Sentinel: Occupancy Based HVAC Actuation using Existing WiFi Infrastructure within Commercial Buildings

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Occupancy-driven Building HVAC

Office Room

Occupant

Vacant

Occupied

Wi-Fi Client

Access Point

HVAC Control (via BACnet)

HVAC: Heating, Ventilation and Air Conditioning
Outline

• Overview
• Motivation
• WiFi Based Sensing
• Challenges
• Implementation
• Results
• Conclusion
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Why is HVAC Efficiency Important?

US Energy Consumption\(^1\)

- Commercial: 29%
- Residential: 30%
- Industrial: 19%
- Transportation: 22%

Commercial Buildings Energy Breakdown\(^1\)

- Lights: 17%
- HVAC: 40%
- Plug loads: 23%
- Misc: 20%

36% electricity
39% carbon emissions

Occupancy based control of HVAC can provide 15% – 40% energy savings\(^2\)

2. OBSERVE: Occupancy-Based System for Efficient Reduction of HVAC Energy - Erickson et al. IPSN 2011
Occupancy Based HVAC Control

Static Occupancy Schedule

- HVAC ON
- 6:00AM to 10:00PM

Actual Occupancy

- Occupied
- Vacant
- HVAC Zone

- Building partitioned to zones
- Independent control of each zone
- Occupancy can be used to turn off unused zones

Commercial Building

Existing Occupancy Solutions

• Modern buildings use motion sensors
  ➢ Cannot detect stationary occupants²
  ➢ Expensive to install in existing buildings

• Wireless sensors based solutions
  ➢ Use of camera¹ or combination of sensors²
  ➢ Hard to deploy and maintain at scale³

• Leverage existing infrastructure
  ➢ Accurate, scalable
  ➢ Inexpensive, easy to maintain

3. @scale: Insights from a large, long-lived appliance energy WSN. Dawson-Haggerty et al. In IPSN 2012
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WiFi Based Sensing

- Self-calibrated indoor localization not accurate
- More accurate solutions require war driving, complex client apps
- Locate up to 1000 devices in real-time
- Significant energy savings even with coarse grained localization

WiFi Based Sensing

- Assume visitor cannot enter without owner present
- Division of spaces into personal and shared
- Assume person in office whenever within vicinity
- Sacrifice savings when occupant is just outside office

![Diagram showing personal and shared spaces with access points and possible locations marked]
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Partitioning the Building

- Zones may consist of more than one room
- Zones contain both personal and shared spaces
- Some personal spaces converted to shared spaces

**Zone Type** | **Area**  | **Electric Power** |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Personal</td>
<td>37.50%</td>
<td>63.90%</td>
</tr>
<tr>
<td>Shared</td>
<td>58.30%</td>
<td>66.90%</td>
</tr>
</tbody>
</table>

Contribution of each type of space to area and electricity in our building testbed

**Max savings of 33.1%**
Challenges with Using WiFi for Occupancy Sensing

- Occupant does not use WiFi
- Device battery may run out
- Phone forgotten at home
- Need to lend office to visitor

Solution: Provide web based manual HVAC override
Leveraging WiFi Connectivity for Occupancy Sensing

• Assumption: WiFi radio is always connected
• Reality: WiFi radio duty cycled to save power
• Android, Windows Phone: Can change settings
• iPhone: Not possible to change settings
  ➢ Change settings to fetch mail every 15 mins
• May impact battery life
  ➢ Smartphone app for reduced battery impact
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Building Testbed – CSE, UCSD

- Built in 2004, 145,000 sq ft, 5 floors
- HVAC: VAV with reheat coil, 237 zones
- Occupants: Faculty, staff and students
Collecting WiFi Data

- Authentication packets contain:
  - Client MAC, AP MAC, client username

- Book keeping information:
  - Start, stop, hand-off and periodic liveness packets
Acquiring Metadata Information

- Mapping of occupant offices from HR manager
- Office Room
- Location of AP from network manager
- Identify smartphone from hand-offs
- Connectivity info from WiFi logs
- User identity from WiFi logs
- WiFi Devices
- Occupant

Access Point
Occupancy Based HVAC Control

• Three modes of operation in each zone
• Occupied (Weekdays 6am – 6pm)
  ➢ Adequate ventilation, 4°F band (e.g. 70°F – 74°F)
• Standby (Weekdays 6pm – 10pm)
  ➢ Minimum ventilation, 8°F band (e.g. 68°F – 76°F)
• Unoccupied (Nights & Weekends)
  ➢ Minimum ventilation, 12°F band (e.g. 66°F – 78°F)
• When we turn “Off” HVAC, we go into Standby mode
HVAC Working & Savings

- Electrical power is cubic proportional to occupancy
- Only essential ventilation at 0% occupancy

AHU: Air Handler Unit
VAV: Variable Air Volume

CENTRAL PLANT SUPPLIES
HOT AND COLD WATER

HOT WATER PIPE

% HVAC Electrical Power

% Occupancy
Sentinel: Overall Architecture

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Results – User Study

• Survey of 187 out of 415 building occupants
• 61% users always connected to WiFi
• Reasons for not using WiFi:
  ➢ Poor WiFi coverage
  ➢ Good cellular data plan
  ➢ Device connectivity problems with WPA2

![Bar graph showing the number of people using different devices and connectivity features.](image)
Results – Accuracy

- 116 occupants, 10 days, 436 events
- Ground truth collected manually
- 86% accuracy, 6.2% false negatives

Occupancy Trends Across a Week for 38 Participants

March 18 – 24, 2013
Results – Energy Savings

- Control of 55 out of 237 HVAC zones for 1 day
- 17.8% HVAC electrical energy savings
Conclusion

• Occupancy information is crucial to effective use of HVAC in commercial buildings.
• It is possible to use existing WiFi infrastructure for occupancy detection in building spaces.
• Our occupancy model applies to personal spaces. Shared spaces are currently not subject to HVAC control.
• 86% detection accuracy using WiFi, 6.2% false negatives
  ➢ WiFi connectivity issues lead to inaccuracies
• 23% of building area controlled using Sentinel
  ➢ 17.8% HVAC electrical energy savings for 1 day
Thank You!

Questions?

Acknowledgements:
Thomas Weng, Hidetoshi Teraoka, Du Li, UCSD Facilities Management, UCSD Academic Computing Services, Anonymous reviewers
Extra Slides
Detailed Error Analysis

- False Negative
  - Unknown
  - System Error
  - people Error
  - Zone of Detection
  - Incorrect Device
  - Device Error
  - iOS Stop
  - iOS Start

- False Positive
Domestic Water Heat Exchanger

HVAC Heat Exchanger

Air Mixer

Cooling Coil

CRAC

HOT WATER SUPPLY*

HOT WATER RETURN*

COLD WATER SUPPLY*

COLD WATER RETURN*

Supply Air

Return Air

Supply FAN

RETURN FAN

*CENTRAL PLANT SUPPLIES HOT AND COLD WATER
Impact on Battery Life

3 day usage study across 20 smartphone users