

Building Energy and Comfort Management through Occupant Behaviour Pattern Detection Based On a Large- Scale Environmental Sensor Network

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Building Energy Consumption

IMPACTS OF U.S. BUILDINGS ON RESOURCES

40% primary energy use*

72% electricity consumption*

39% CO₂ emissions*

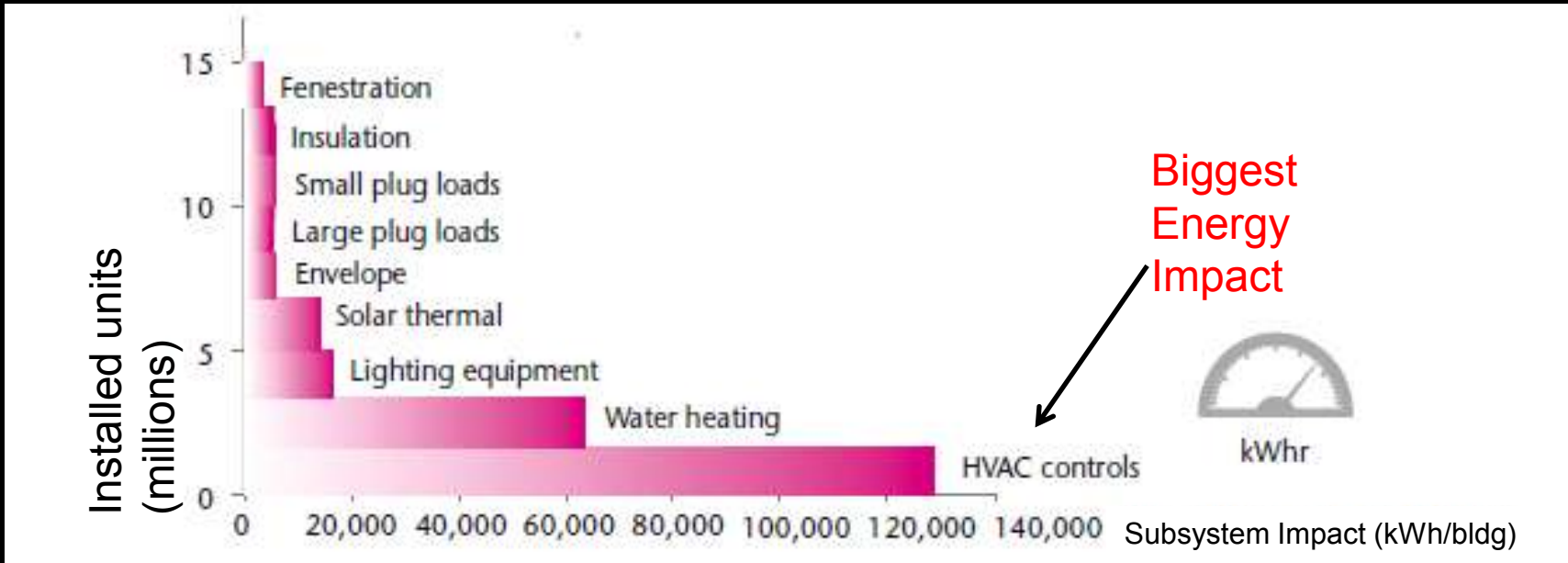
13.6% potable water consumption**

Sources:

*Environmental Information Administration (2008). EIA Annual Energy Outlook.

** U.S. Geological Survey (2000). 2000 data.

Energy Saving Potentials for Building HVAC Control



**Transforming the Market: Energy Efficiency in Buildings* by world business council for sustainable development (WBCSD), 2009.

Dream

Reduce energy consumption in buildings while maintaining occupant's comfort

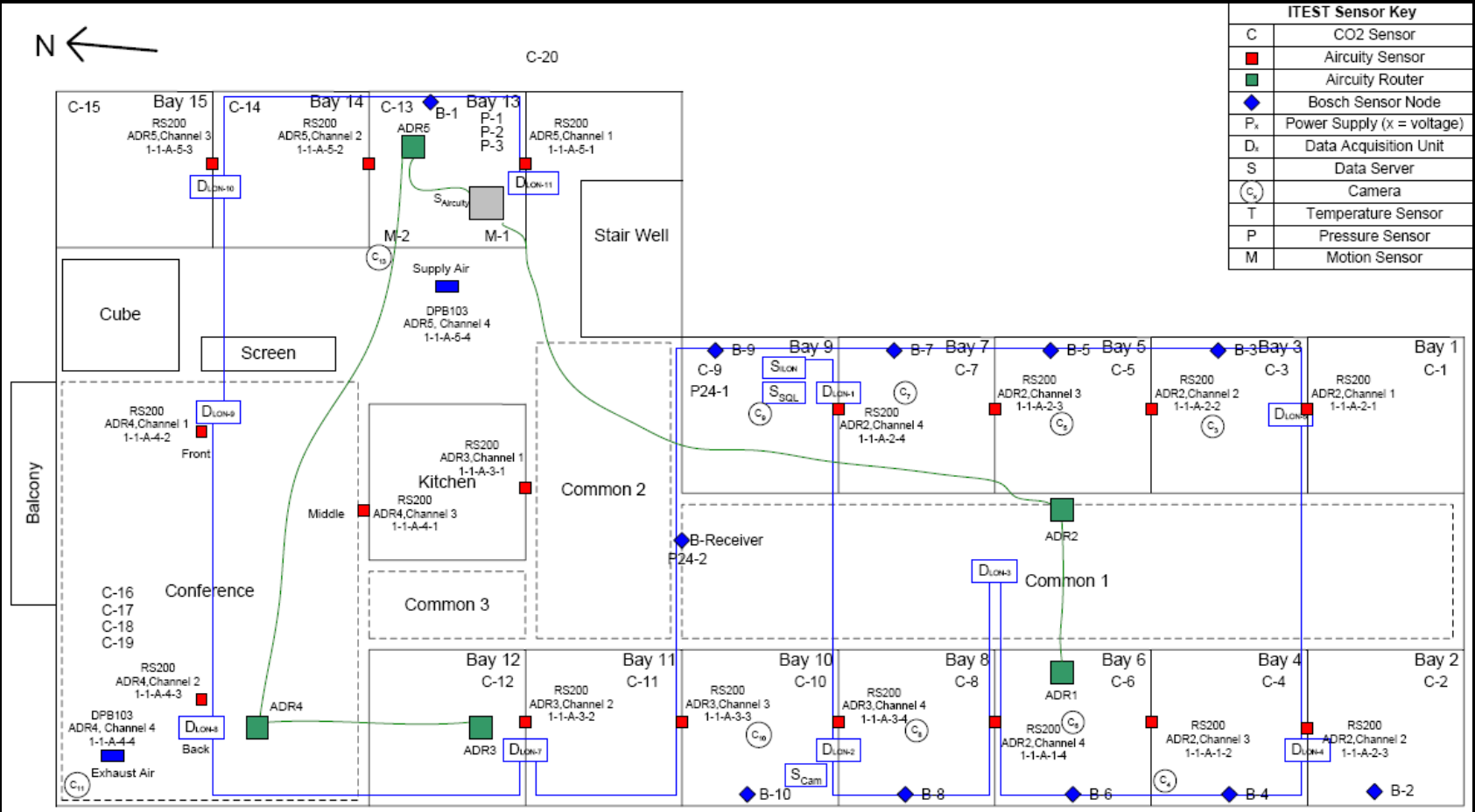
How to?

Best achieved by understanding occupant's behavior and patterns both in activities and energy consumption.

Objective

Develop and implement algorithms for environmental sensor-based modeling and prediction of user behavior in intelligent buildings, and evaluate its energy impacts.

Test-bed Setup

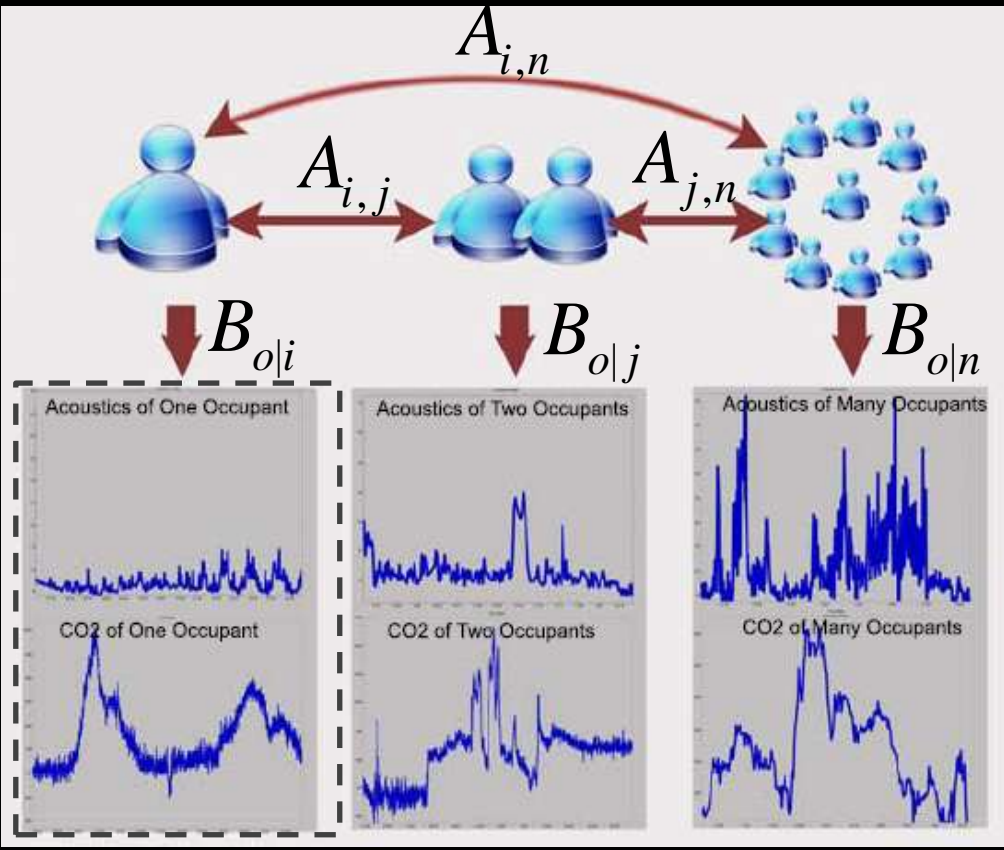


The data is collected continuously since January 29th, 2008

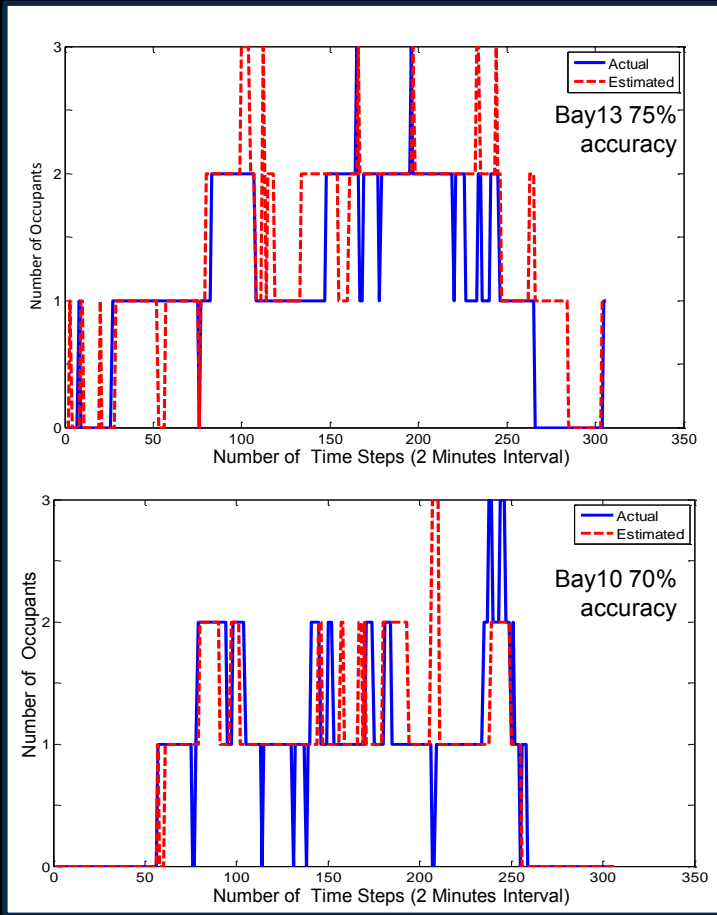
Intelligent Workplace, CMU

A Generalized Occupancy Model (1) -- Number of Occupants

Implemented Method: Hidden Markov Model (HMM)



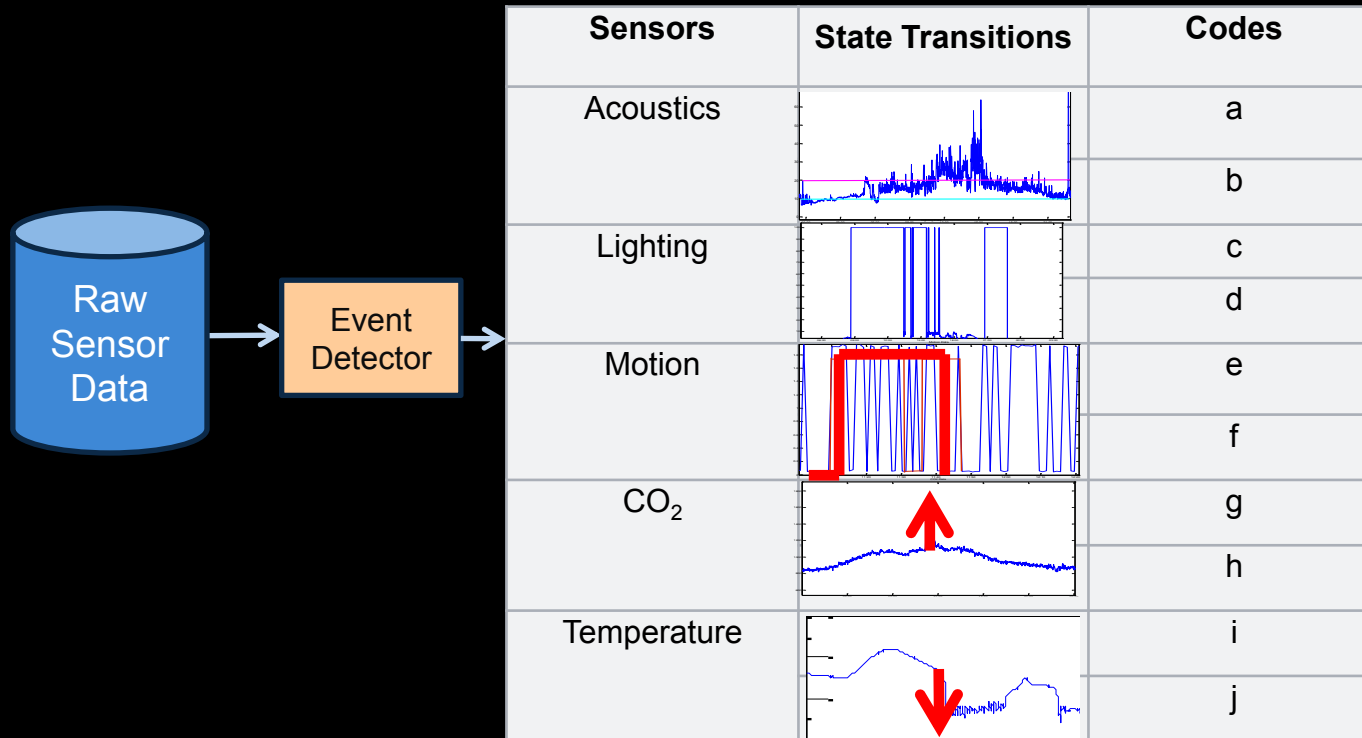
HMM Structure



Testing Results

A Generalized Occupancy Model(2)--Occupancy Duration

Motivation: Sequential Data Mining

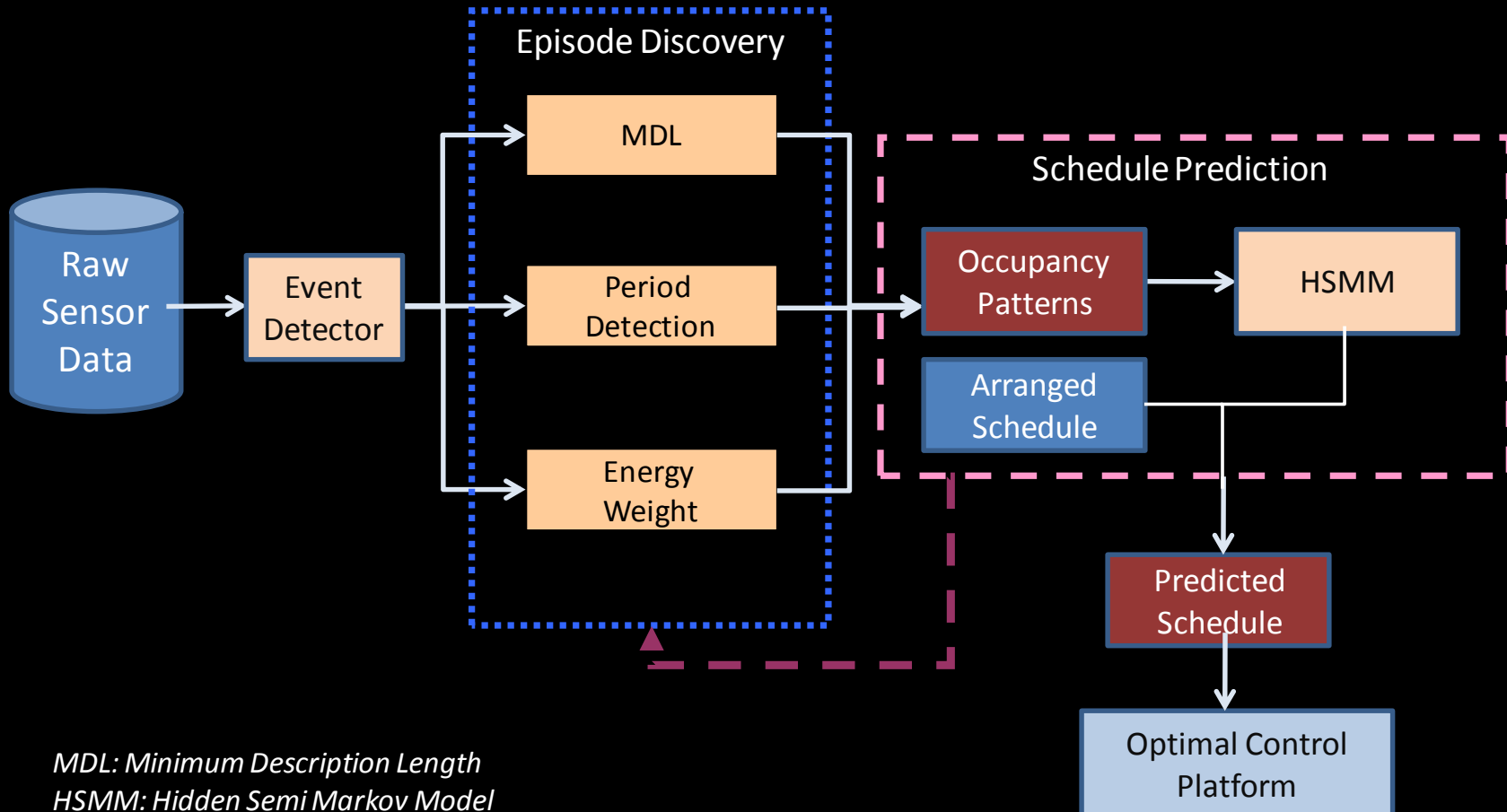


Sample events (60 minutes):

agghkjhkjkjkjiljhjkkililaagbfbfchdekcfefdllebcqbfglhibelfbcbgk

A Generalized Occupancy Model(2)--Occupancy Duration

Implemented Method : Episode Discovery + Hidden Semi Markov Model (HSMM)



MDL: Minimum Description Length

HSMM: Hidden Semi Markov Model

A Generalized Occupancy Model(2)--Occupancy Duration

Results of Occupant Patterns

Example Events

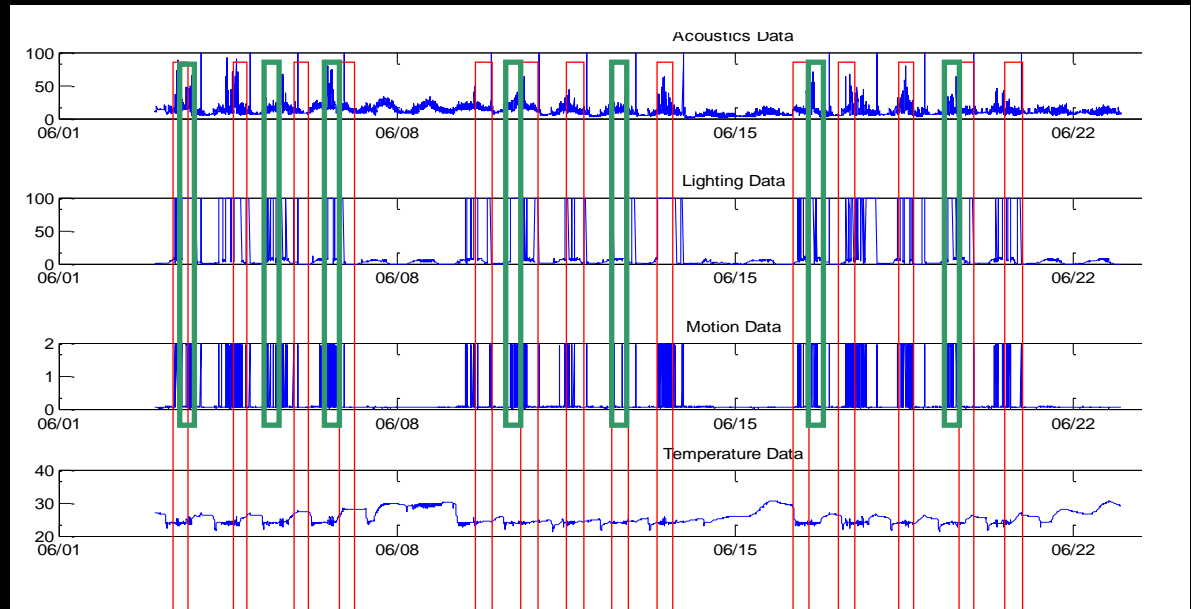
'bfjbe'



'becfb'

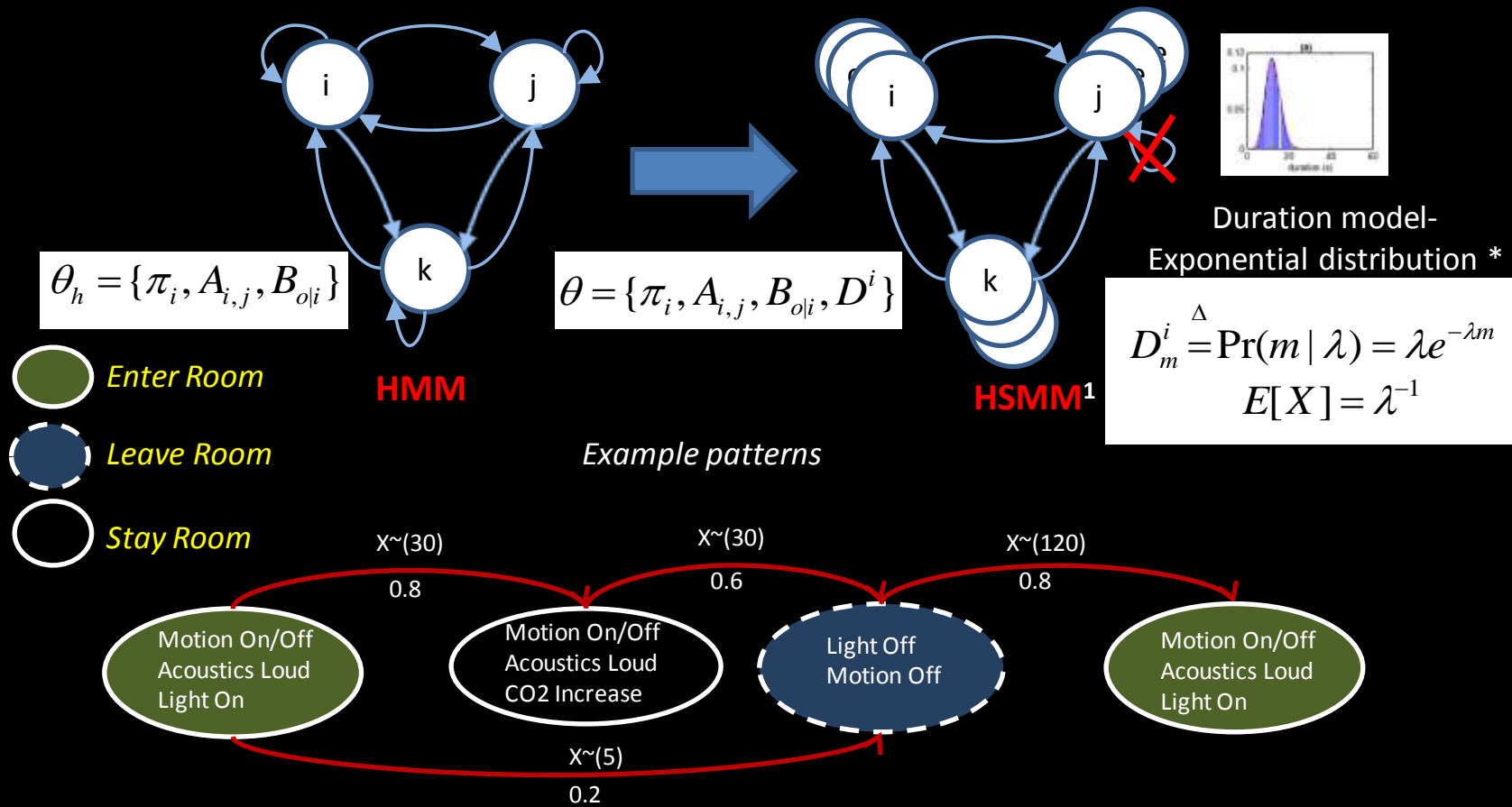


- e: motion off->on
- c: light off->on
- b: acoustics happen
- f: motion on->off
- j: temp decrease



Raw sensor data from June 1st, 2009 to June 22th, 2009

A Generalized Occupancy Model(2)--Occupancy Duration



¹Duong, T.V. Phung, D.Q. Bui, H.H. and Venkatesh, S. Human. 2006. Behaviour Recognition with Generic Exponential Family Duration Modelling in the Hidden Semi-Markov Model. *In Proceedings of the 18th international Conference on Pattern Recognition*. Vol. 3.

Energy and Comfort Management

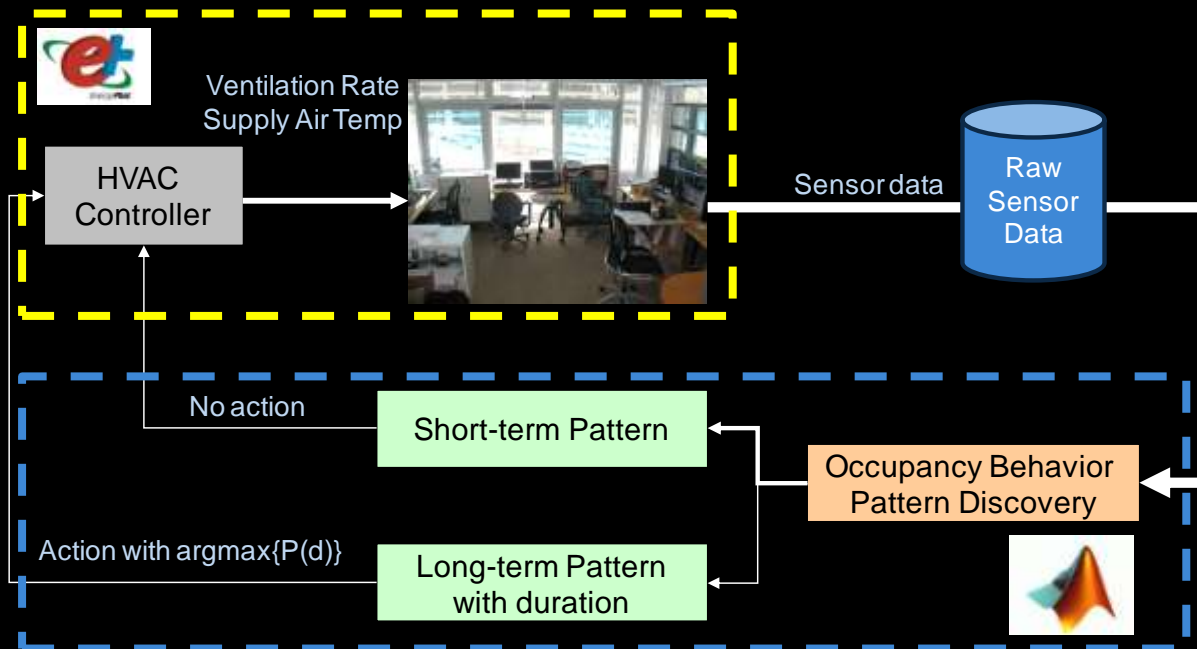
Type of patterns

1. long-term patterns

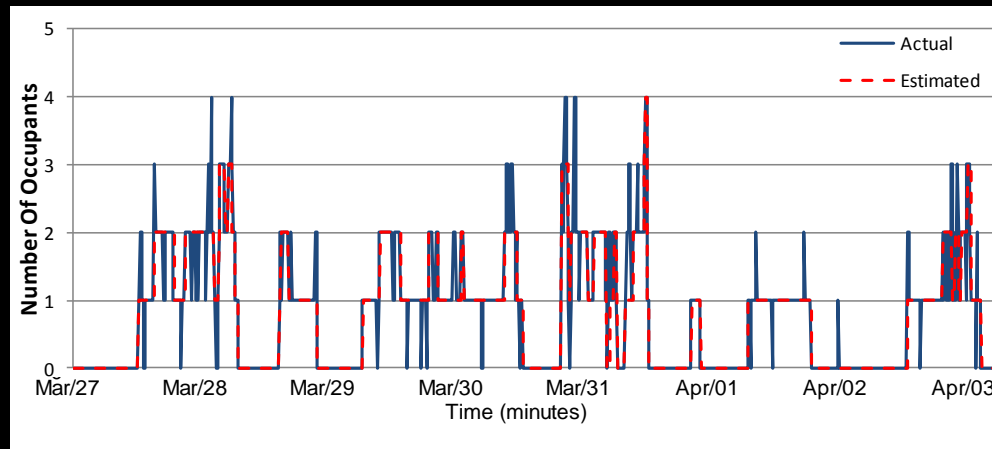
'cfbgefbfeefefefhibgefged' (need n hours to finish)

2. short-term patterns such as 'cedf'.

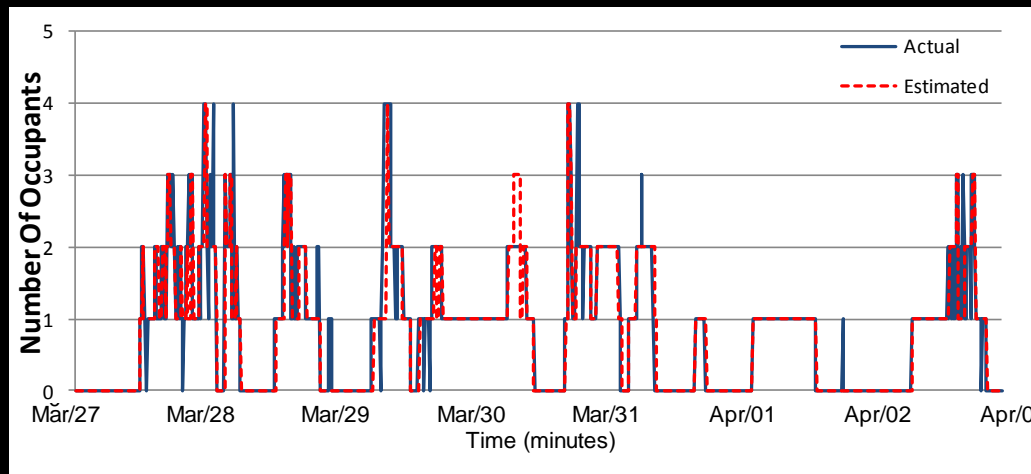
Light on → motion on → light off → motion off (finish in 5 minutes)



Number of Occupants



Occupancy estimation results for Bay 10 from March 27th to April 3rd with GMM-HMM showing 82% accuracy



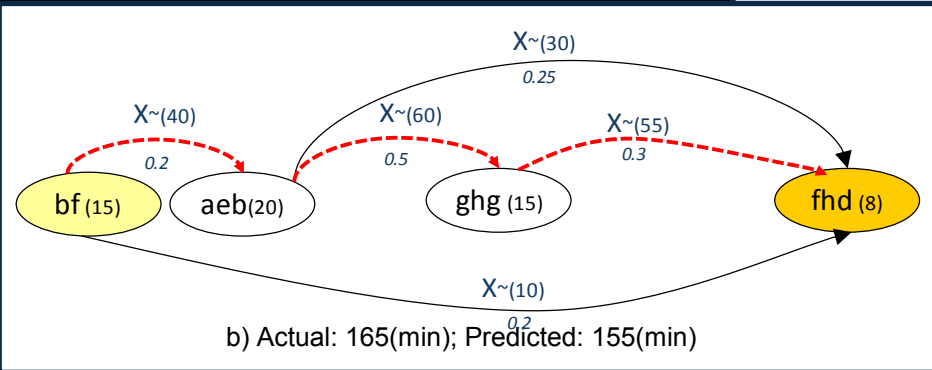
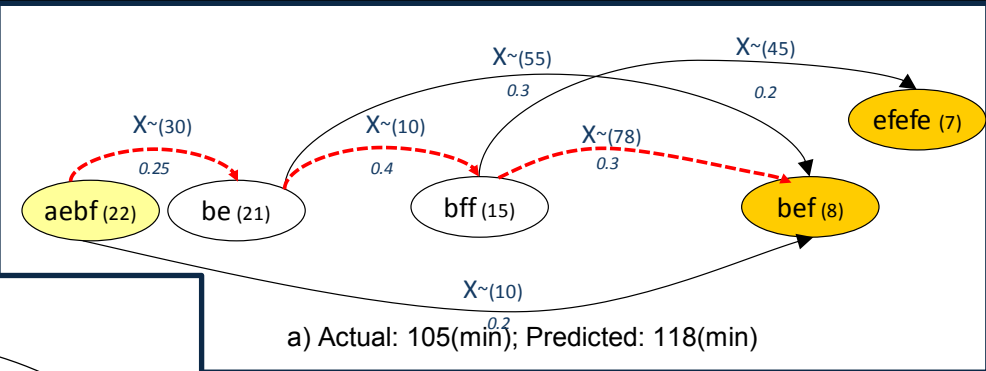
Occupancy estimation results for Bay 13 from March 27th to April 3rd with GMM-HMM showing 85% accuracy

Occupancy Duration

	# of Patterns	Longest Pattern	Most Compressed Pattern	Other Patterns
MDL (Bay 10)	7	begef (12)	aebf (22)	bfe, bff, efefe, bb, ghg
PD (Bay 10)	5	ebbfe(18)	be (51)	gfb, fge, beh
MDL (Bay 13)	9	efefbbe (11)	bf (15)	cef, beg, bbgdf, efef, aa, ghg,gge
PD (Bay 13)	6	bgbefe(12)	aeb (40)	egf, ff, efe, abc, fhd

Discovered patterns on 10 minutes maximal time window in Bay 10

Discovered patterns on 10 minutes maximal time window in Bay 13



E+ Simulation Setup:

- 1) Running period: from March 27th to April 3rd
- 2) Assume a standard VAV system for IW

Control Strategies:

- 1) Cooling set point of 24 °C and heating set point of 22°C from 7:00am to 6:00pm, and night set-backs for cooling of 30°C and heating of 15°C . (Fixed)
- 2) When there is no occupant in the day time, the HVAC set point is set to 27 °C for cooling and 18 °C for heating. (Occupancy-based)
- 3) The zone ventilation rate is designed to be 17 cfm/person (ASHRAE, 2004)

Bay	Fixed Temp. Set-point (kWh)	Occupancy Based (kWh)	Savings (%)	Comfort Not Met (%)
10	64	51	20	14
13	48	40	17	11

Findings

The most important **sensors** for the accurate **occupant behavior pattern** prediction are **CO₂**, **acoustics** and **motion**.

The developed occupant behavior pattern method can achieve 83% accuracy in terms of number of occupants prediction

The maximum observed number of occupants is 4. In case of higher number of occupants, lower prediction accuracy may be expected.

The **energy savings** are mainly from the **dynamic control of HVAC system** based on the real-time occupancy schedules.

The energy savings from this study is based on simulation results with EnergyPlus's "perfect" control. In reality, with a local controller, the temperature responses maybe different and the savings could be affected as well.

Thank you!

