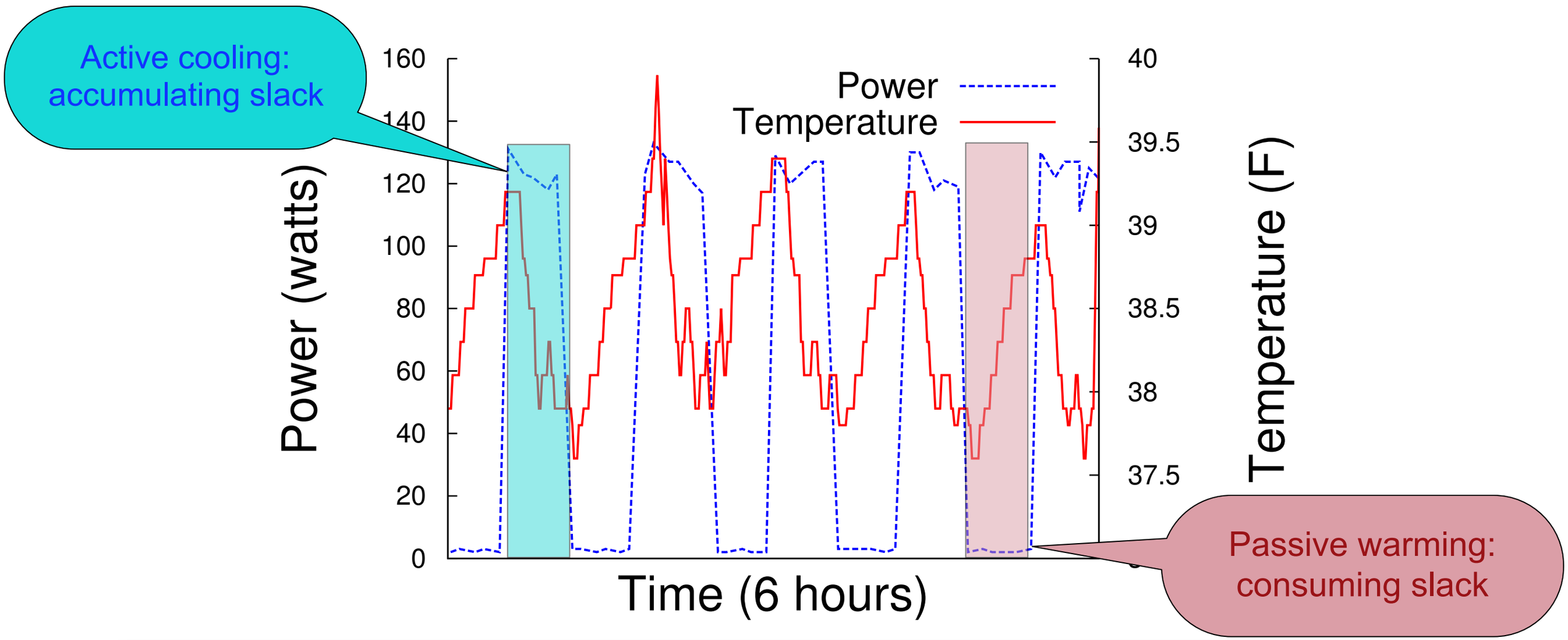
- Background loads cycle on and off
- Exact on/off times (mostly) don't matter
- Schedule cycling of background loads



- Interleave background loads to flatten peaks

Scheduling Loads: Slack

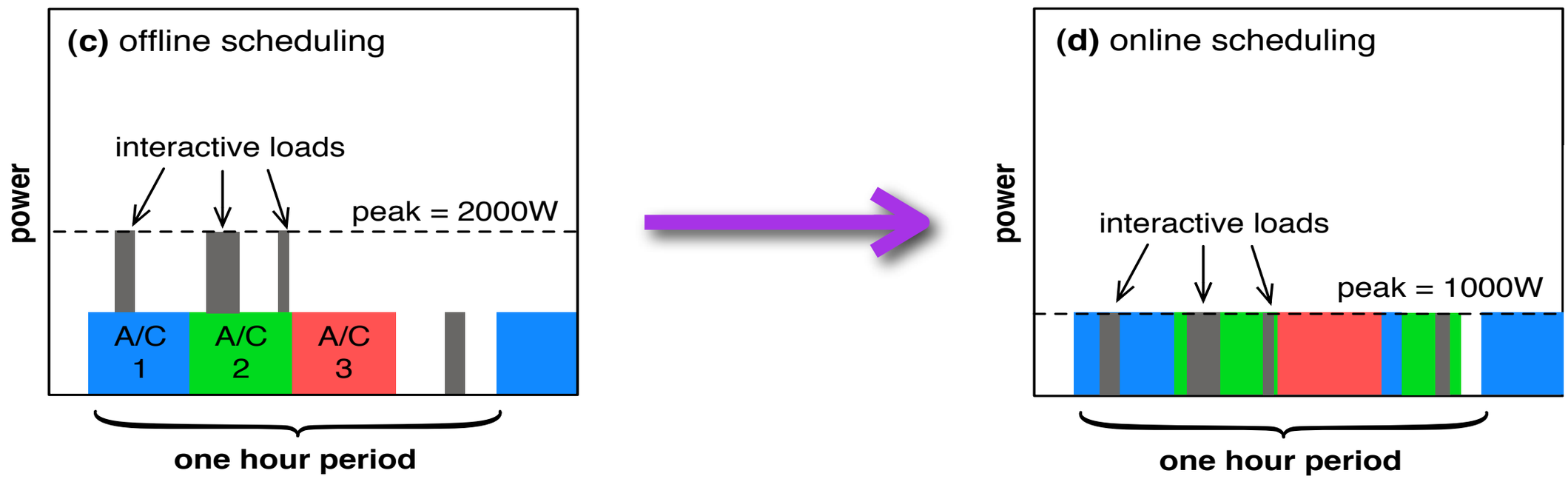
- Periodic background loads exhibit 'slack'
  - Measure of how long background load can remain off
  - Based on guardband (e.g., fridge temperature range)



- Control slack by modifying device duty cycle

SmartCap Scheduler

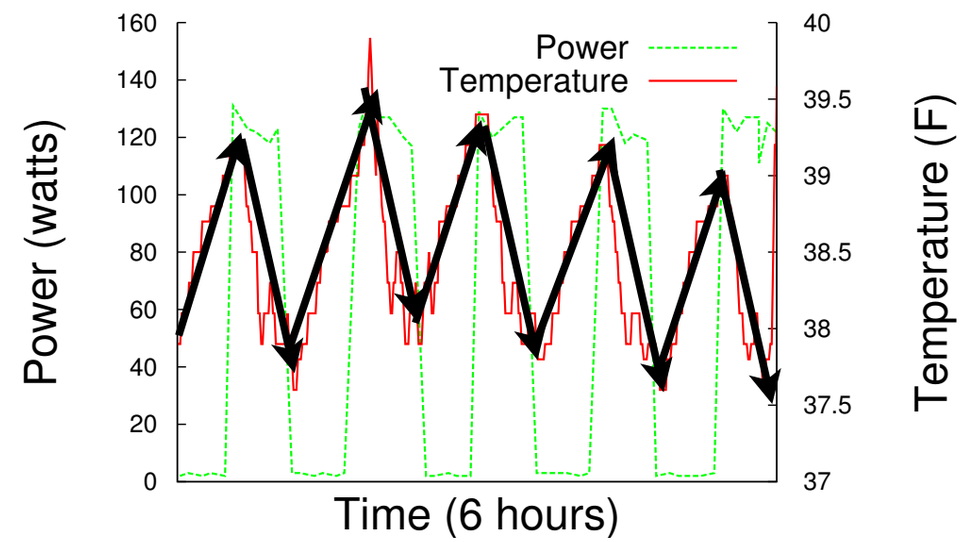
- Schedule based on remaining slack
- **Least Slack First** (LSF)
  - Operate loads in order of ascending slack
- Online scheduler
  - Respond to foreground (interactive) loads



- Preempt background loads by interactive loads

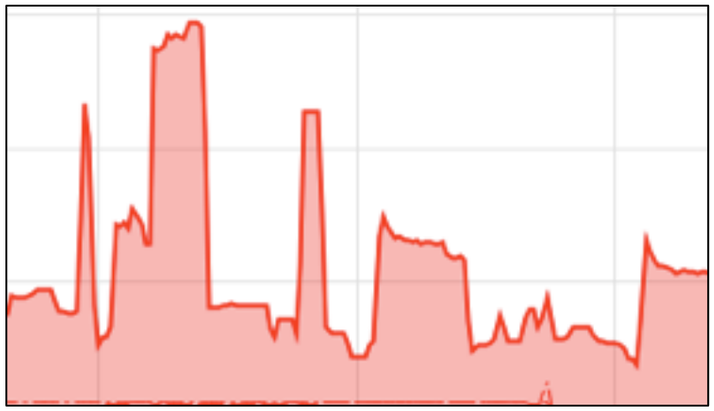
SmartCap Evaluation

- Evaluate LSF on home data
  - Computed per-period slack
  - Linear slack model

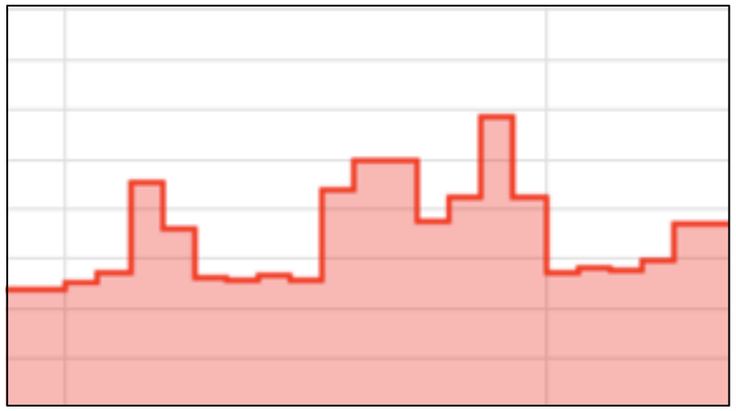


- Flattening metric
  - Average deviation from mean

- Flattening period
  (a) One day
  (b) Four hours



Daytime

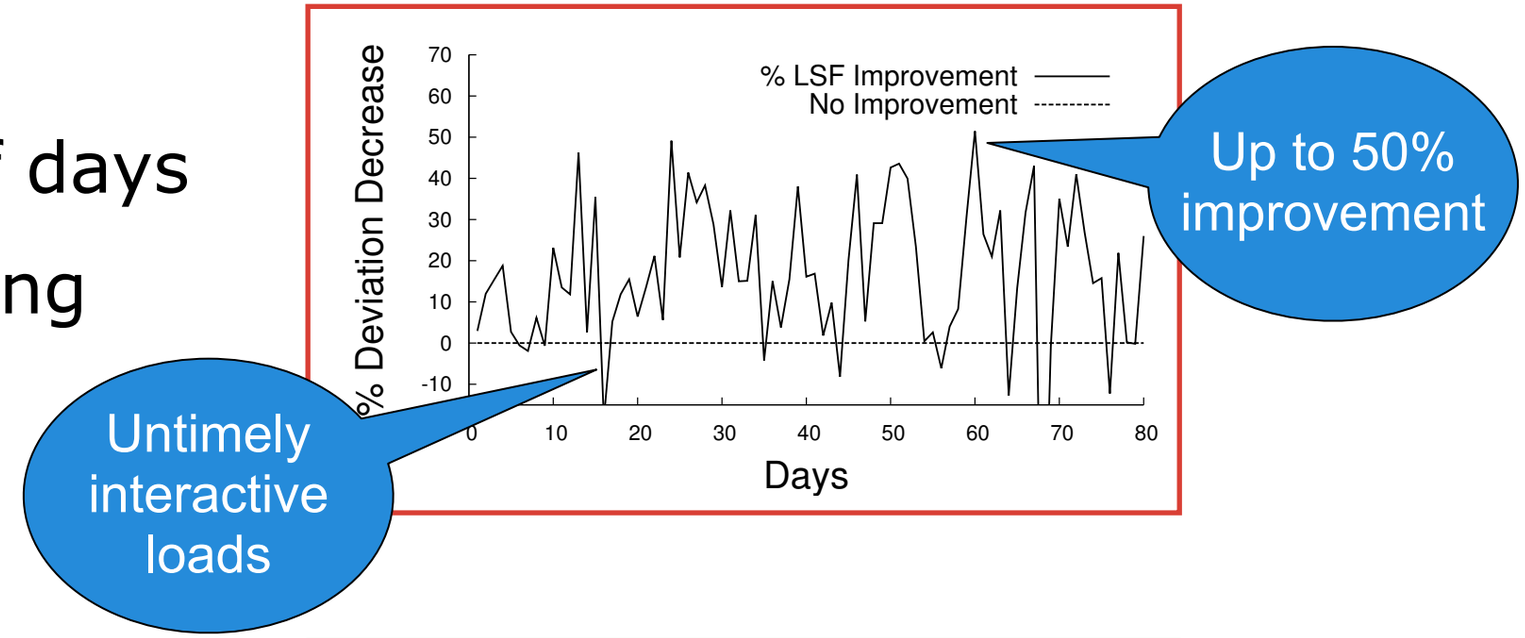


Nighttime

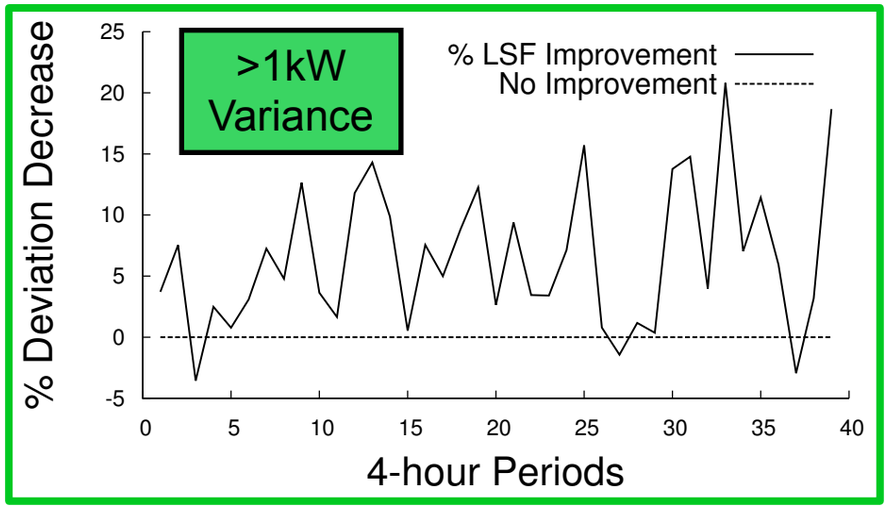
- High deviation period (mealtimes) or low (nights)

Evaluation: Smart Home

- Day-long periods
  - Flattening on **91%** of days
  - **16%** average flattening



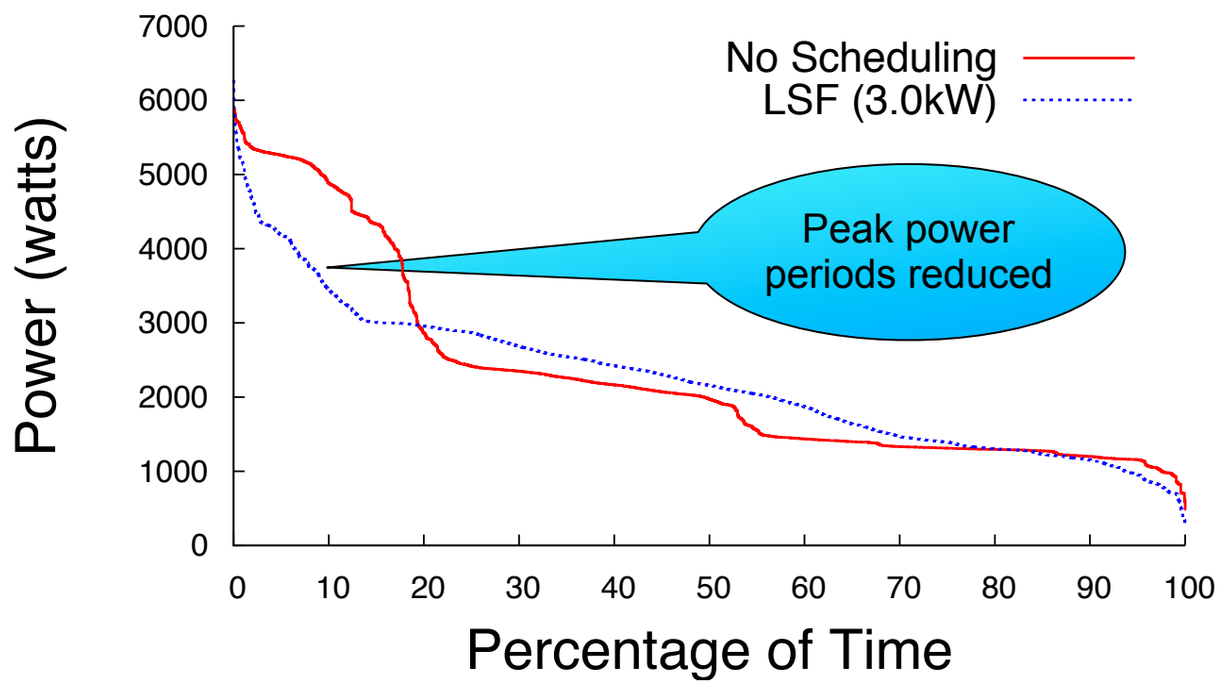
- Four-hour periods
  - **High** variance (31%)
    - **>20%** flattening
  - **Low** variance (69%)
    - **<3%** flattening



- LSF especially good at flattening high peak periods

Evaluation: Electric Vehicle

- **Electric Vehicle (EV)**
  - Peaky typical usage
  - Grid unreadiness at scale
  - EV load added to home data

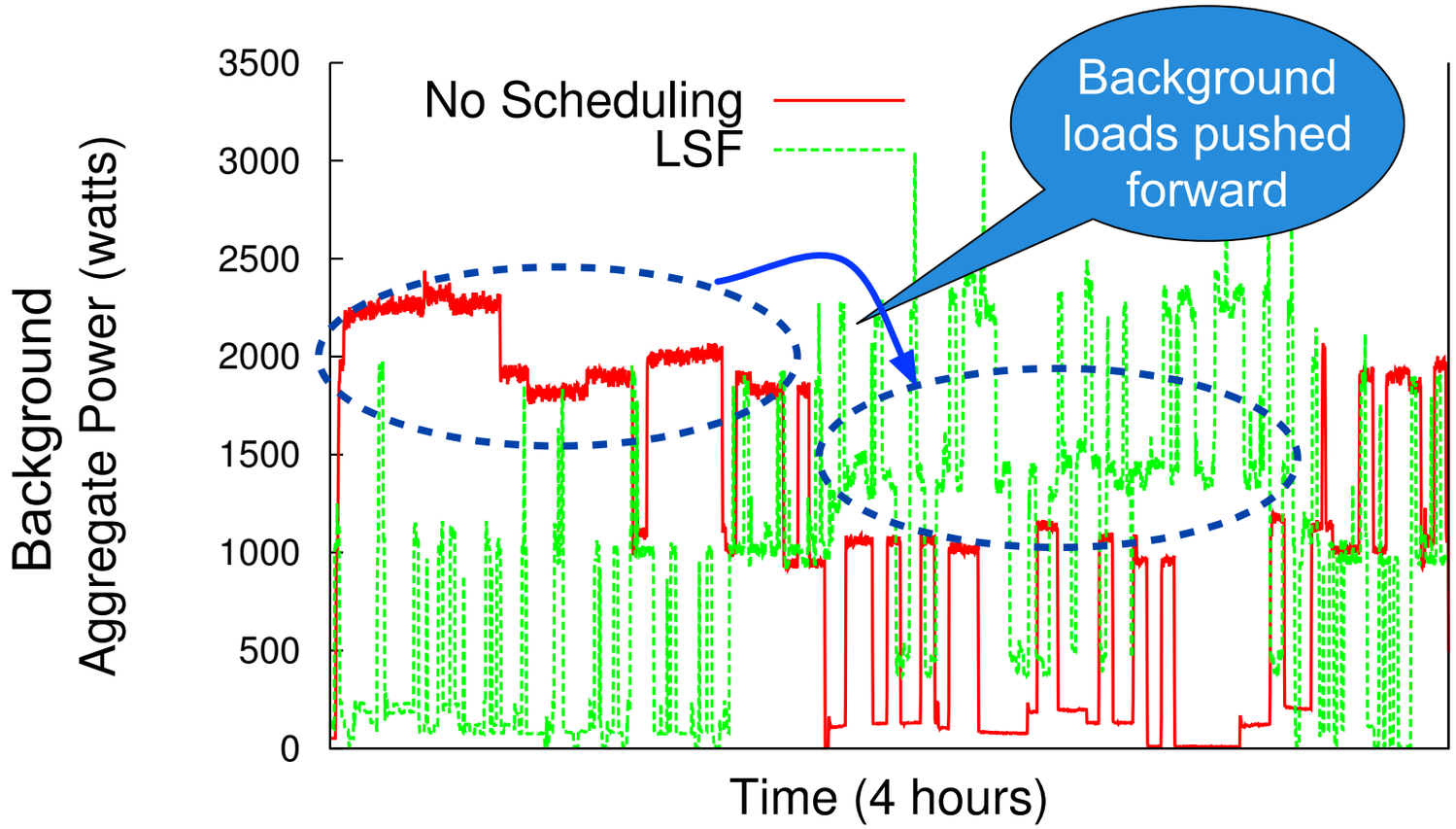


- EV is good candidate for LSF: **22%** flattening

Evaluation: Lab Testbed

- Live testbed for active control, repeatability
  - 'Smart appliances' via programmable Insteon switches

- Active background scheduling in LSF



- **23%** flattening (background + interactive) on testbed

Related Work

- Demand-side energy management
  - Load shifting [Keshav, GreenNet 10]
  - Prediction [Schülke, SmartGridComm 10]
  - Batteries [Zhu, BuildSys 11], [Bar-Noy, WEA 08]

- Background schedulers
  - Optimizing for renewables [Taneja, SmartGridComm 10]
  - Offline scheduling [Bakker, SmartGridComm 10]

Conclusions

- Demand-side energy management for peak reduction
- SmartCap flattens transparently
  - Modifies **only** background loads
  - Interactive loads unaffected
- **20-30%** flattening using Least Slack First
- Additional savings possible with modest user changes
  - Subject of ongoing work

Questions?

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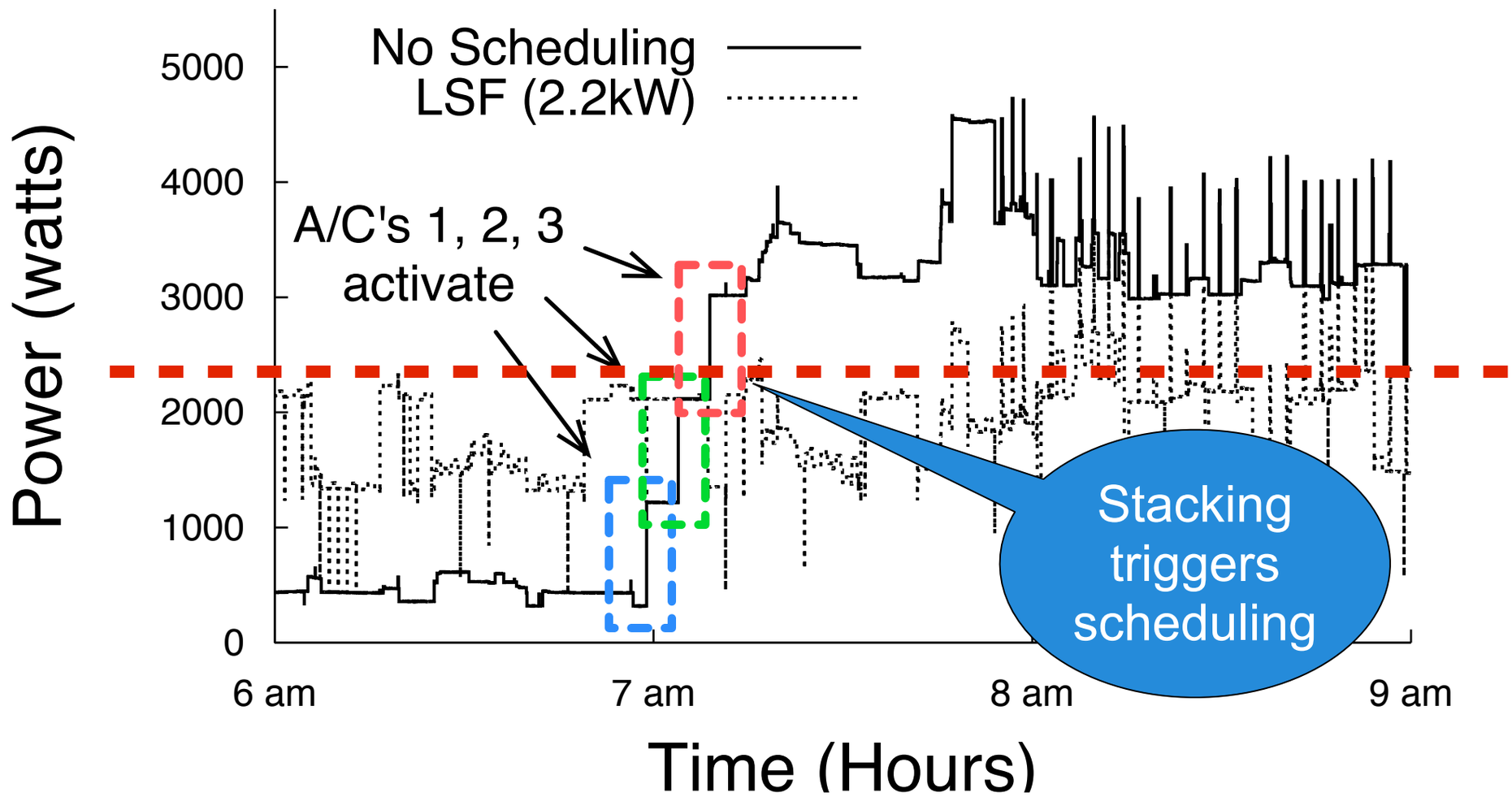
Least Slack First Threshold

- Threshold power to preempt loads
  - Start scheduling when threshold is reached



- Adaptive threshold (moving average of past use)