Building Sensors and Energy Monitoring Systems

William Healy
National Institute of Standards and Technology
Gaithersburg, MD USA

Building America Meeting on Diagnostic Measurement and Performance Feedback for Residential Space Conditioning Equipment

April 26, 2010

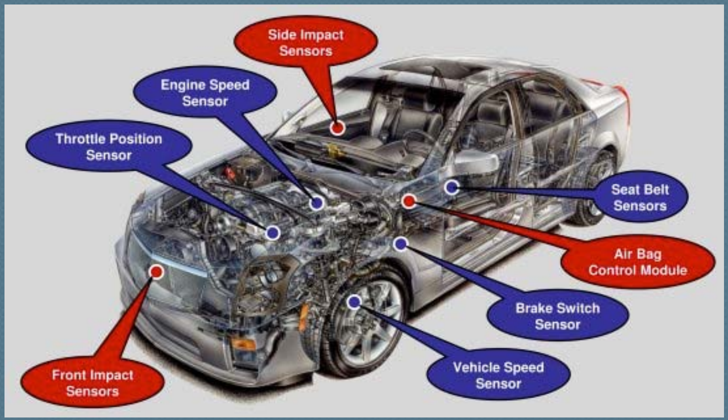
Overview

- Sensors for Building Applications
  - Current Status
  - Key Challenges
- Energy Monitoring Systems in Homes

Cars vs. Buildings

TYPICAL NEW CARS

- 40-50 sensors per car
- Wide range of types
  - Temperatures
  - Pressure sensors
  - Accelerometers
  - Oxygen
  - Fluid level
  - Proximity



TYPICAL BUILDINGS

- Residential
  - Thermostat
  - Electric meter
  - Gas meter
  - Water meter
  - Smoke sensors
  - CO sensors
  - Others embedded in equipment
- Commercial (in addition to those seen in residential apps)
  - RH
  - Occupancy
  - Light
  - CO_2

Cars vs. Buildings (cont.)

- Buildings do contain a large number of sensors
- Many sensors in buildings are contained within equipment and inaccessible outside that equipment
- Pace of change much slower in types and number of sensors included in buildings compared to automobiles
  - 30 years ago, typical automobile had 5 sensors
  - Were the amount and types of sensors used 30 years ago in buildings drastically different?

Bottom Line – There are still many places where improved sensing could be valuable in buildings

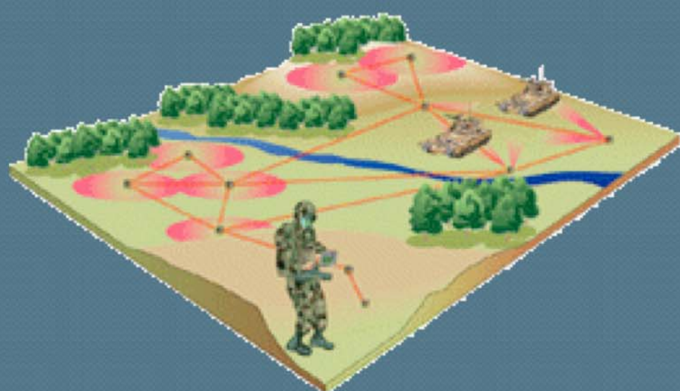
"Smart Systems" in Homes

- From Wikipedia:
  "Smart Systems typically consist of diverse components, such as:
  1. sensors for signal acquisition
  2. elements transmitting the information to the command and control unit
  3. command and control units that make decisions and give instructions based on the available information
  4. components transmitting decisions and instructions
  5. actuators that perform or trigger the required actions"

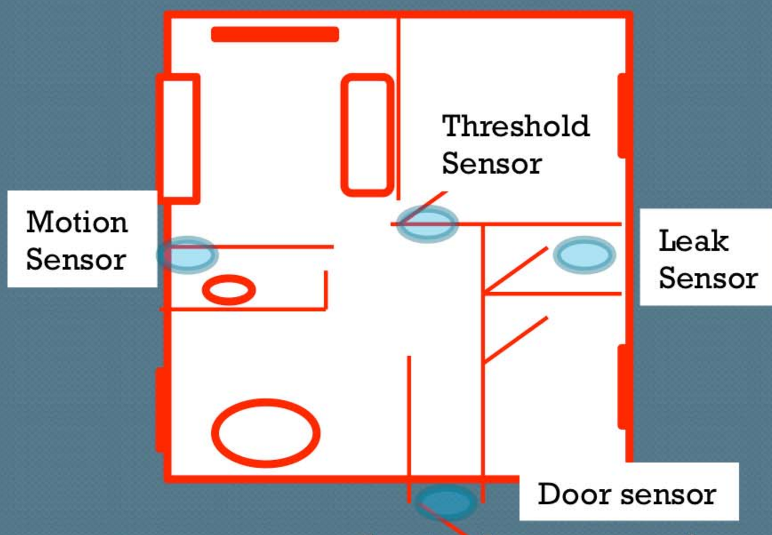
Ubiquitous Sensing

- Sensing everything, everywhere
- Real-time
- Two areas of significant interest:

Military



Home Care



Certainly, the concept raises privacy concerns … but where can improved sensor technology play a role in achieving smart buildings?

Role of Sensors in Buildings

- A prerequisite to a smart building
- Ubiquitous sensing could enhance smart building operations by:

Providing finer spatial resolution of measurements

Sensing new physical quantities to improve occupant comfort and reduce energy consumption

Enabling monitoring of more building equipment

Challenge 1: Development of New Types of Sensors

- Low cost is key
- MEMS advancements and other micro- and nano-scale research could lead to novel sensing technology
- Move from

Sensor → **Data**

To….

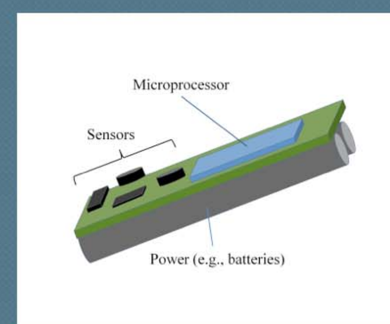
"Smart" Sensor → **Information**

Characteristics of Smart Sensors

-- on board microprocessing

-- data analysis before data transmission

-- combining raw data from multiple sensors to develop higher level information at sensor node



Improved Sensors

- Examples of types of sensors either needed or in need of improvements for building applications
  - Low-cost electric power meters
  - Low-cost and easy-to-install gas flow meters
  - Low-cost and easy-to-install water flow meters
  - Ventilation sensors (e.g., air flow rates)
  - Indoor Air Quality sensors (e.g., VOC's, particulates)
  - Reliable occupancy sensors
  - Light sensors (e.g., intensity & color)
  - Thermal comfort

Sensors for Diagnostics of Residential Space Conditioning Equipment

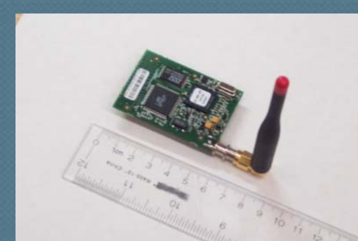
- **How are we doing?**
  - Are accuracies of sensors sufficient?
    - Temperature
    - RH
    - Pressure
    - Power
  - Are new sensors needed?
  - Are any new features needed for those sensors that already exist?

Challenge 2: Integration

- Sensors must be easily installed in a building and must easily integrate into a building monitoring and/or control system
  - Easy, low-cost, and fast physical installation
  - Little expert knowledge required to activate sensor
  - Little expert knowledge required to include and make use of data in monitoring system

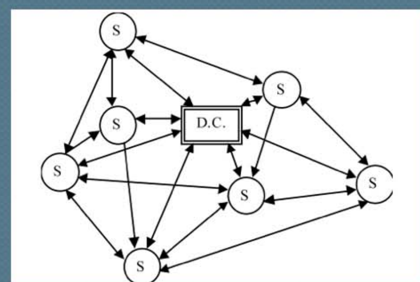
Wireless: Easing Installation

- Wireless
  - Eliminates wiring costs
  - Eliminates intrusion of wiring
  - Increases initial cost of equipment
    - On-board radio, antenna
    - Software to manage wireless data transmissions on board sensor node
  - Many commercial products have emerged over the last 5 years.



Wireless

- Enabling Advancements



Standards

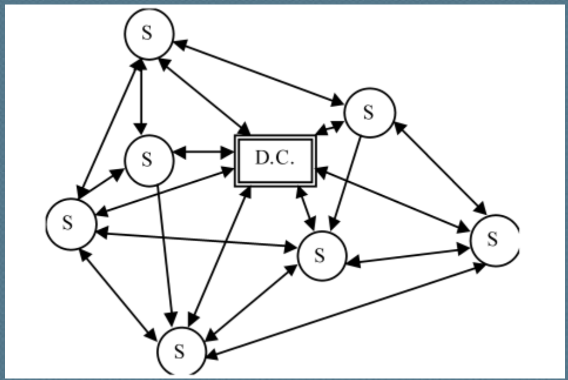
Small, low power
Radio hardware

Networking Algorithms
Mesh Networking

- IEEE 802.15: Radios for low-power communications
- ZigBee, EnOcean, etc.
- BACnet + wireless

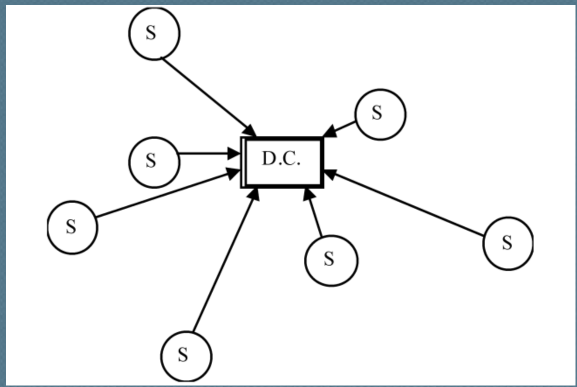
Networking Options

MESH NETWORKS



- Internet Model
- Multiple paths from sensor to data collector
- Expandable
- Ad-hoc networks can be self-healing
- Disadvantages:
  - More complex software
  - More data transmissions by intermediate nodes leads to shorter battery life

STAR NETWORKS



- Point-to-point communications
- Simpler system
- More predictable power requirements
- Disadvantages:
  - Prone to disruption from single points of failure
  - Limited range

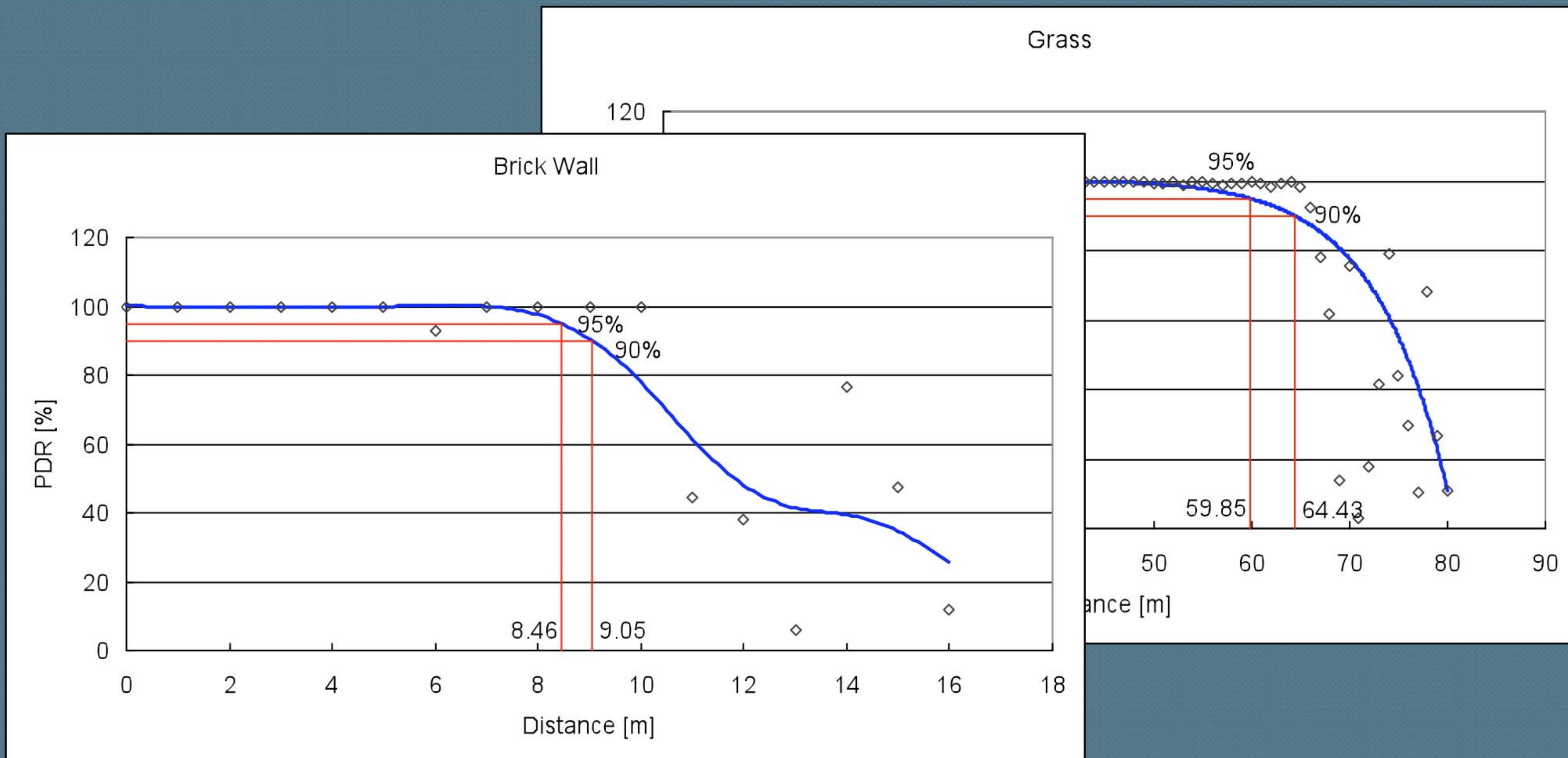
Protocol Options

Application	Key Design Issues	Protocols
Telephones	Quality of Service, Latency	CDMA2000
Internet	Bandwidth	IEEE 802.11 (WiFi™) IEEE 802.16 (WiMAX)
Peripherals	Bandwidth	IEEE 802.15.1 (Bluetooth™) Wireless USB
Sensors	Power	IEEE 802.15.4 (ZigBee©) EnOcean©

Wireless Issues

- Still need cost reductions
- Reliability concerns
  - Buildings present challenging environment
  - Interference
    - Most hardware uses same open spectrum used by wireless internet, cordless phones, and other consumer products
- Power management
- Interoperability
- Ease-of-use and maintenance
- Security

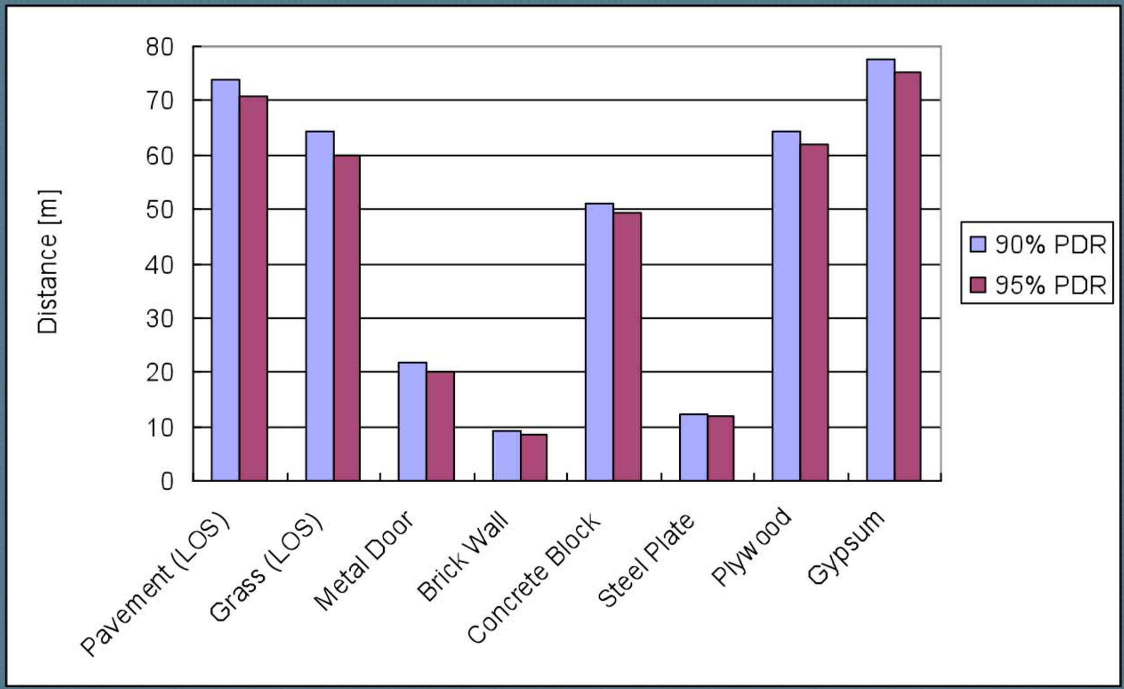
Reliability – Distance Effects



PDR: Packet Delivery Rate = $\frac{\#\ of\ successful\ transmissions}{total\ \#\ of\ transmissions}$

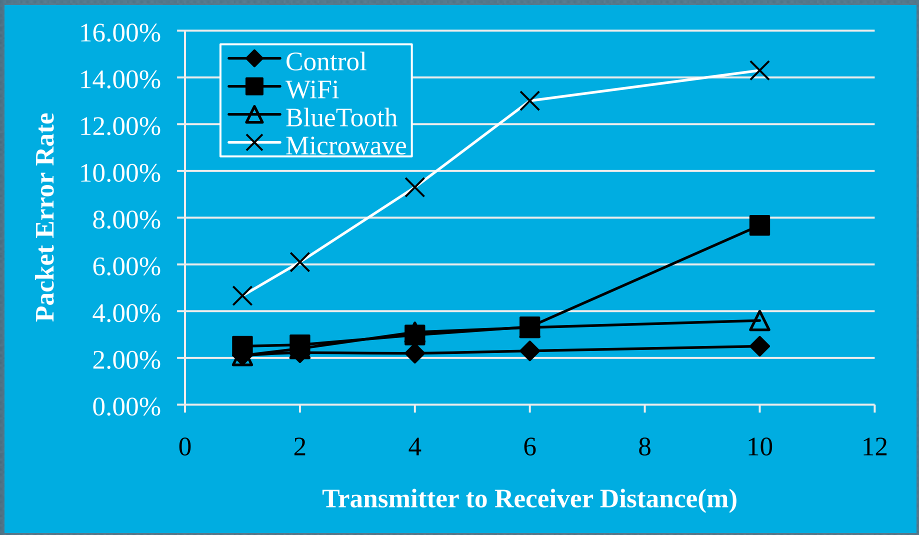
Signal Attenuation with Materials

- Typical data for maximum separation distances between transmitters operating at 0 dBm to attain Packet Delivery Rates of 90% and 95%

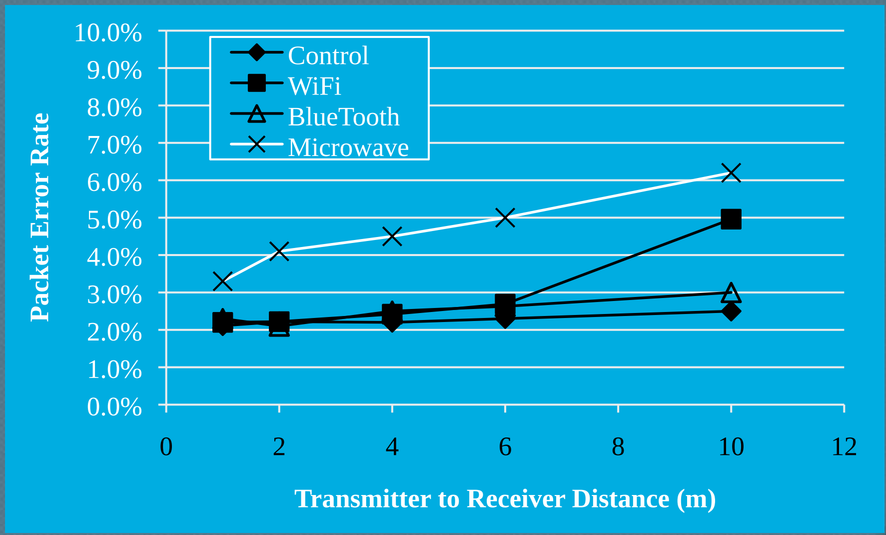


Interference

- IEEE 802.15.4 uses 2.4 GHz Industrial, Scientific, and Medical Band – same as many other protocols.
- Other non-communication sources of radiation in this band, e.g., microwaves



Interference Source to Receiver Distance = 0.5 m



Interference Source to Receiver Distance = 4 m

Data integration

- Most networking schemes in place enable self-forming networks
- Plug-and-Play ?
  - IEEE 1451 – Standard for smart sensors
    - Each sensor maintains on-board identification information
    - Standard provides for multiple physical connections to network, both wired and wireless
    - Automatically announce its existence when connected to network
    - Requires more hardware and software
- Lingering Needs
  - Standard data models
  - Holy Grail…self-locating sensors
    - It is feasible outdoors, but indoor installations present a wide range of challenges

Challenge 3: Sensor Maintenance

Wish List

- Self-Diagnosing
- Self-Healing
- Self-Calibrating
- Self-Correcting

Self-Maintaining Sensors

Self-Diagnosing → Low Battery Alerts, Gross Damage Alerts

Self-Healing → Ad-hoc networks can self-heal

Self-Calibrating → Research phase

Self-Correcting → Research phase

Redundancy provided by sensor networks can be utilized

Power Issues – Wireless Sensors

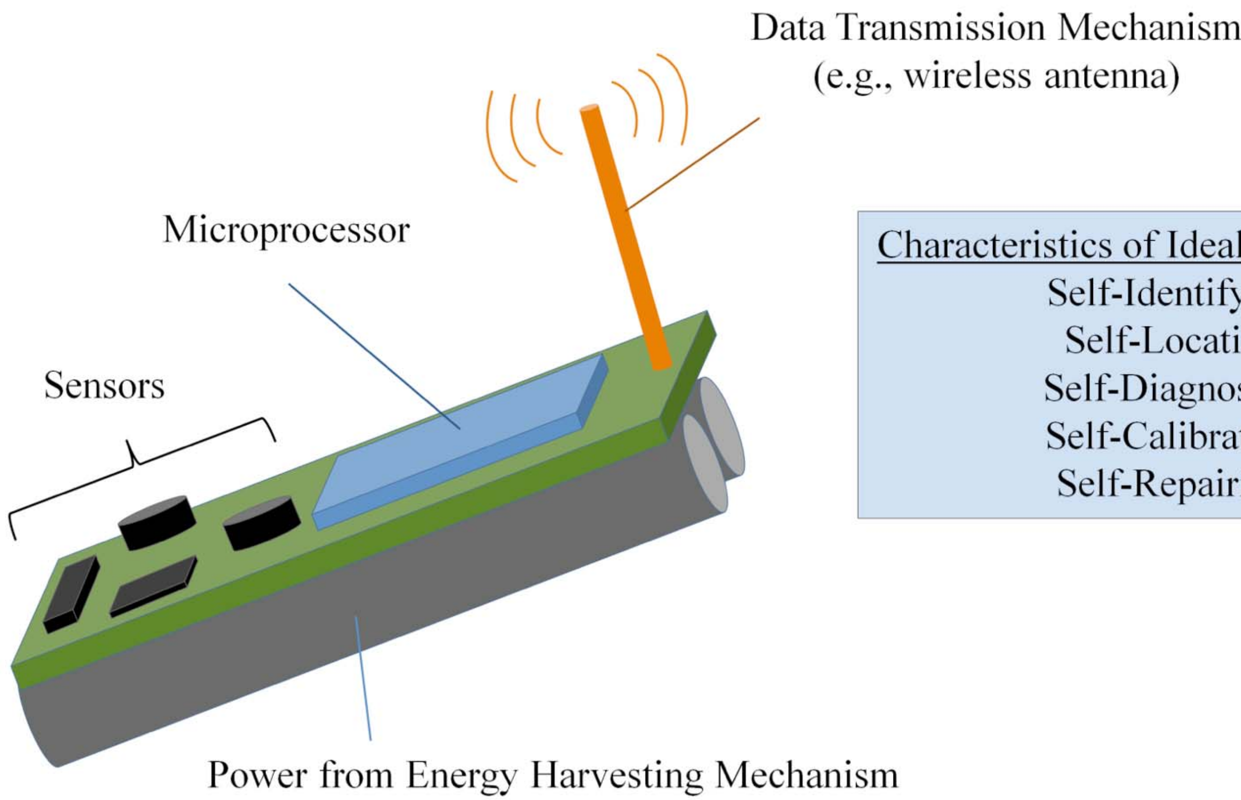
- Battery power
  - Typical energy consumption of wireless sensors:

Radio mode	Power consumption (mW)
Transmit	15
Receive	13
Idle	12
Sleep	0.016

→ Lesson: Transmit and Receive messages as little as possible

  - Typical shelf life of batteries ~ 5 years
- Energy Harvesting
  - Photoelectric
  - Thermoelectric
  - Vibrations

Ideal Smart Sensor

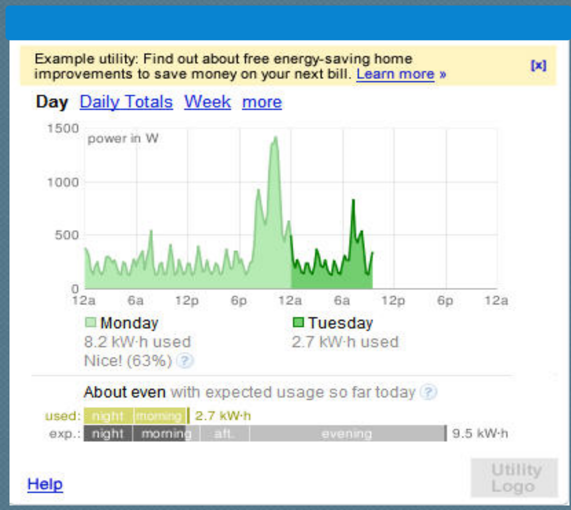


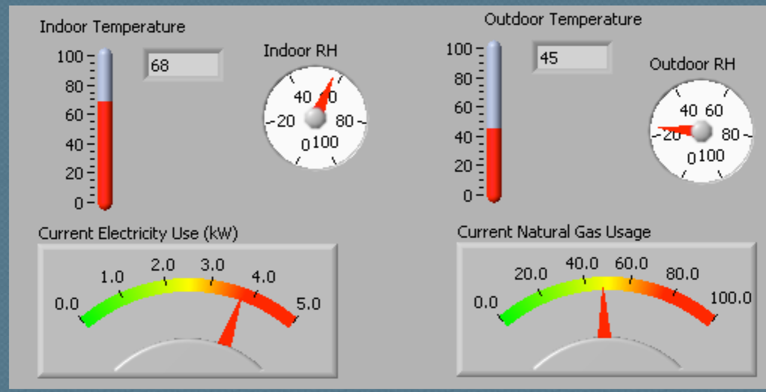
<u>Characteristics of Ideal Smart Sensor</u>

Self-Identifying
Self-Locating
Self-Diagnosing
Self-Calibrating
Self-Repairing

The Use of Sensors to Provide Feedback to Building Occupants

Potential for Energy Feedback



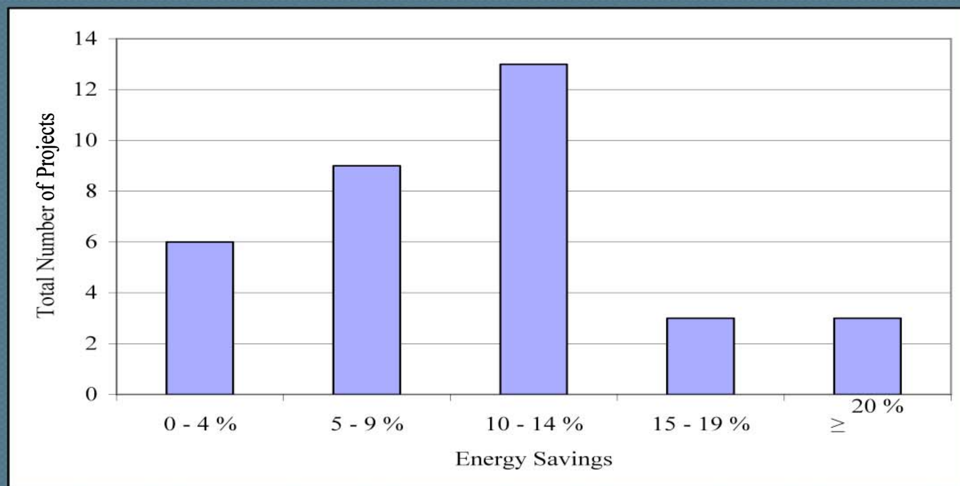


U.N. Intergovernmental Panel on Climate Change:
"Infrequent meter readings provide insufficient feedback to consumers on their energy use and on the potential impact of their efficiency investments"

World Business Council for Sustainable Development:
"Technical devices to measure energy consumption and provide immediate feedback help to cut energy consumption by as much as 20 %"

Key Studies of Energy Feedback

- Darby (2006) Review of 34 energy feedback studies:
  - Typical savings between 5 % and 15 % for direct feedback
  - End of month feedback (e.g., utility bills) resulted in 0 % to 10 % savings
  - Wide distribution of savings:



- Parker et al. (2006) two year study of 22 homes in Florida
  - Average change in energy usage of **-7.4 %**; significant variation (from -27.9 % to +9.5 %)
- Ontario Hydro One Study (2006) of over 400 homes
  - Average change in energy usage of **-6.4 %**

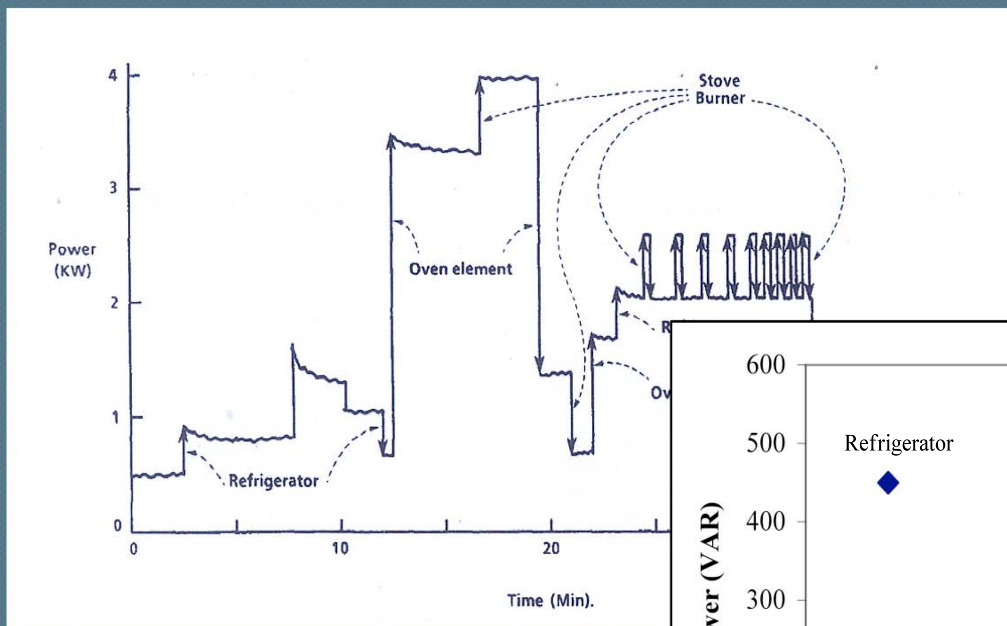
What is available now?

- Whole-house electricity monitoring
  - 17 products identified in 2009
  - Most provide instantaneous power
  - Some provide logging capabilities
  - Range of installation procedures
- Information Technology products for feedback
  - 6 products identified in 2009 (probably undercounted) – most were in development
  - Rely on other sources to provide data
- Point-of-use monitors
  - Five identified in 2009
  - Device inserted between outlet and end-use

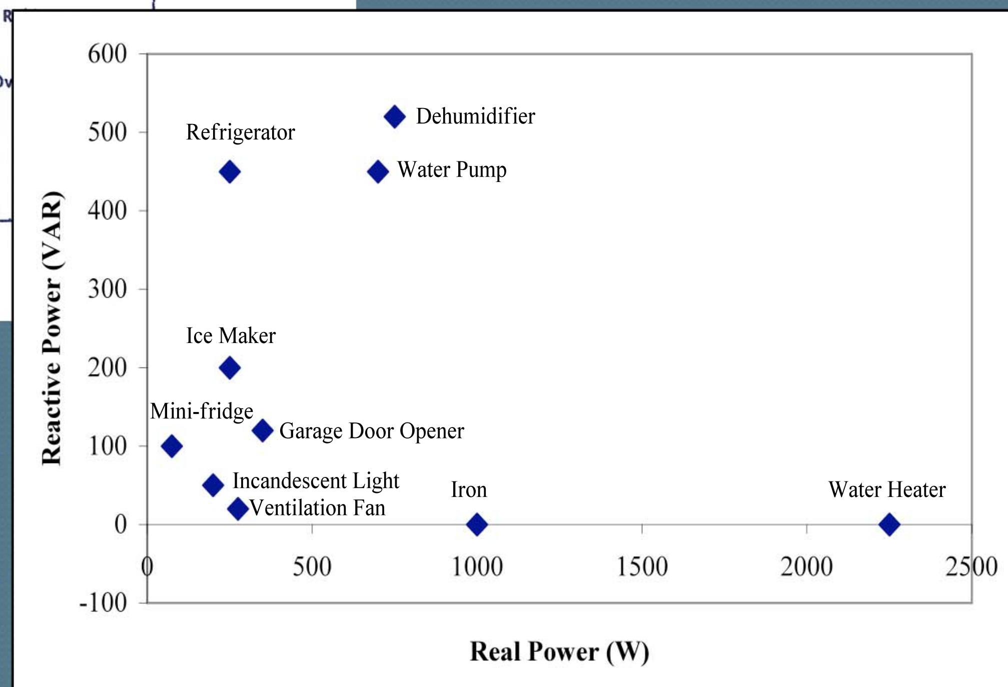
Approaches

- Sensor-rich
  - Many low-cost sensors monitoring end-uses
  - Data collection, analysis, and display at a central point
- Analysis-rich
  - Fewer sensors (e.g., single sensor at main meter)
  - Signal analysis to dissect end-uses
  - "Non-invasive load monitoring"
    - MIT work from the 1980's and 1990's

Non-invasive load monitoring



From Hart (1992)



Reactive power may be needed to differentiate end-uses

Challenges In Use of Non-Invasive Load Monitoring

- Proliferation of new electronic devices has added more signatures to track
- Variable speed motors do not have distinct signature
- Cost
  - Current commercial implementation costs ~$8k

But….it may have application for FDD

Challenges in Implementing Energy Monitoring Systems

- Decreasing cost
- Creating easy-to-install systems
  - Will not require professional plumber, electrician, or HVAC technician
  - Cannot require cutting into pipes
  - Should not require major electrical work
  - Software setup should be straightforward
- Improving methods to determine fossil fuel consumption
- Key Questions:
  - How accurate must the measurements be?
  - How can we minimize the number of sensing points yet still provide adequate information for fault detection?

Conclusions

- Key challenges related to sensor use in buildings
  - Development of new sensors
  - Integration of sensors in a more straightforward manner
  - Preservation of sensor performance with little human involvement
- Home Energy Monitoring Systems
  - Many systems have recently emerged
  - Many improvements are still needed
    - Ease of installation and use
    - Cost
    - Presentation of data to user