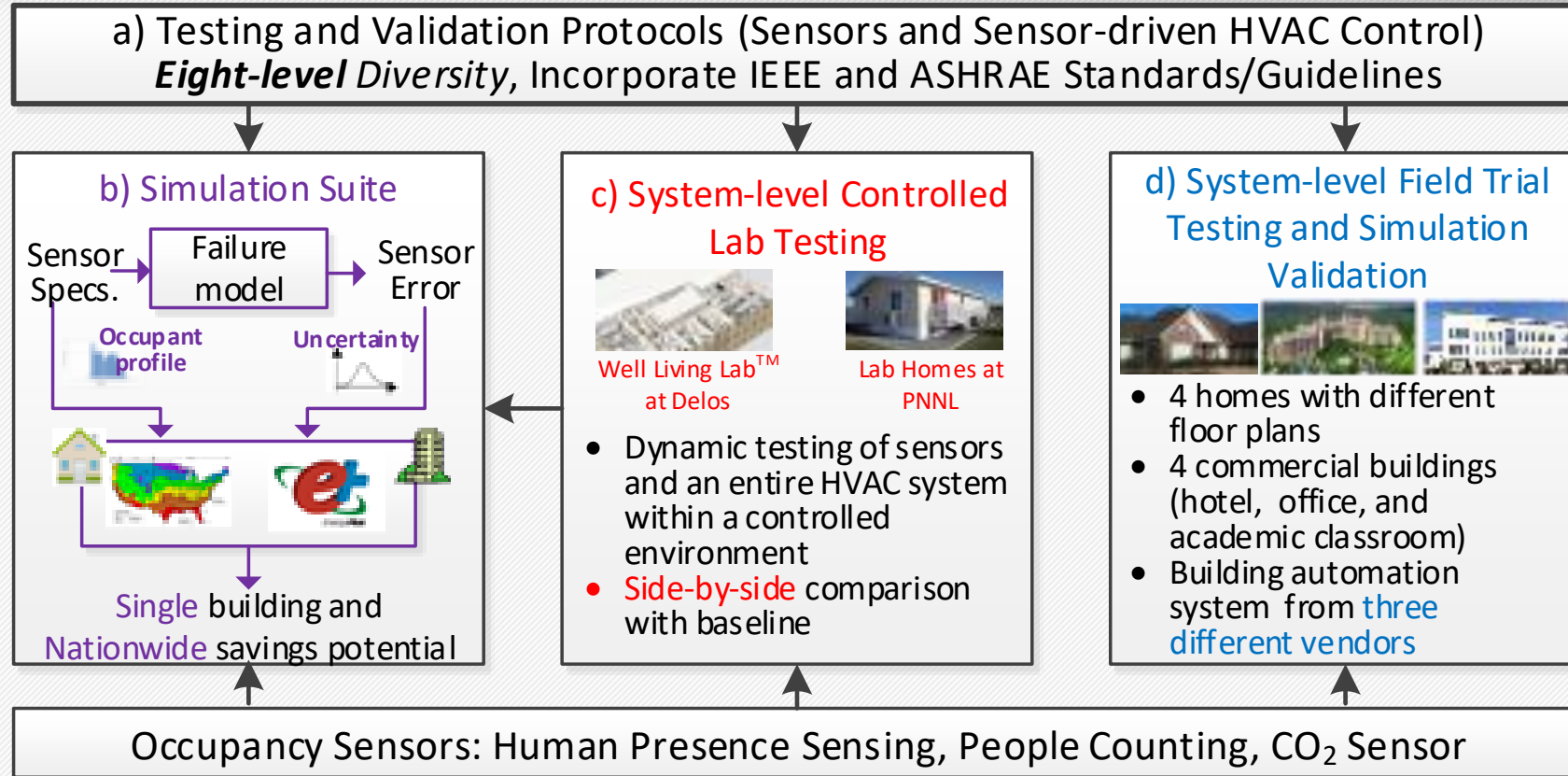# Quantification of HVAC Energy Savings for Occupancy Sensing in Buildings through an Innovative Testing Methodology

Zheng O'Neill, PhD, PE
The University of Alabama, Tuscaloosa, AL
November 9th 2018

SBIoT Workshop, November 9th, Omaha, NE

Outline

- Introduction and Overview
- Methodology
- Preliminary Results
- Ongoing and Future work: Community Engagement

Overview of the Proposed Work

a) Testing and Validation Protocols (Sensors and Sensor-driven HVAC Control) **Eight-level** *Diversity*, Incorporate IEEE and ASHRAE Standards/Guidelines

b) Simulation Suite

Sensor Specs.

Failure model

Sensor Error

Occupant profile

Uncertainty

Single building and Nationwide savings potential

c) System-level Controlled Lab Testing

Well Living Lab[TM] at Delos

Lab Homes at PNNL

- Dynamic testing of sensors and an entire HVAC system within a controlled environment
- Side-by-side comparison with baseline

d) System-level Field Trial Testing and Simulation Validation

- 4 homes with different floor plans
- 4 commercial buildings (hotel, office, and academic classroom)
- Building automation system from three different vendors

Occupancy Sensors: Human Presence Sensing, People Counting, CO_2 Sensor

- A novel protocol with an eight-level diversity and a simulation suite to investigate various types of occupancy sensors for detection failure rates and energy saving potentials in real-world retrofit scenarios
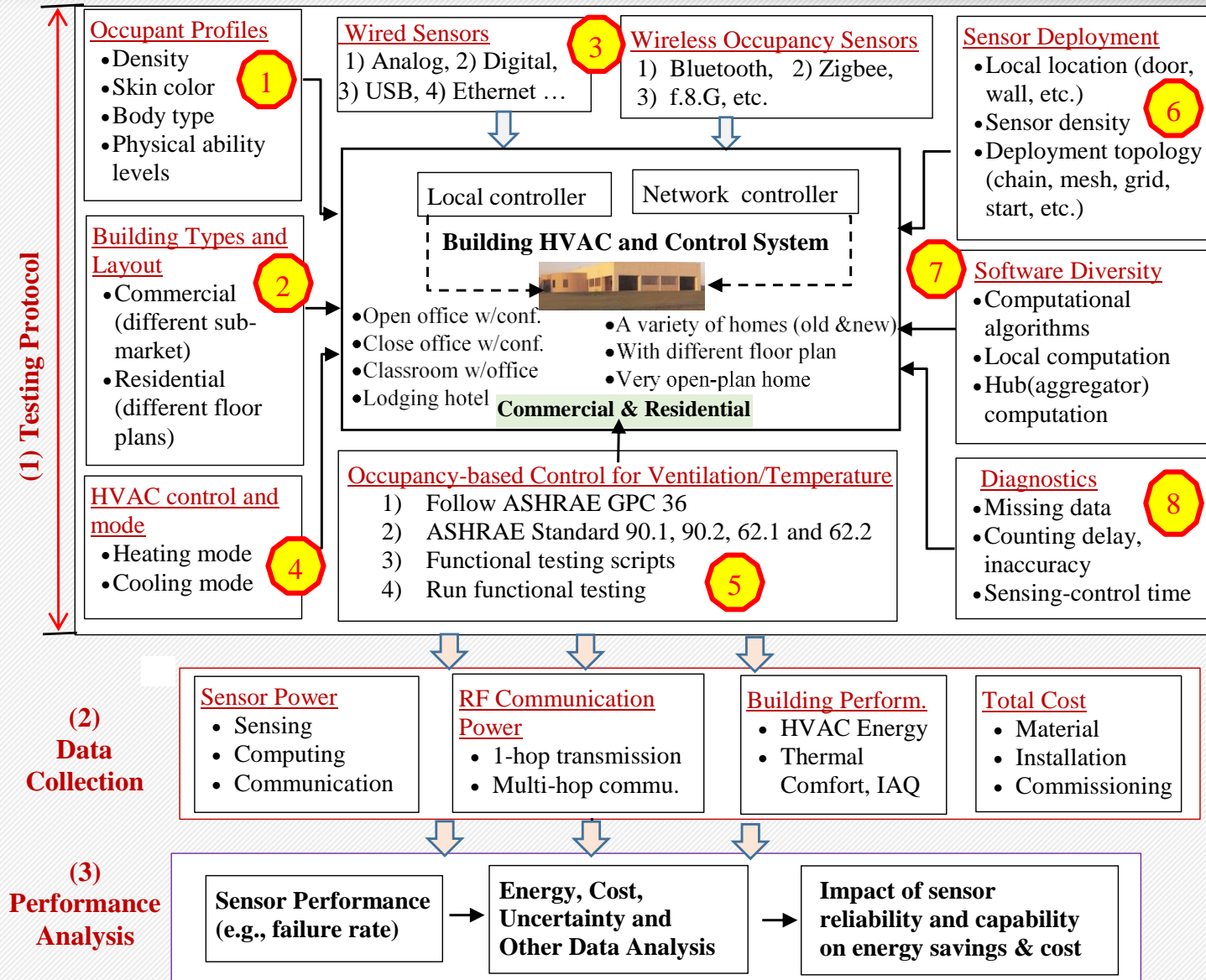- Controlled lab testing and system-level field testing

Challenges and Novelty of the Work

Testing and Validation **Challenges**: Complexity and uncertainty due to diversity of types of occupant sensors, deployment topologies, software, installations, and HAVC control strategies
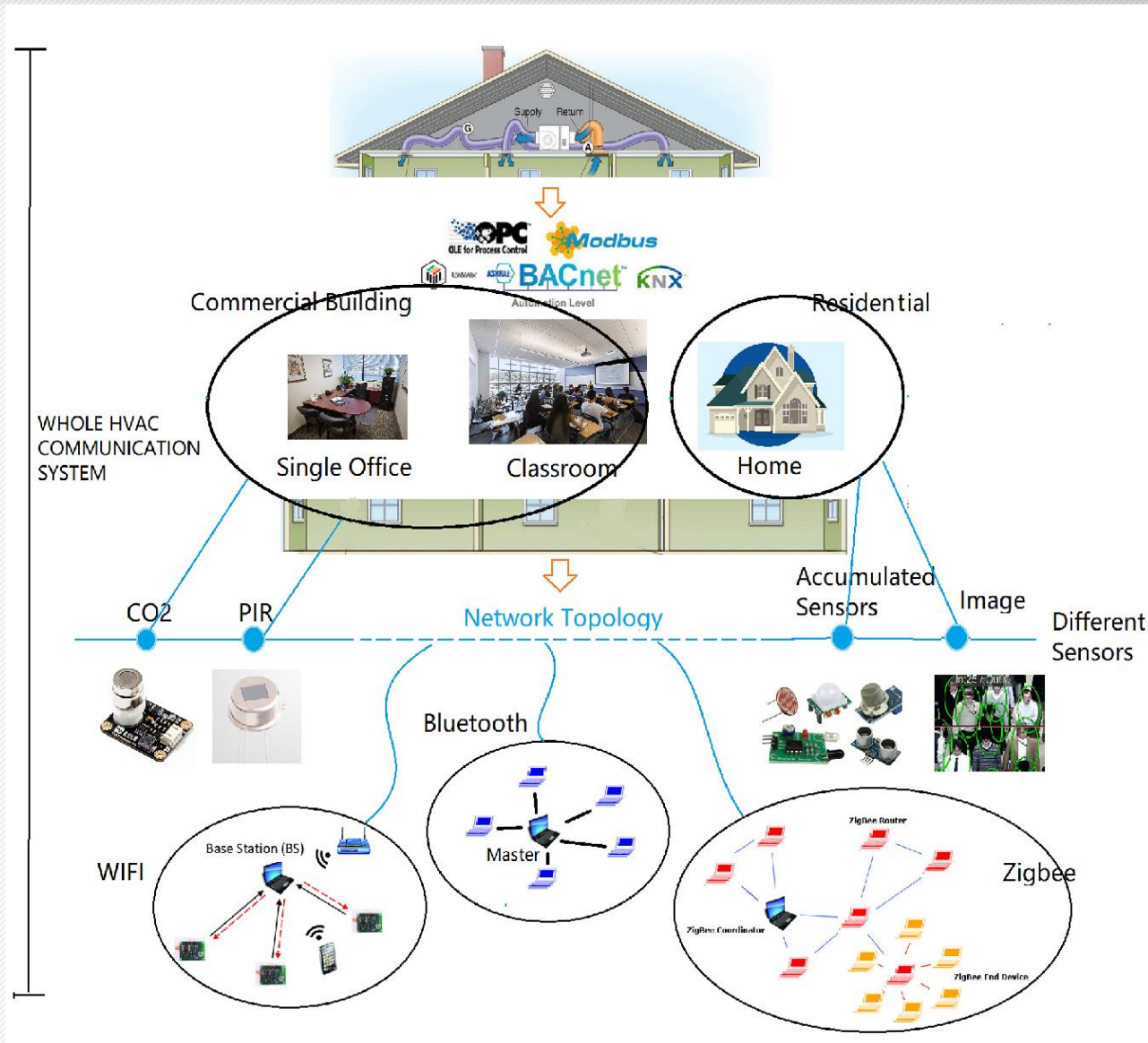
Novelty:

- Testing protocol with eight-level diversity
  - ➤ 1) occupant profile diversity, 2) building type and floor plan diversity, 3) sensor diversity, 4) HVAC controls and mode diversity, 5) Functional testing diversity, 6) deployment location diversity, 7) software diversity, and 8) diagnostic diversity

- Simulation suite with uncertainty quantifications of sensor errors

- Integration with Well Building Standard concept

- Testing data analytics with advanced Machine Learning algorithms

- Market transition through proactive engagements with HVAC standards committees, control consulting and building automation companies

a. Testing Protocol with Eight-level Diversity

(1) Testing Protocol

Occupant Profiles ①
- Density
- Skin color
- Body type
- Physical ability levels

Wired Sensors
1) Analog, 2) Digital,
3) USB, 4) Ethernet …

③ **Wireless Occupancy Sensors**
1) Bluetooth, 2) Zigbee,
3) f.8.G, etc.

Sensor Deployment ⑥
- Local location (door, wall, etc.)
- Sensor density
- Deployment topology (chain, mesh, grid, start, etc.)

Building Types and Layout ②
- Commercial (different sub-market)
- Residential (different floor plans)

Local controller   Network controller

Building HVAC and Control System

- Open office w/conf.
- Close office w/conf.
- Classroom w/office
- Lodging hotel

- A variety of homes (old &new)
- With different floor plan
- Very open-plan home

Commercial & Residential

⑦ **Software Diversity**
- Computational algorithms
- Local computation
- Hub(aggregator) computation

HVAC control and mode ④
- Heating mode
- Cooling mode

Occupancy-based Control for Ventilation/Temperature
1) Follow ASHRAE GPC 36
2) ASHRAE Standard 90.1, 90.2, 62.1 and 62.2
3) Functional testing scripts
4) Run functional testing ⑤

Diagnostics ⑧
- Missing data
- Counting delay, inaccuracy
- Sensing-control time

(2) Data Collection

Sensor Power
- Sensing
- Computing
- Communication

RF Communication Power
- 1-hop transmission
- Multi-hop commu.

Building Perform.
- HVAC Energy
- Thermal Comfort, IAQ

Total Cost
- Material
- Installation
- Commissioning

(3) Performance Analysis

Sensor Performance (e.g., failure rate) → **Energy, Cost, Uncertainty and Other Data Analysis** → **Impact of sensor reliability and capability on energy savings & cost**

5

Sensor Integration with Building Automation System

- Sensor communication with Building automation system
  - BACnet gate way
  - Lonworks, Modbus
  - Wired sensors vs. wireless sensors
- Volttron
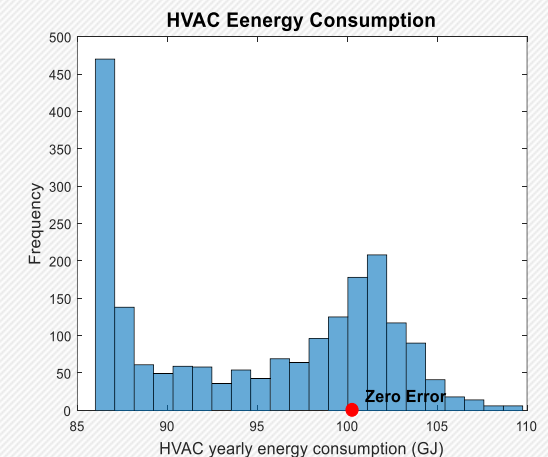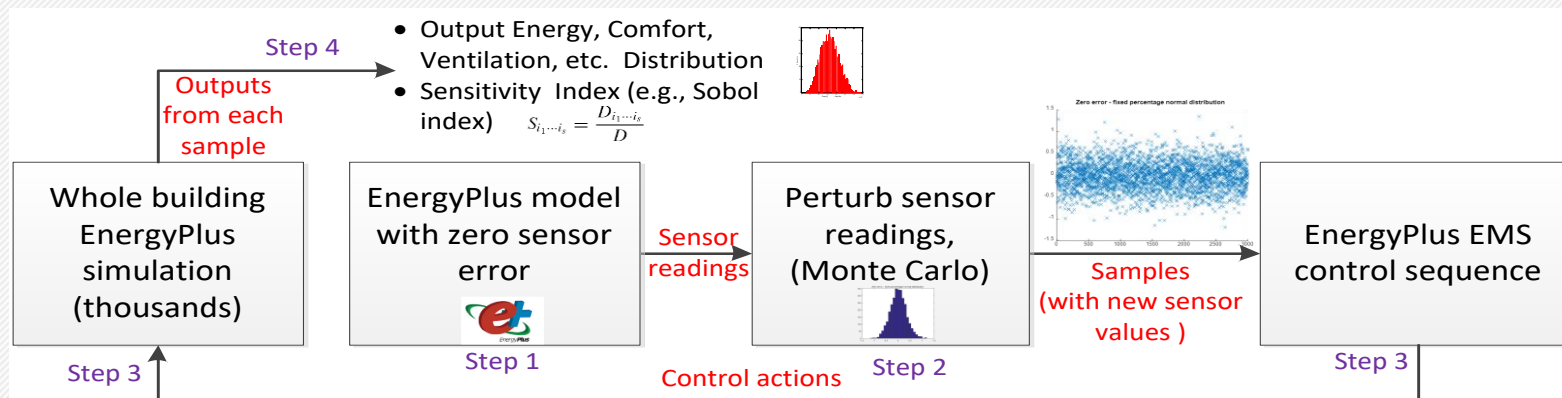- sMAP (Simple Measurement and Actuation Profile)

Use EnergyPlus EMS module to simulate controls and sensor faults

Medium Office

Large Office

Large Hotel

Primary School

Single family home
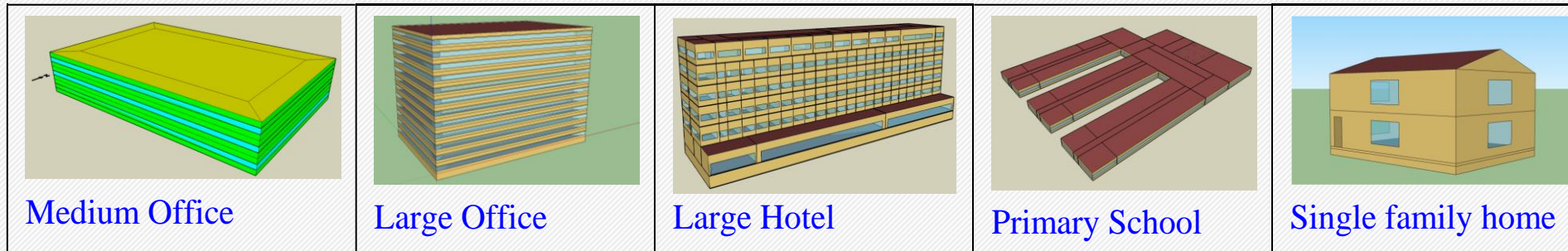
- 16 climate zones
- Nationwide energy savings

Scenarios	Ideal impact with ground truth sensed (zero sensor error)	Impact with deterministic sensor error	Impact with stochastic sensor error

- Output Energy, Comfort, Ventilation, etc. Distribution
- Sensitivity Index (e.g., Sobol index) $S_{i_1 \cdots i_s} = \frac{D_{i_1 \cdots i_s}}{D}$

Step 4

Outputs from each sample

Whole building EnergyPlus simulation (thousands)

EnergyPlus model with zero sensor error

Sensor readings

Perturb sensor readings, (Monte Carlo)

Samples (with new sensor values)

EnergyPlus EMS control sequence

Step 3

Step 1

Control actions

Step 2

Step 3

HVAC Eenergy Consumption

Zero Error

HVAC yearly energy consumption (GJ)

Frequency

7

Sensor Error Analysis – Testing Methodology

- ASHRAE GPC 36 (RP-1747) CO_2 based demand control ventilation
- Comply with ASHRAE 62.1
- Dynamic reset zone level ventilation rate
- Coordinate the zone level and the AHU economizer controls
- Implementable on the DDC system
  - Trim & Response
  - No iterations
- Field demonstrations

Zone CO_2 sensor

Zone supply air CO_2 sensor

Zone supply air flow sensor

$$V_{bz} = MIN\left(P_z R_p + A_z R_a \left| \frac{\max[0, (C_{bz} - C_{sz})] E_z V_{pz} R_p}{km} + A_z R_a \right.\right)$$

$$Zone_{co2} = Zone_{co2\_accurate} + CO2_{bias}$$

$$Zone_{airflow} = Zone_{airflow\_accurate} \times [1 + bias\%]$$

- Zone air CO2 concentration bias with $(\mu, \sigma) = (0, 100)$ ppm
- Air flow rate bias with $(\mu, \sigma) = (0, 0.333)$

Interior-B CO2 Concentration Bias/ppm

East-A SA Flow Rate Percentage Bias/100

HVAC Eenergy Consumption

OAR

OAR is the ratio of the actual outside air flow (Voa) to the required ventilation rate (Vot)

- Energy Resource Station at Iowa Energy Center
- 8 Test rooms
- 2 VAV AHUs
- 8 VAV terminal VAV box
- Dynamic occupancy schedule
- 2,000 samples (i.e., 2,000 E+ simulations)
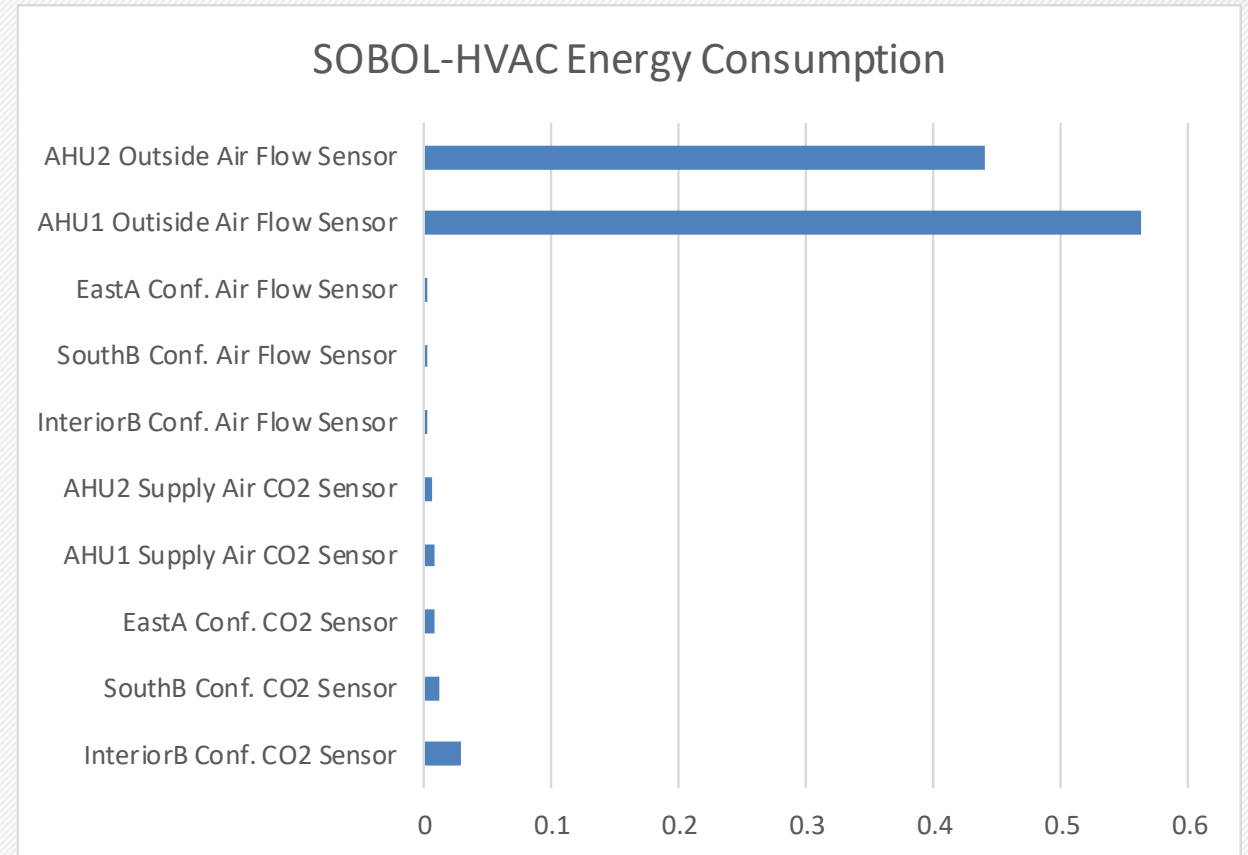- Errors from 10 sensors (perturbed at the same time)
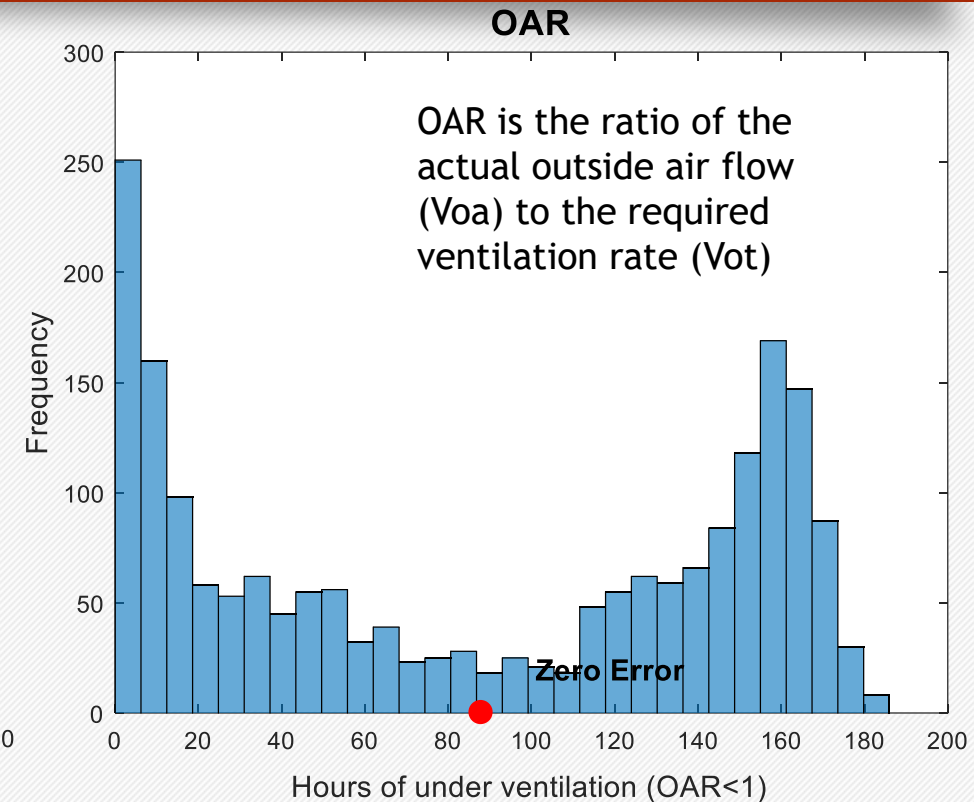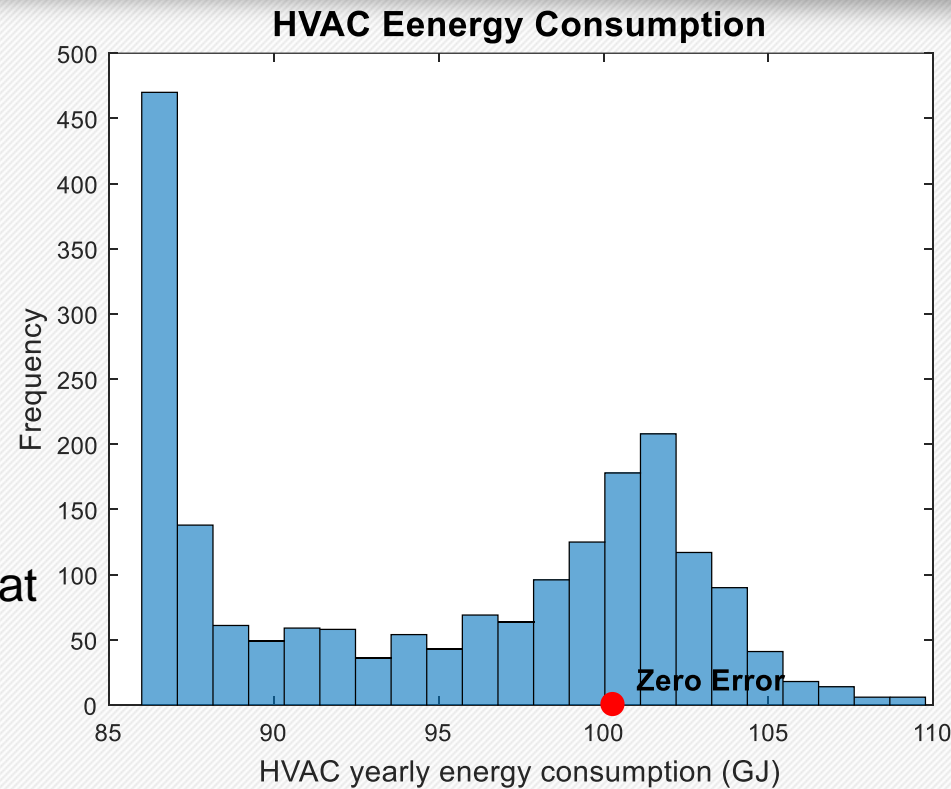
- Red dot is the case without sensor errors
- Distributions have 2 modes
  - ➢ Nonlinearities in EnergyPlus
  - ➢ Proposed DCV sequences include limits to protect against impacts of sensor error (e.g. Vot<=design Vot)

Sensor Error Analysis – Preliminary Results (2)

Sensor Error Impacts on HVAC Energy Consumption

- 10 sensors
  - 3 zone CO_2 sensors
  - 2 AHU supply air CO_2 sensors
  - 2 AHU outside air flow sensors
 - 3 zone supply air flow sensors

SOBOL-HVAC Energy Consumption

Sensor	Value
AHU2 Outside Air Flow Sensor	~0.44
AHU1 Outiside Air Flow Sensor	~0.57
EastA Conf. Air Flow Sensor	~0.005
SouthB Conf. Air Flow Sensor	~0.005
InteriorB Conf. Air Flow Sensor	~0.005
AHU2 Supply Air CO2 Sensor	~0.006
AHU1 Supply Air CO2 Sensor	~0.008
EastA Conf. CO2 Sensor	~0.007
SouthB Conf. CO2 Sensor	~0.012
InteriorB Conf. CO2 Sensor	~0.028

Axis: 0 0.1 0.2 0.3 0.4 0.5 0.6

- AHU1 OA flow sensor has the largest impact on HVAC energy consumption
- AHU2 OA flow sensor has the second largest impact
- Zone CO_2 sensors and AHU supply air CO_2 sensors have smaller impacts
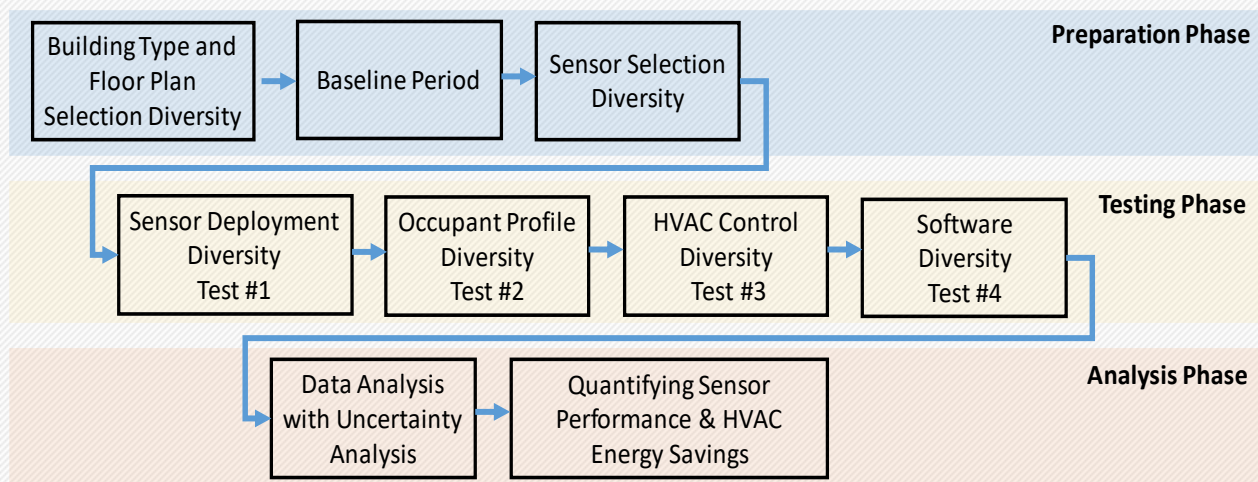
Sensor Error Impacts on Ventilation Performance

- CO_2 sensor accuracy has more influence on the ventilation performance compared with air flow sensor accuracy
- Ongoing study with more building types and more climate zones

SOBOL-Hours of Under-ventilated

- AHU supply air CO_2 sensors have the largest influence on ventilation performance, while other CO_2 sensors at the zone level have relatively large impacts as well
- The impact from flow sensors is relatively small
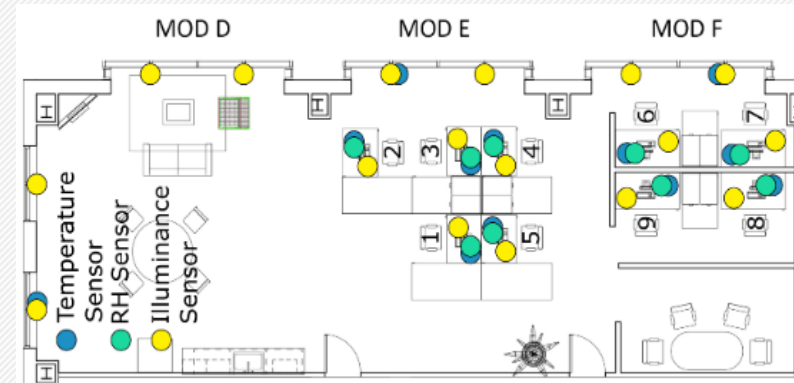
11
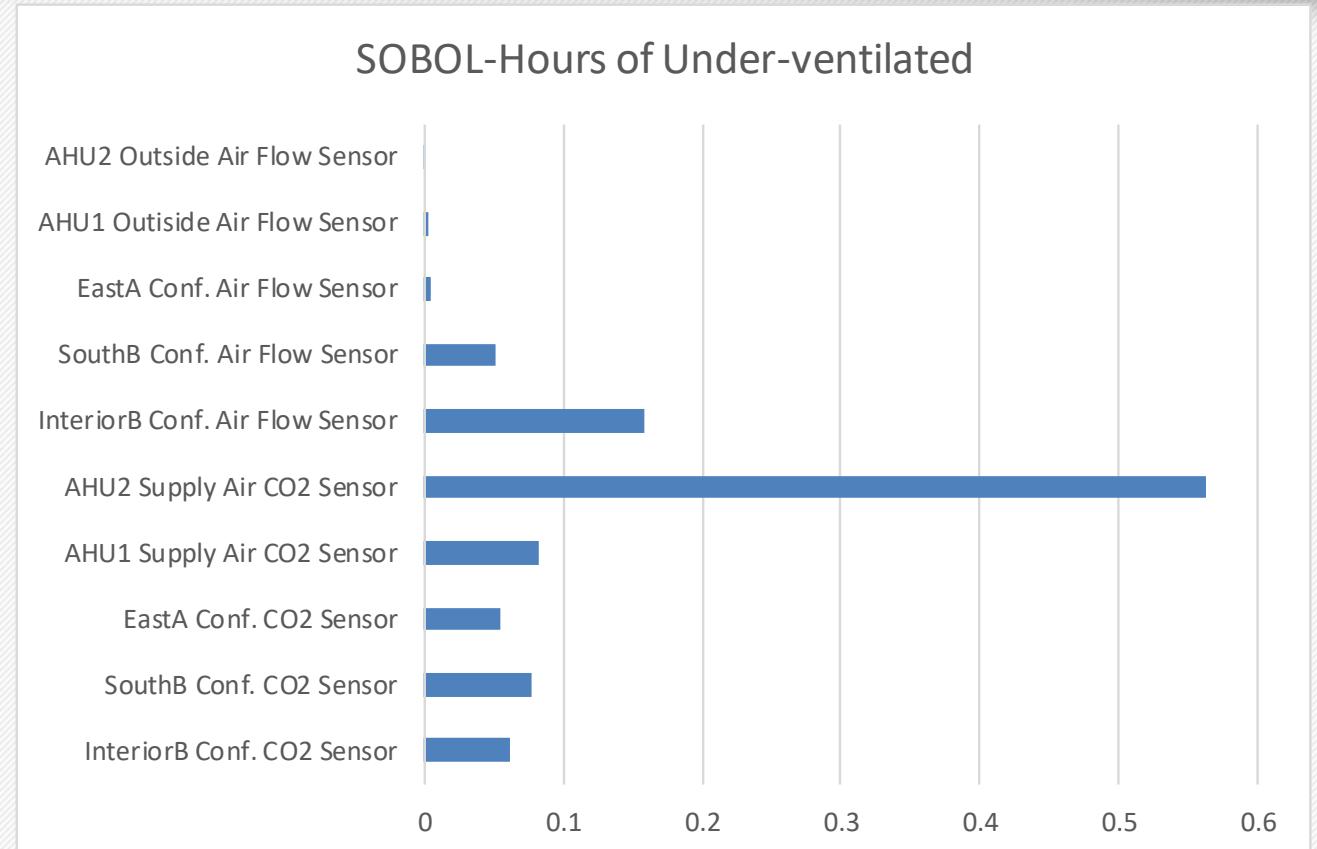
c. System Level Controlled Lab Testing (1)

- PNNL will host system level controlled lab testing for residential building setting
  - PNNL's Lab home
  - Two identical 1,500 ft^2 all-electric 3 BR/2BA homes
  - Both homes contain full end-use metering, a suite of environmental sensors, and remote data collection

| | Preparation Phase |
| Building Type and Floor Plan Selection Diversity → Baseline Period → Sensor Selection Diversity | |

| | Testing Phase |
| Sensor Deployment Diversity Test #1 → Occupant Profile Diversity Test #2 → HVAC Control Diversity Test #3 → Software Diversity Test #4 | |

| | Analysis Phase |
| Data Analysis with Uncertainty Analysis → Quantifying Sensor Performance & HVAC Energy Savings | |

c. System Level Controlled Lab Testing (2)

- Well Living Lab (WLL) - the first scientific research center exclusively committed for **human-centered** research to understand human-building interactions.
  - State-of-the-art IoT and BMS system and sensor network
  - Comprehensive monitoring for real-time operational and environmental information
  - Enhanced environment and system control capabilities
  - Exceptional reconfigurability, flexibility and adaptability
- WLL will host a system-level controlled lab testing with commercial building settings
  - Configure three modules with office settings to host the dynamic testing for the proposed occupancy-driven HVAC control

d. System Level Field Trial Testing

- Control logics will follow ASHRAE GPC 36 in at least one commercial building
- Measurement & verification will follow ASHRAE Standards & Guideline (e.g., Guideline 14)

Building	Building Characteristics	Scope of Test Plan
Tuscaloosa City Hall Complex, Tuscaloosa, AL	Office building in climate zone 3A; Floor plan: open office with conference room, close offices with conference room; Control: WebCTRL	2nd floor with 27 VAV boxes served by one AHU
South Engineering Research Center Building, Tuscaloosa, AL	Academic building in climate zone 3A; Floor plan: classroom with office rooms; Control: Schneider Electric	Classrooms and offices served by two AHUs on the 2nd floor
Marriott Residence Inn on Riverwalk, San Antonio, TX	A hotel building in climate zone 2A; Floor plan: hotel rooms with public space; Control: WebCTRL	Public space with six rooftop units
Applied Engineering and Technology Building, San Antonio, TX	Academic building in climate zone 2A; Floor plan: classroom with office ; Control: Siemens	Ground floor with 20+ mixed class rooms and offices
2 residential houses in Tuscaloosa, AL	Residential home built in 1970 and 2010 (modern open floor plan)	4 bedroom single family house
2 residential houses in San Antonio, TX	Residential home built in 1940 and 2000 (modern open floor plan)	3 and 2 bedroom single family house

Ongoing and Future Work: Community Engagement

- Alignment of protocols with market needs
  - ➤ Engage with other ARPA-E SENSOR teams and other research teams
  - ➤ Identify applicable associations
  - ➤ Engage with key stakeholders with competitive landscape & strengths
  - ➤ Adapt energy models to include financial considerations

- Codes and standards development plan
  - ➤ Sensor and system requirements related to advanced occupancy-based controls
  - ➤ ASHRAE standards 90.1, 62.1
  - ➤ **Start to initiate the new ASHRAE standard/guideline***
  - ➤ Organize annual workshop
    - ▪ **Concurrent with ASHRAE annual meeting in Kansas City (June 2018)***

- Project industry advisory board
  - ➤ Siemens, UTC/ALC, JCI…
  - ➤ PNNL, ORNL…
  - ➤ Recruit more members

* With Dr. Kristen Cetin at Iowa State University

Thank You! Questions and Discussions

Zheng O'Neill, PhD, PE
Associate Professor
Department of Mechanical Engineering
Department of Civil, Construction and Environmental Engineering
The University of Alabama
Box 870276
Tuscaloosa, AL 35487-0276 USA
Ph: (205) 348-6982 | Fax: (205) 348-6419
Email: ZONeill@eng.ua.edu
http://hvac.ua.edu/