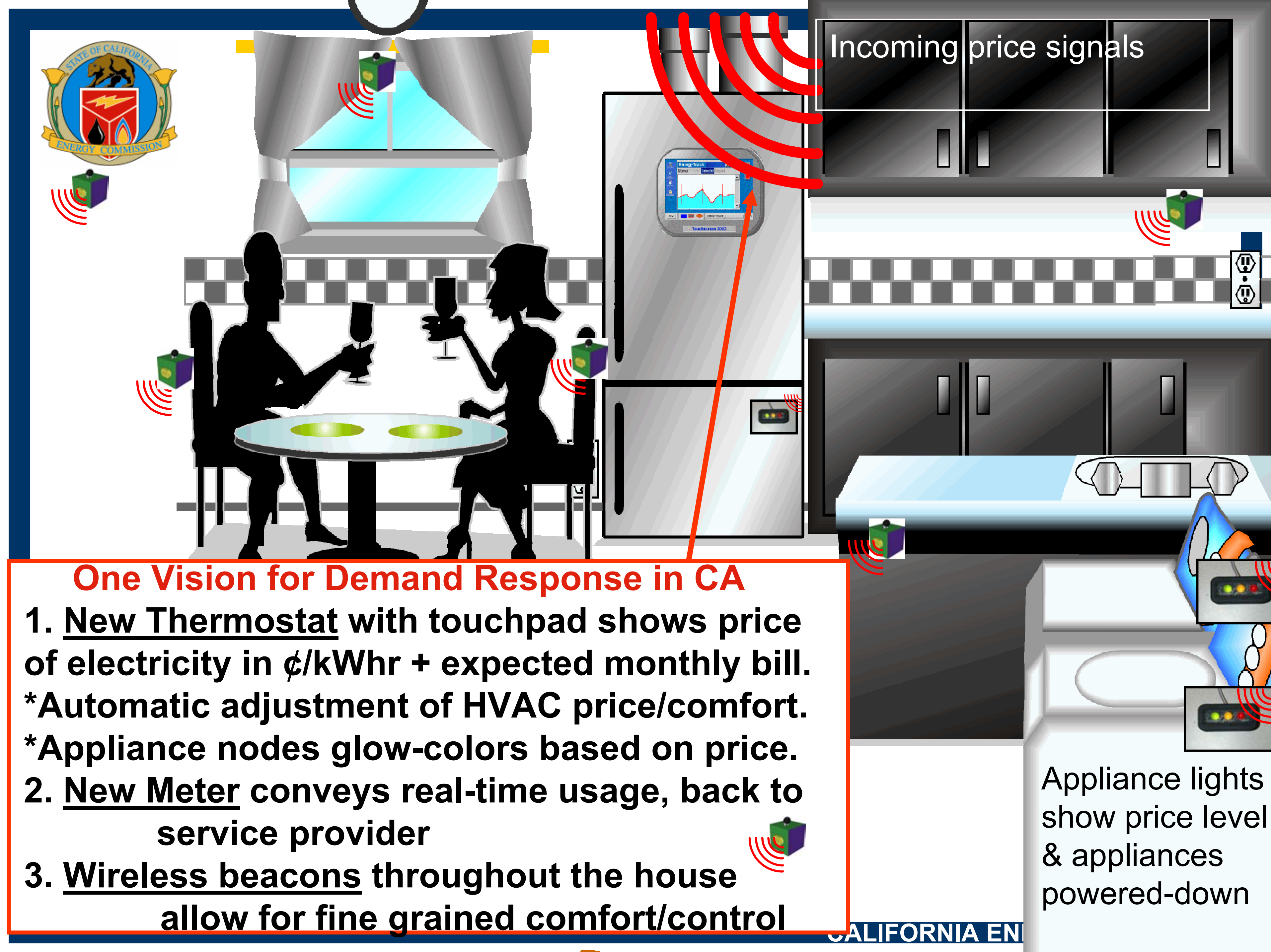
DR ETD – Summary of New Thermostat, TempNode, & New Meter (UC Berkeley Project 6/6/06)

- **New Thermostat, New Temperature Node, & New Meter**
- **Phase One: 3/2003 – 8/2005; Phase Two 9/2005 – 8/2007**
- **Multi-disciplinary Collaboration Team:**
  - David Auslander: ME Dept.
  - Ed Arens & Charlie Huizenga : Center for Built Environment
  - Kris Pister: Berkeley Sensor & Actuator Center, EECS Dept.
  - Jan Rabaey: Berkeley Wireless Research Center, EECS Dept
  - Dick White: Berkeley Sensor & Actuator Center, EECS Dept.
  - Paul Wright: Berkeley Manufacturing Institute, ME Dept.
  - 20 Graduate Student Researchers (13 are funded)
    - Many thanks to all colleagues and students for their contributions

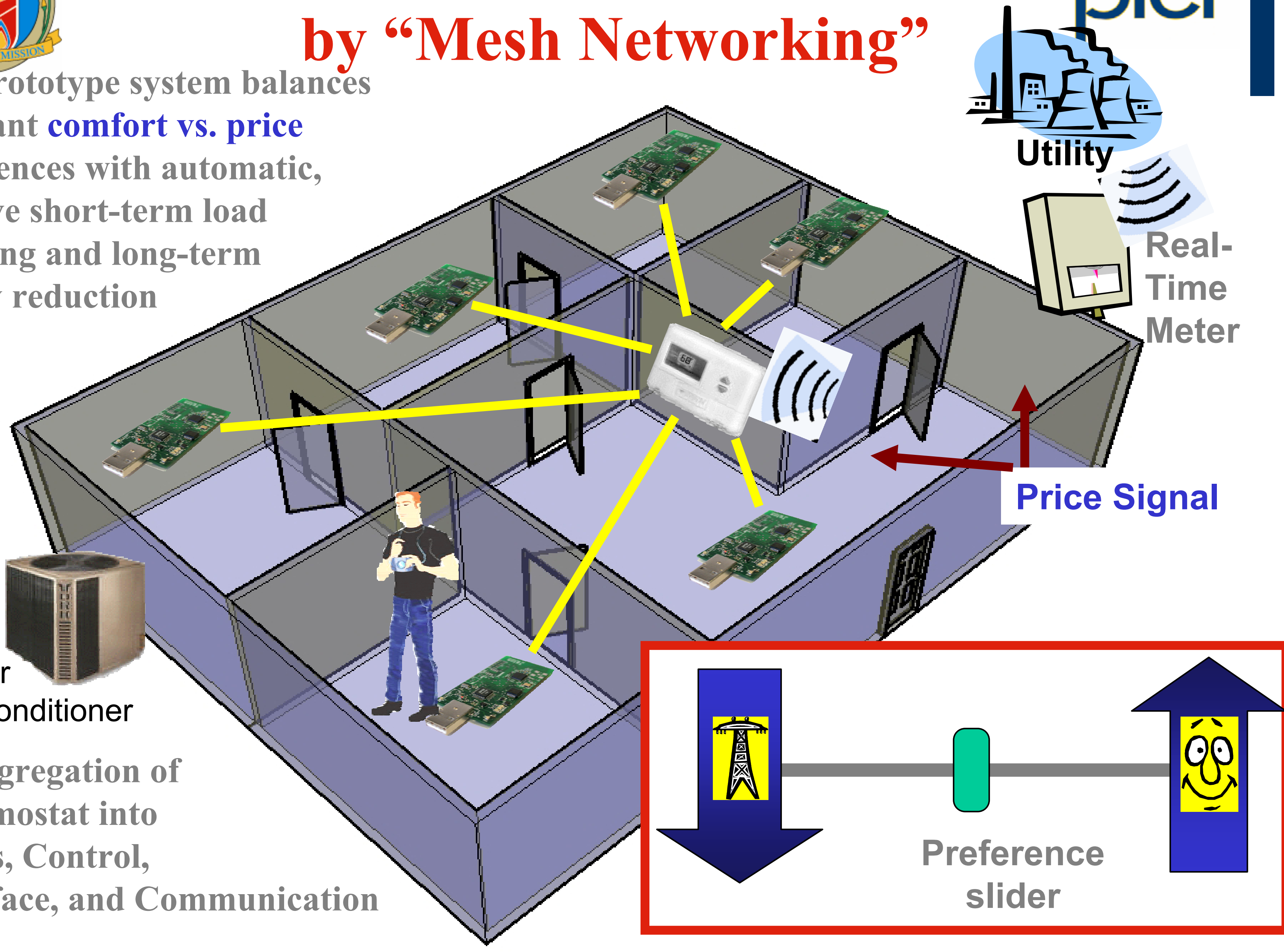

STATE OF CALIFORNIA ENERGY COMMISSION
Incoming price signals
One Vision for Demand Response in CA
1. New Thermostat with touchpad shows price of electricity in ¢/kWhr + expected monthly bill.
*Automatic adjustment of HVAC price/comfort.
*Appliance nodes glow-colors based on price.
2. New Meter conveys real-time usage, back to service provider
3. Wireless beacons throughout the house allow for fine grained comfort/control
Appliance lights show price level & appliances powered-down

DR ETD Project Overview

- **Mid- to long-term R&D (3-8 year objectives)**
  - To help achieve a DR Infrastructure in California
- **Enabling technologies R&D with 10x10x10 goals – not product development**
- **Multi-disciplinary with 4 collaborative sub-teams**
  - 1. Communication 2. Control 3. Sensing 4. Power Supply
  - Leverage DARPA, DoE, NSF, Intel, and other funding
- **"Disruptive"– 10x10x10 improvements, e.g...**
  - 1. Tiny OS (ad hoc self organizing networks)
    Pico radio (low-cost, low-power wireless)
  - 2. Learning algorithms (individualized DR response)
  - 3. Smart Dust (highly integrated control platform)
  - 4. Energy Scavenging (avoid replaceable batteries)

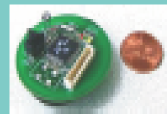
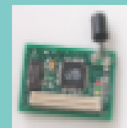
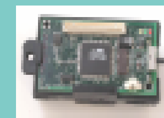
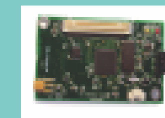
Sub team 1: Radio Communication by "Mesh Networking"

Our prototype system balances occupant **comfort vs. price** preferences with automatic, reactive short-term load shedding and long-term energy reduction

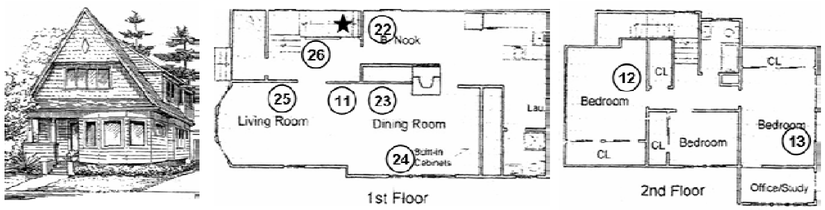


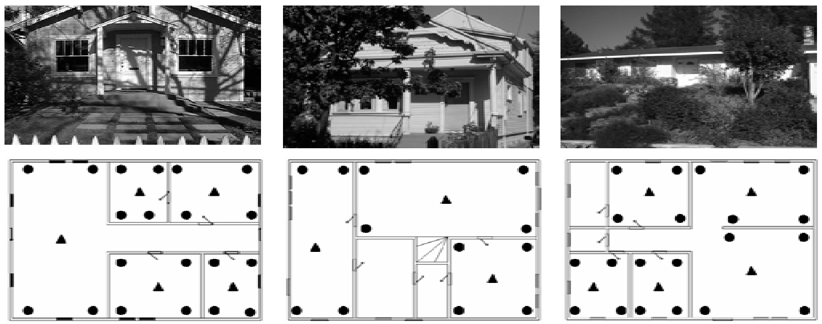
Disaggregation of Thermostat into Nodes, Control, Interface, and Communication

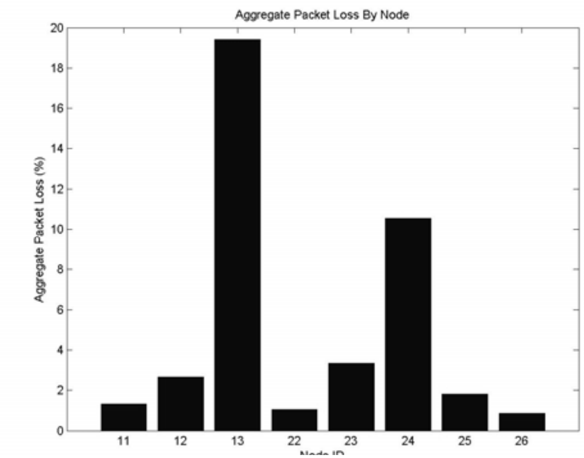
Hardware used with today's Telos 06 device

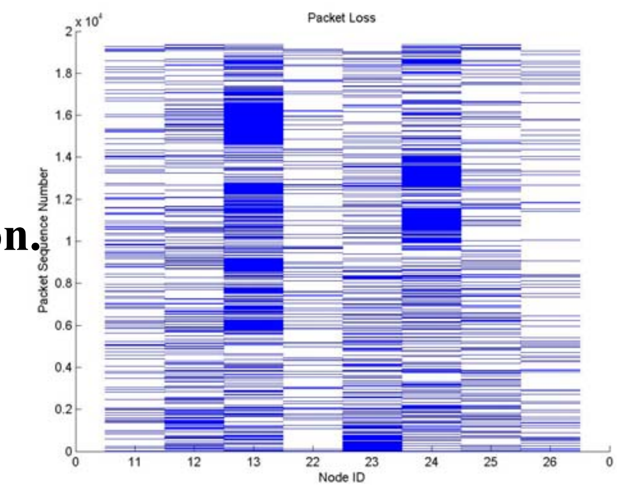
	WeC 1998	René 1999	René 2 2000	Dot 2000	Mica 2001	Mica2Dot 2002	Mica 2 2002	Telos 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

Packet Performance



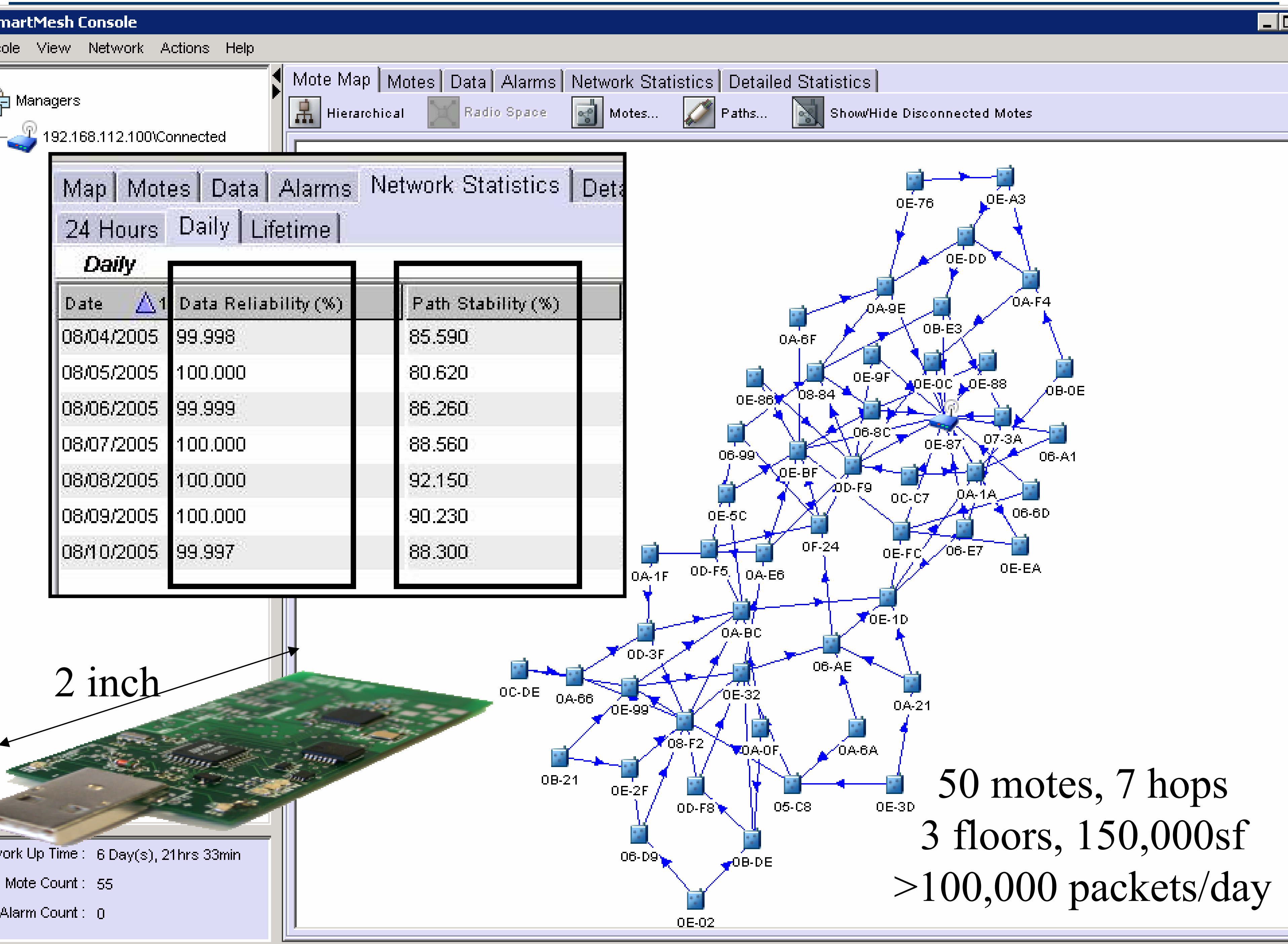






- Aggregate packet loss < 10%.
- Packet loss is greater when all doors are closed.
- Packet loss events last seconds to minutes in duration.
- Packet loss events are mainly single-link.
- Multiple link losses are typically non-contiguous.
- Asymmetry is present in 17 % of all lossy links.

Ota, N. and P. Wright, “Experiences with Wireless Sensor Network Performance in Residential Environments”, ACM RealWSN ’06 Workshop on Real-World Wireless Sensor Networks, Uppsala, Sweden, June 19, 2006.



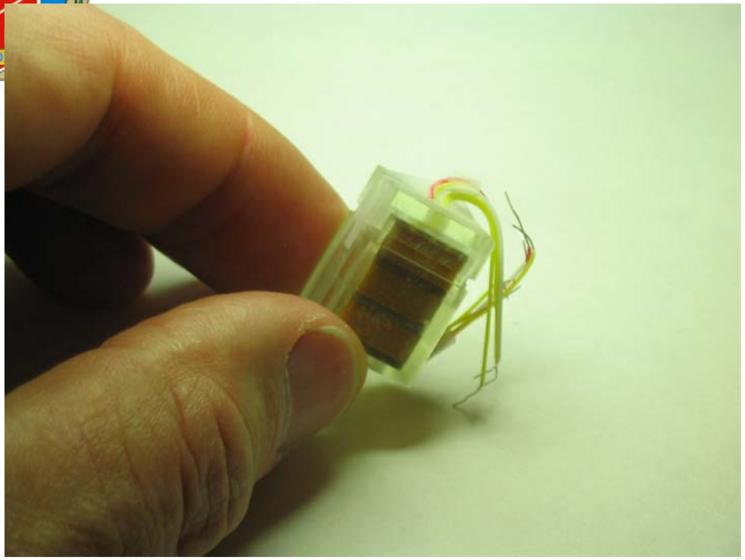
Date	Data Reliability (%)	Path Stability (%)
08/04/2005	99.998	85.590
08/05/2005	100.000	80.620
08/06/2005	99.999	86.260
08/07/2005	100.000	88.560
08/08/2005	100.000	92.150
08/09/2005	100.000	90.230
08/10/2005	99.997	88.300

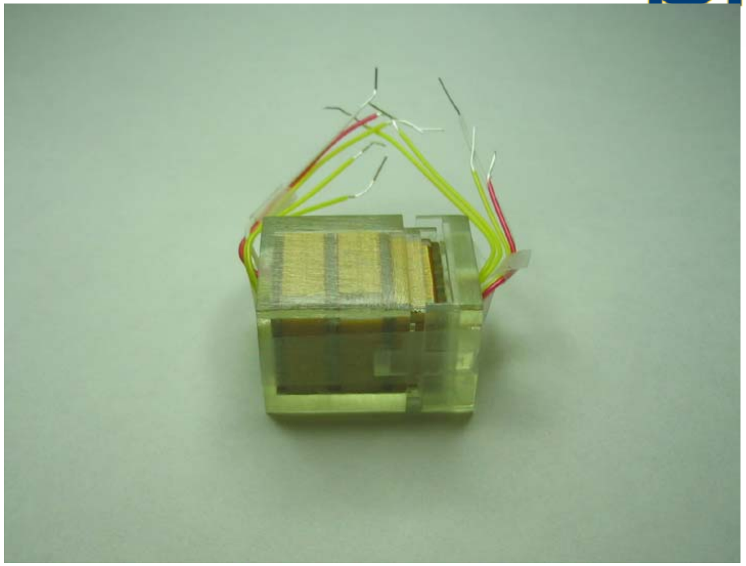
50 motes, 7 hops

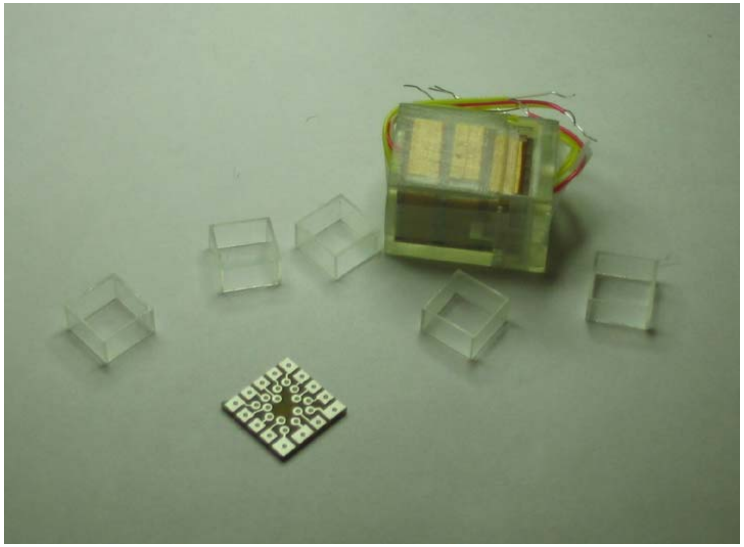
3 floors, 150,000sf

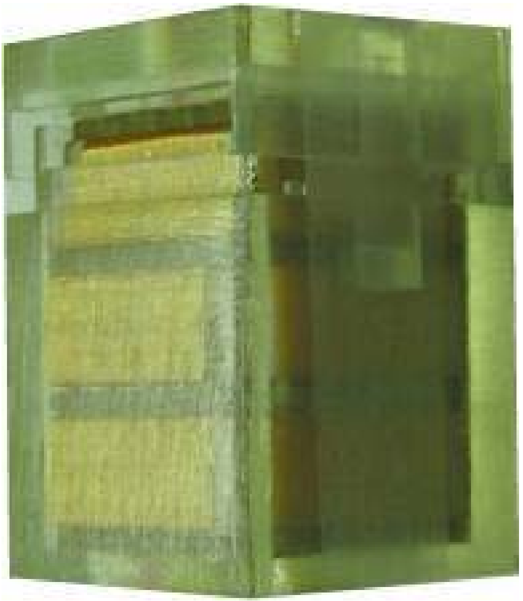
>100,000 packets/day

Towards 10x lower cost: PicoCube Prototype

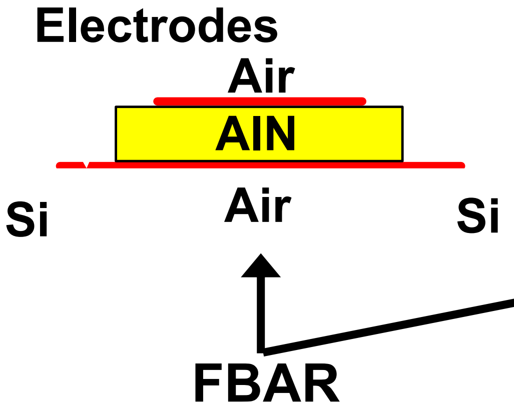


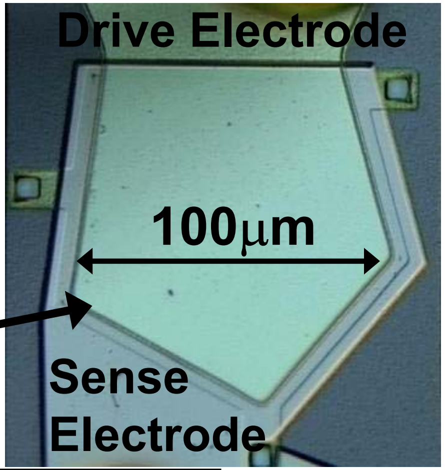






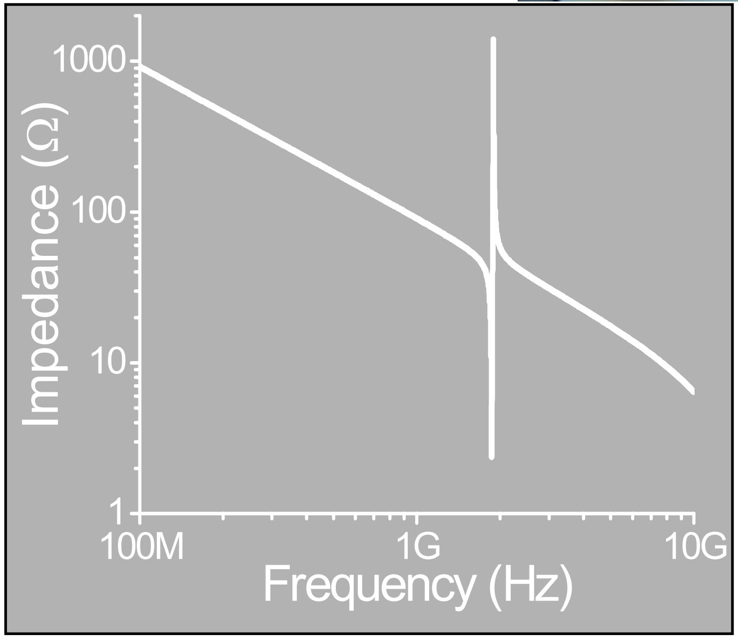
Extensive Use of Innovative MEMS



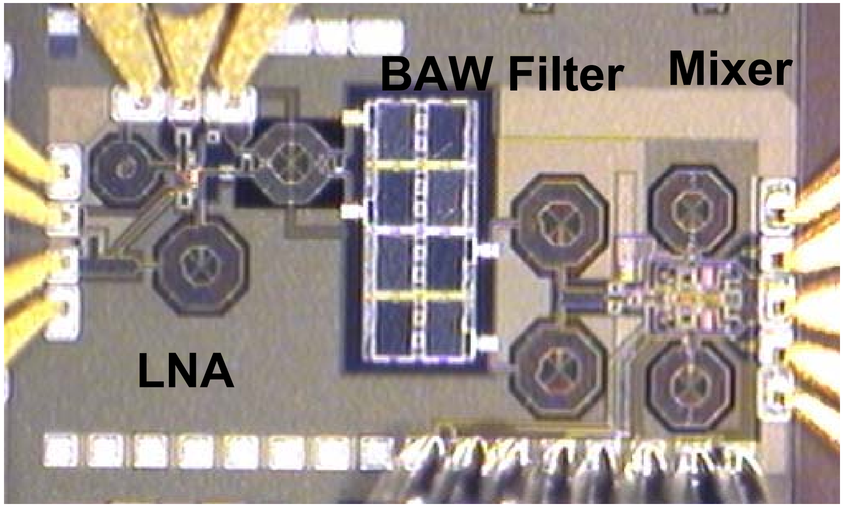


Small form factor

- **MEMS/CMOS co-design**
- **Integration into IC process**



Ruby et. al. (Ultrasonics Symposium 2001)

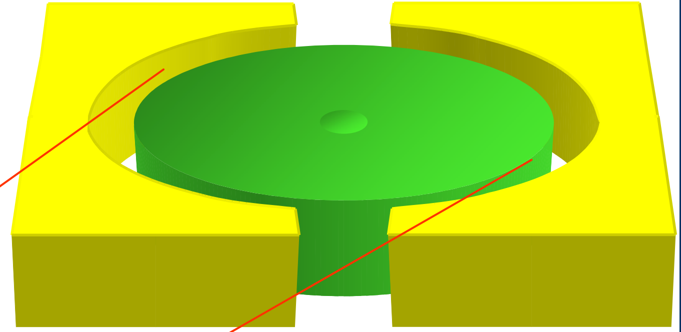


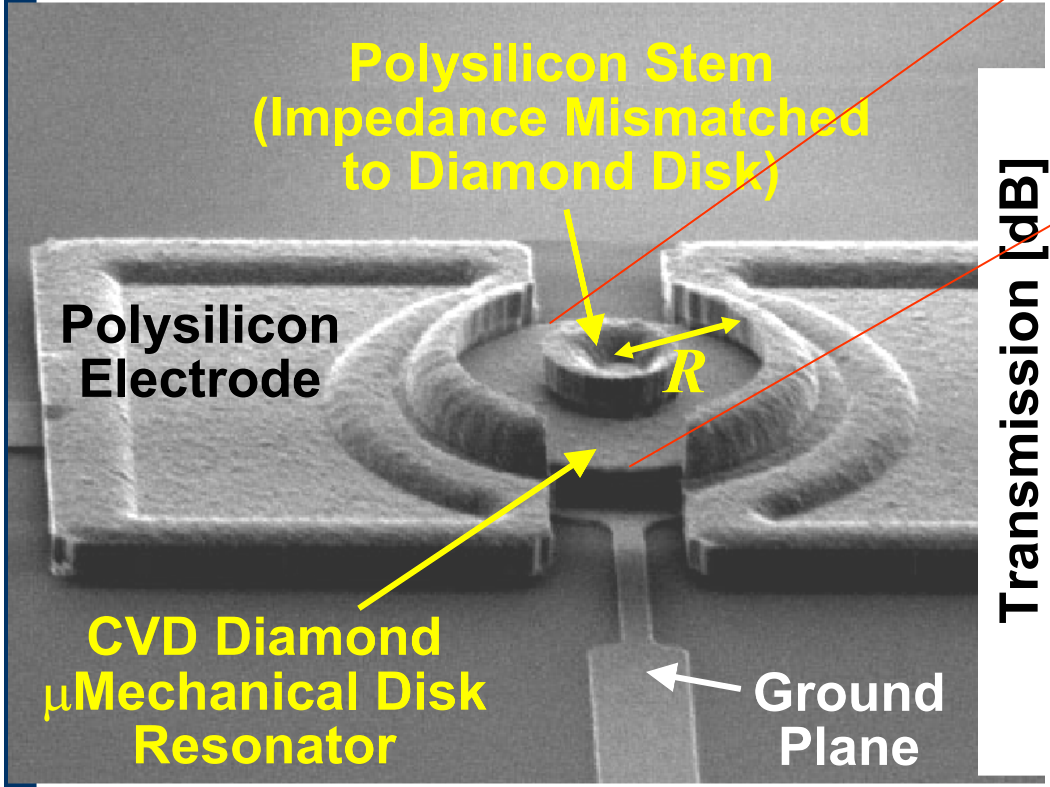
Carpentier et. al. (ISSCC 2005)

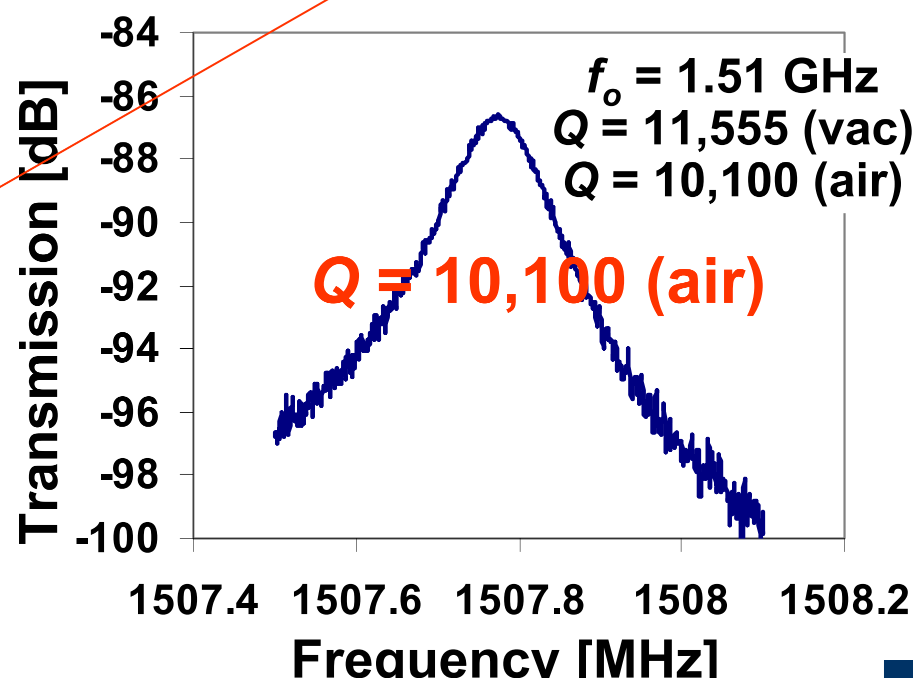
RF MEMS

1.51-GHz, *Q*=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- ***Below***: 20 μm diameter disk





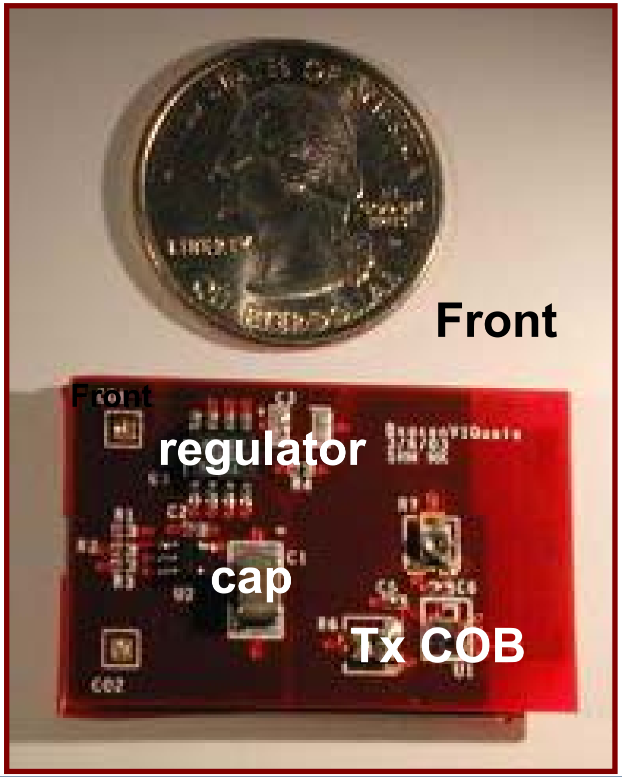


[Wang, Butler, Nguyen MEMS'04]

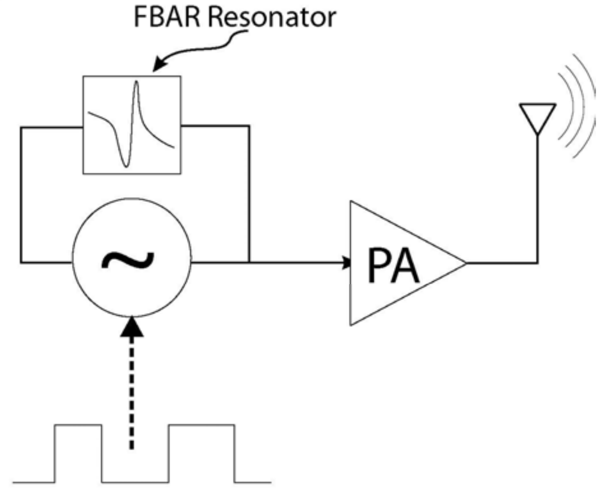
Transmit Beacon

Goals:

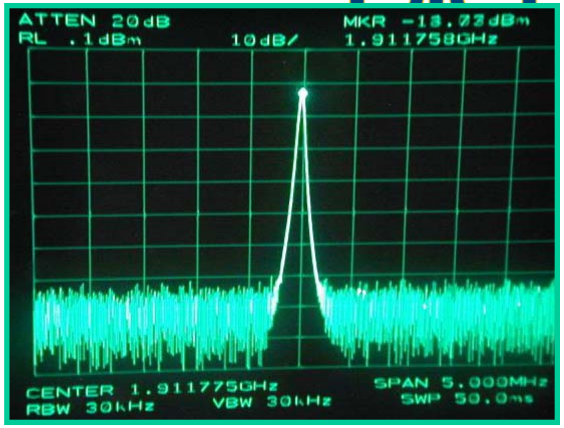
- Push integration limits - limited by dimensions of solar cell and vibrational energy scavenging (BWRC + BMI)



Transmit Beacon - RF



directly modulated oscillator *nonlinear PA*

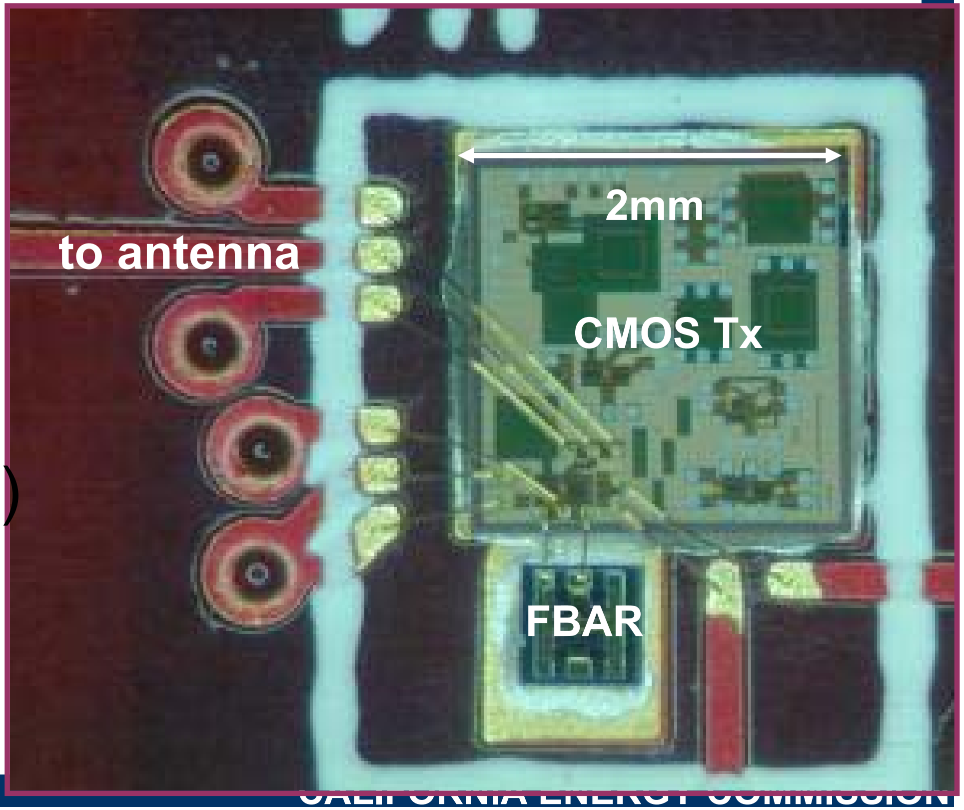


Transmitter:

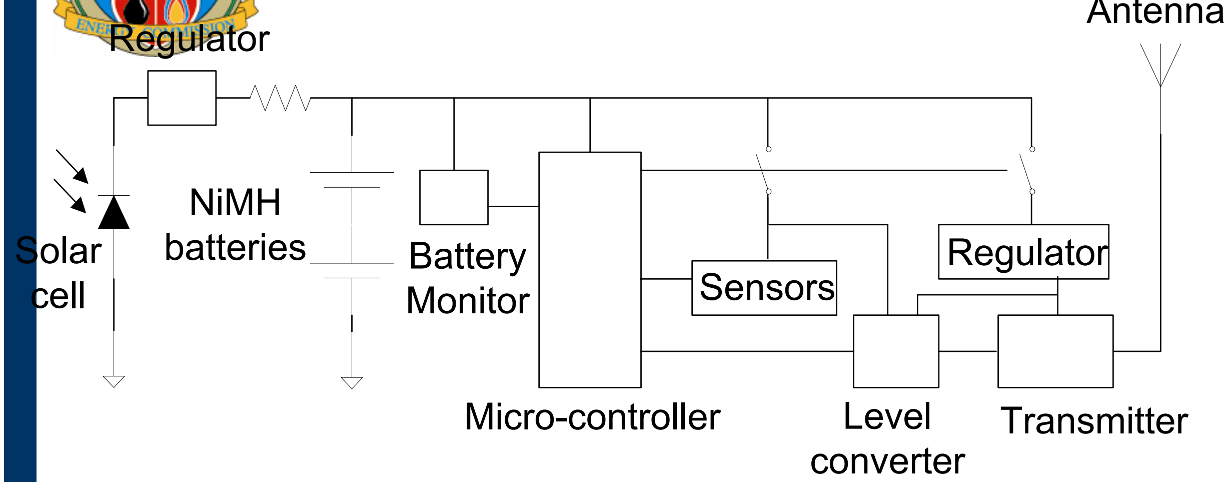
- 0dBm to 50Ω

(-1.5dBm measured @ antenna)

- Slight loss through via

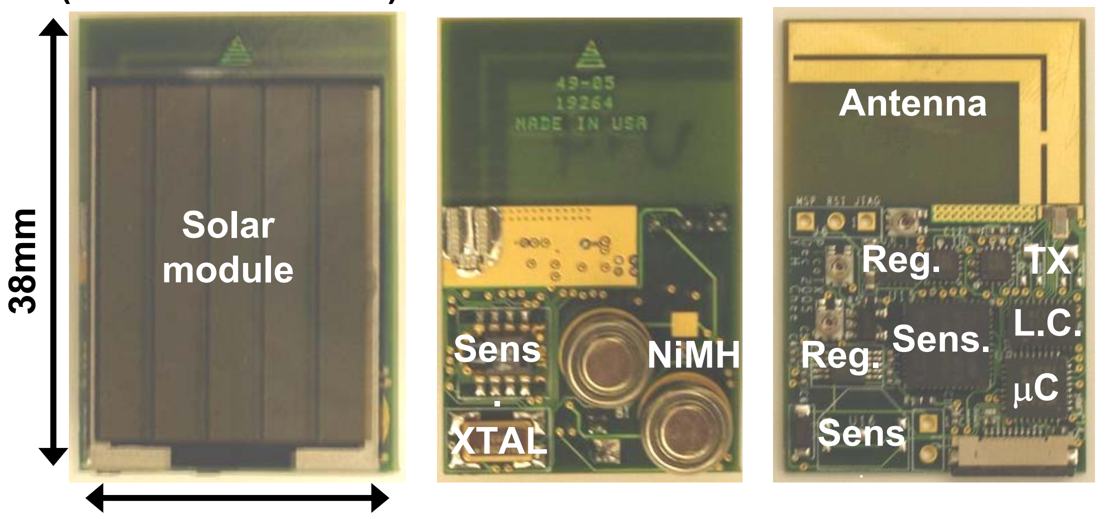


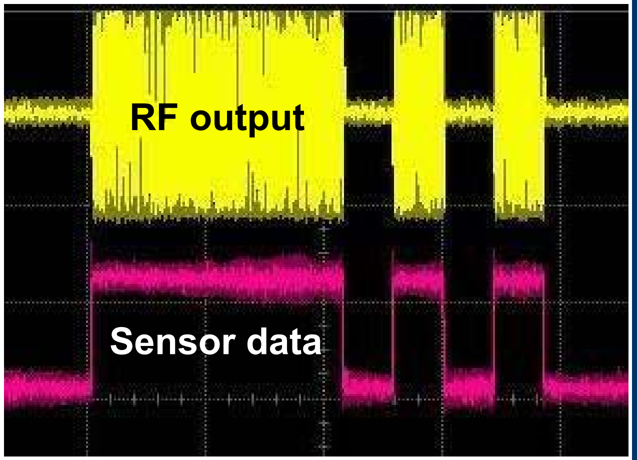
Ultra Low-Power Nodes



- **0 dBm transmitter with PILA antenna**
- **TI MSP430F1232 ultra low power microcontroller**
- **Solar powered with 2 NiMH batteries for secondary storage**
- **Accelerometer, tilt, temperature and humidity sensors**
- **But still many extra components**

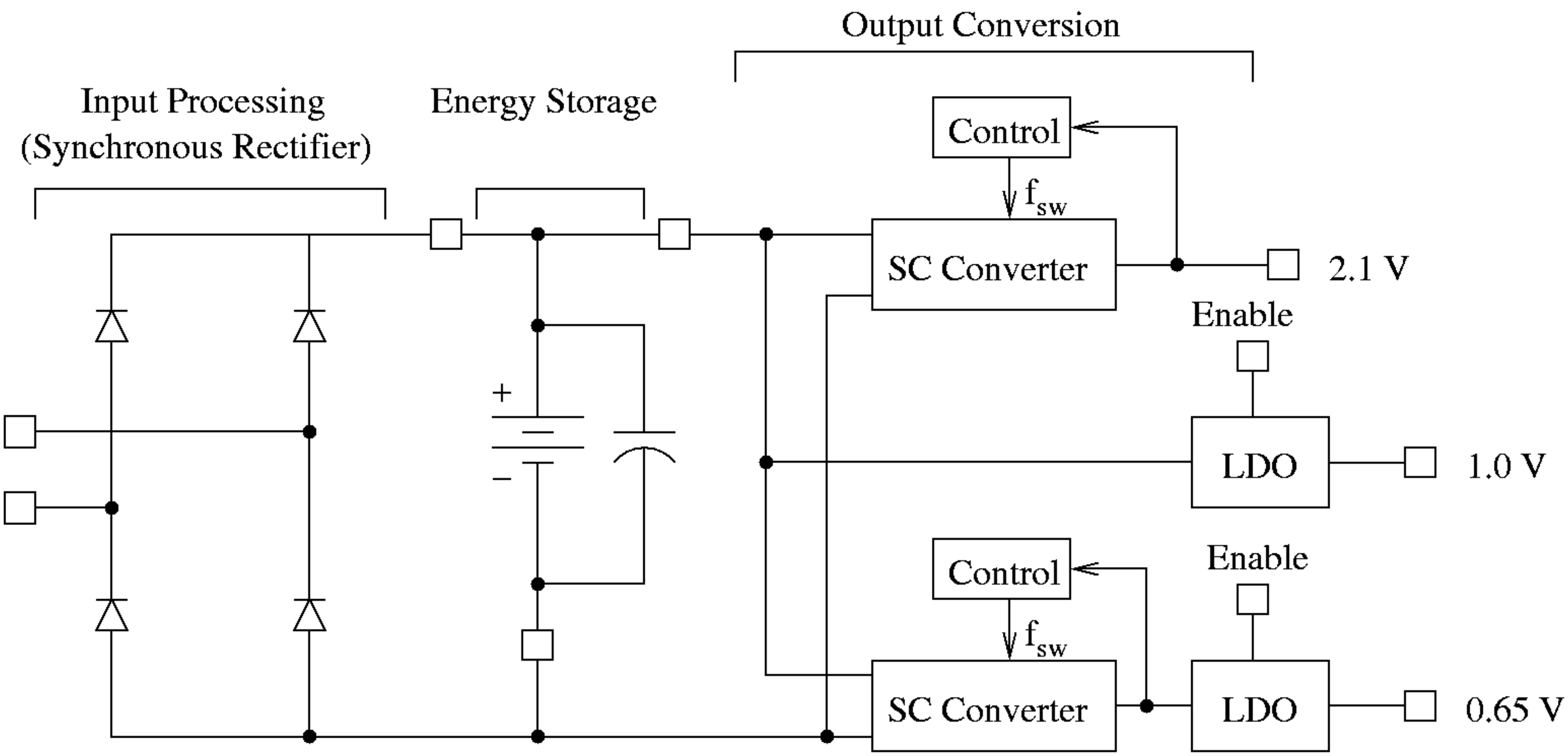
Back (with solar module) **Back** **Front**



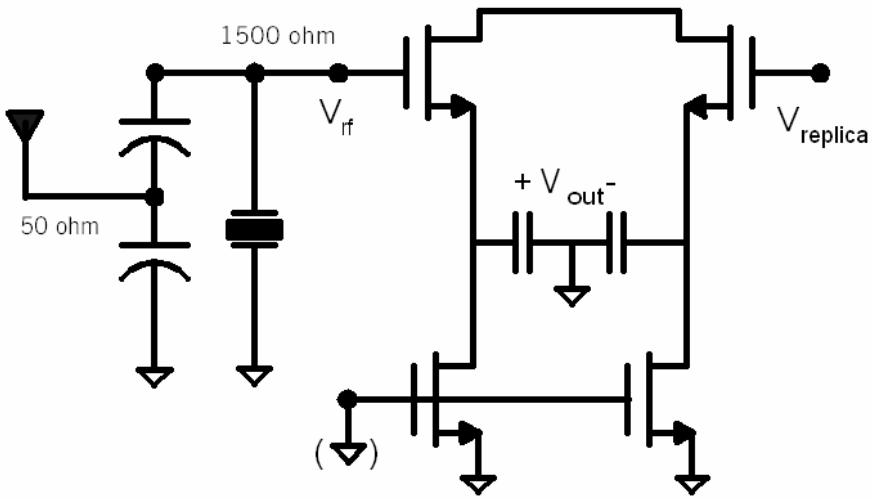


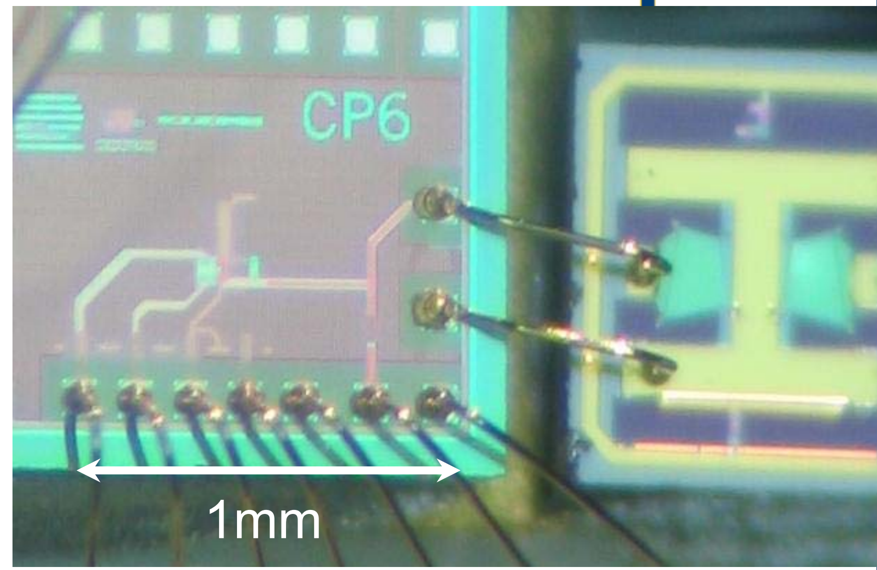
Source: Yuen-Hui Chee

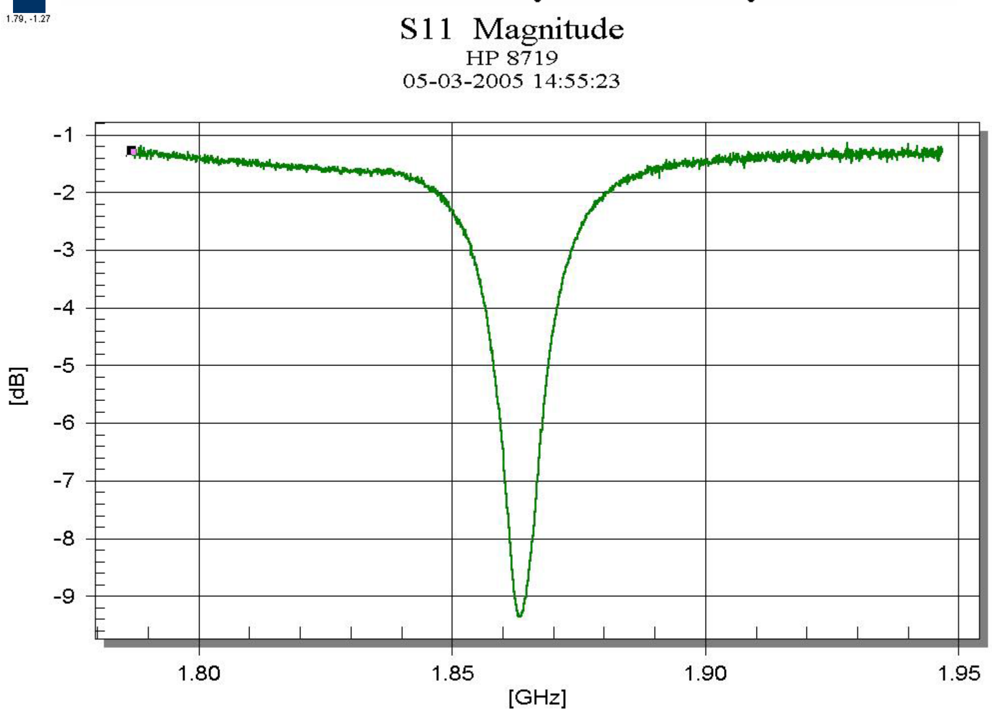
Power IC System Diagram



Passive Wakeup Receiver







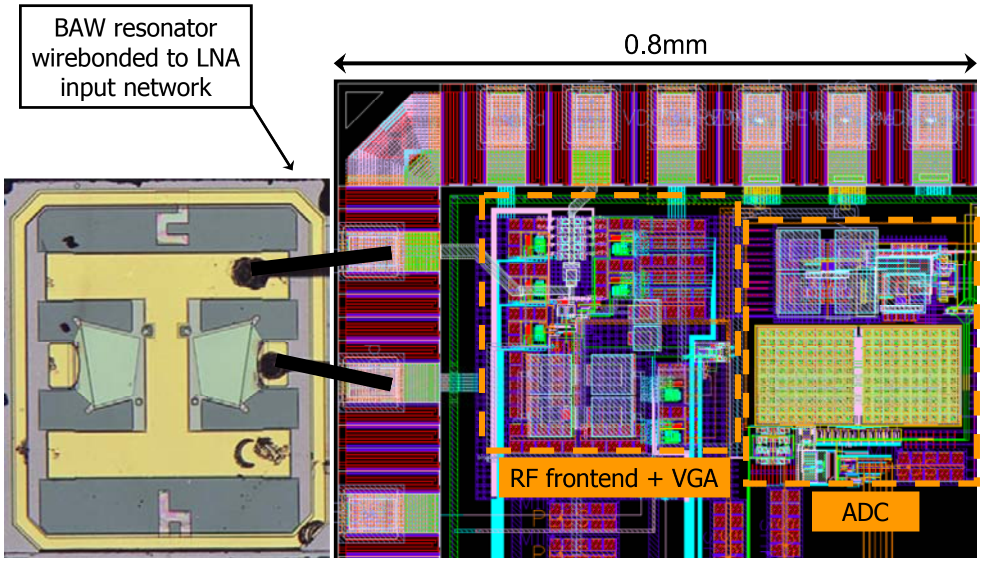
Measured performance:

- P_{RX}=200nW
- Sensitivity=-38dBm (12dB SNR)

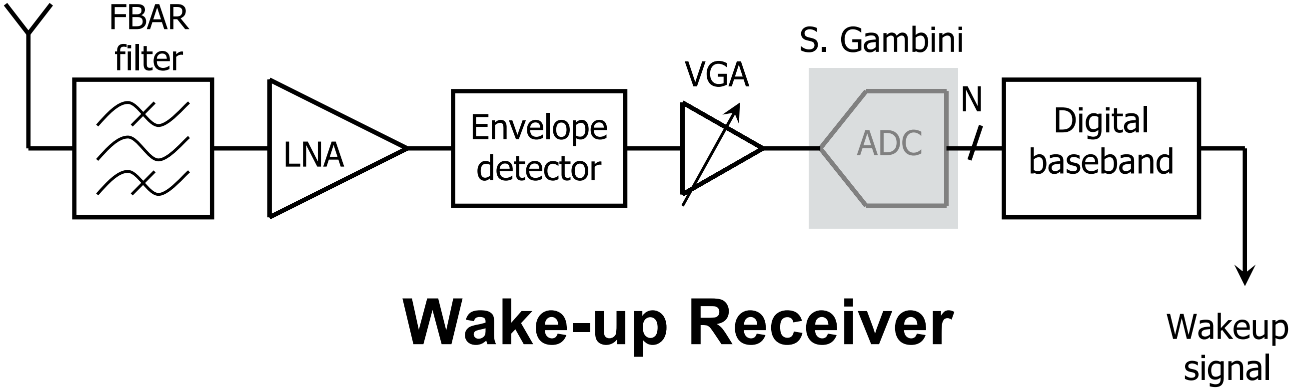
Sensitivity still too low, but suitable for short range (~1m) or with high power transmitter

Solution: Add Gain and Coding

Taped Out – May 06



- On/Off keying (OOK), 100kbps datarate
- Low 0.5V supply to reduce power consumption
- Digital baseband with ultra-low power ADC
- 60 μW overall power dissipation, -60 dBm sensitivity

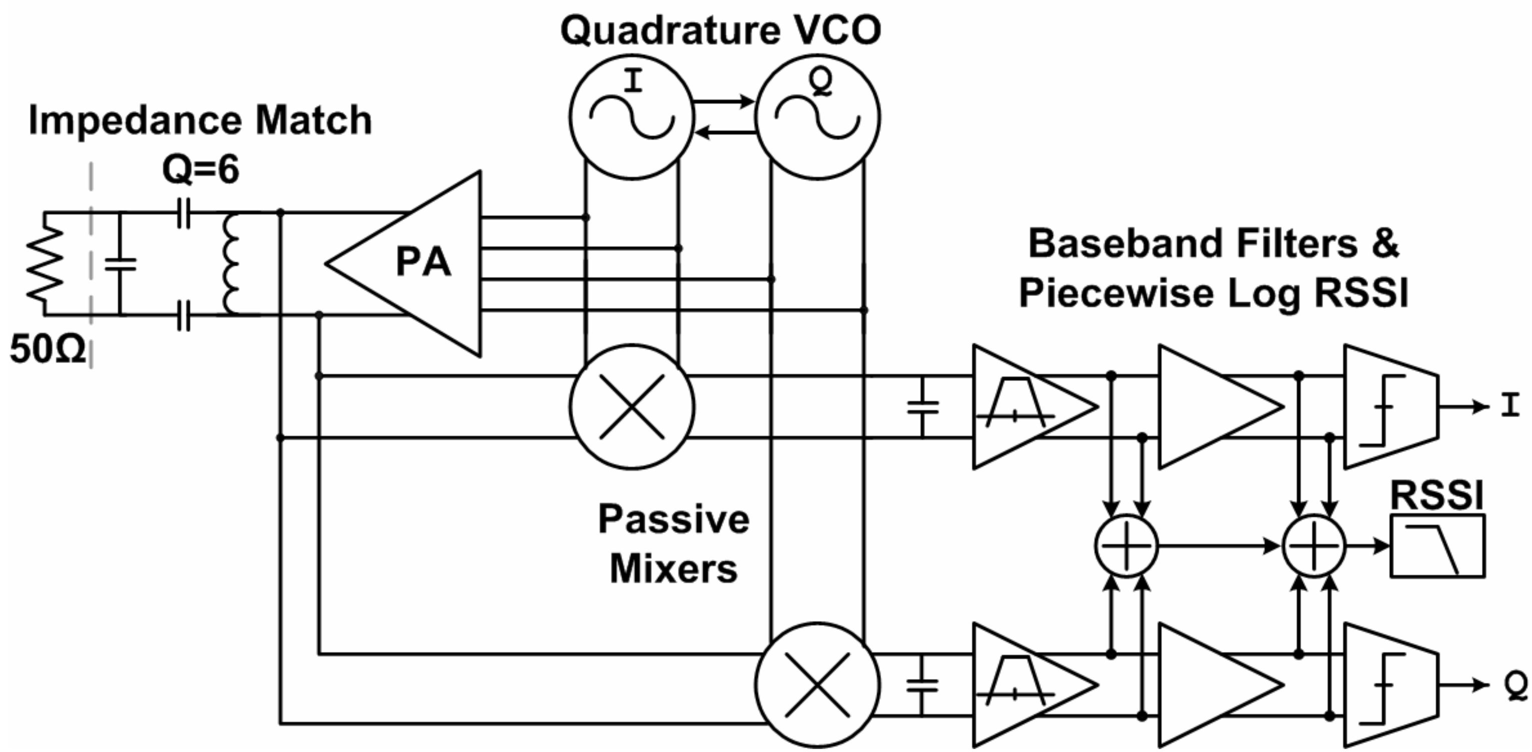


Wake-up Receiver

Courtesy N. Pletcher

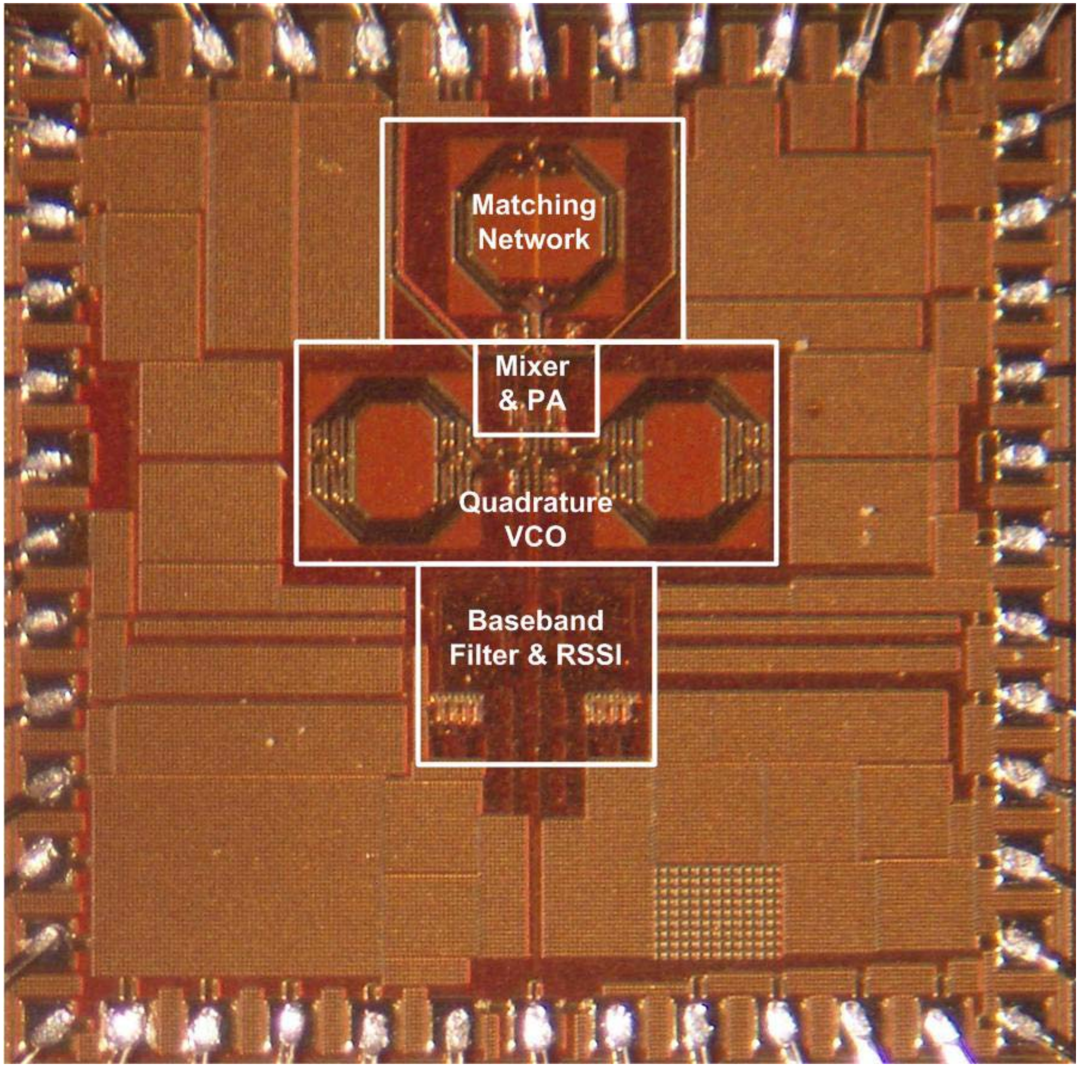
Also working on non-MEMS radios

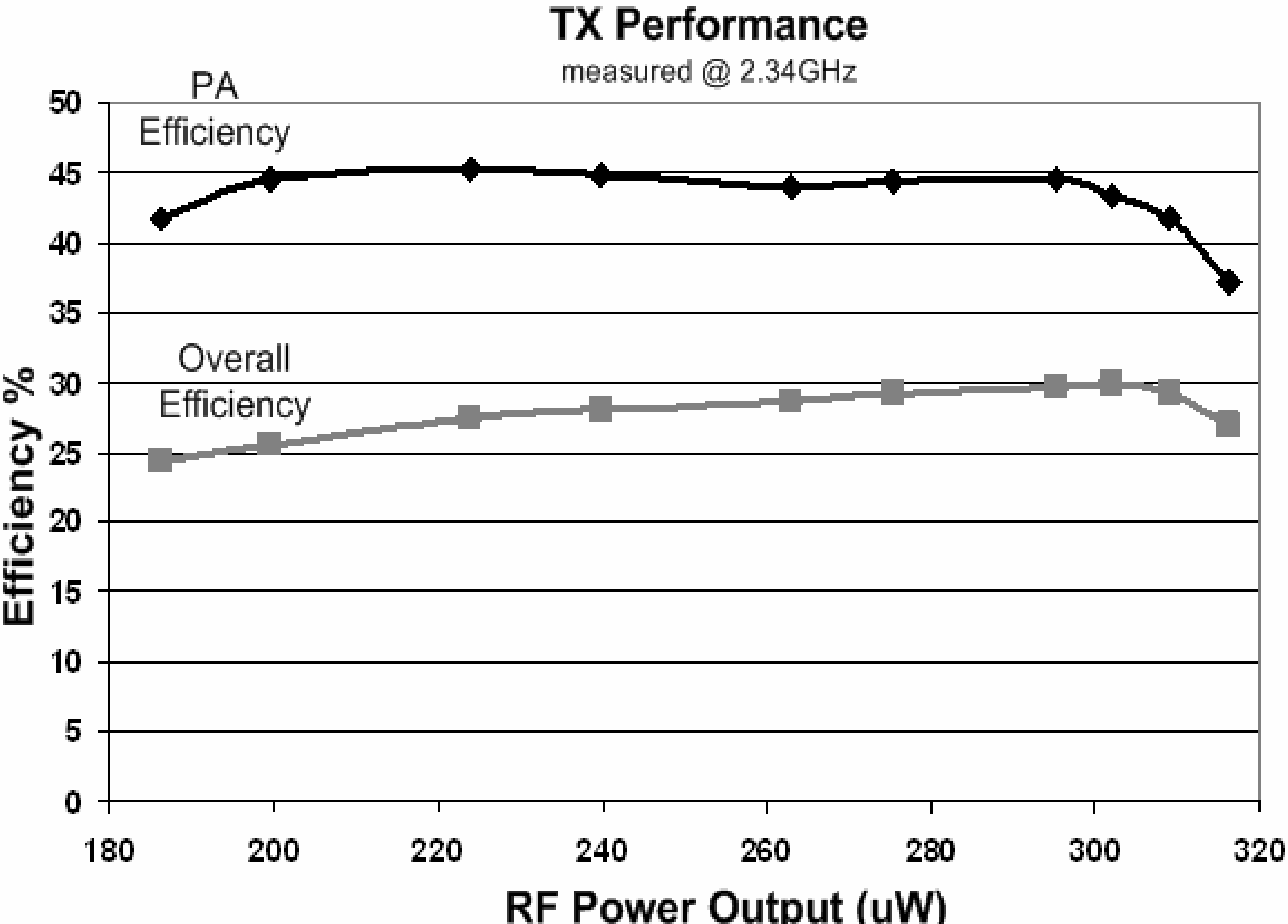
- 2.4GHz Transceiver in 130nm CMOS
- Passive RX front-end: no RF LNA
- 400mV Supply – Solar Cell



Die Photo

- 2.2mmx2.2mm
- Active Area: 0.8 mm^2





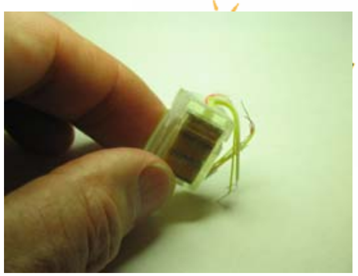
TX Performance
measured @ 2.34GHz
PA
Efficiency
Overall
Efficiency
Efficiency %
0
5
10
15
20
25
30
35
40
45
50
180
200
220
240
260
280
300
320
RF Power Output (uW)

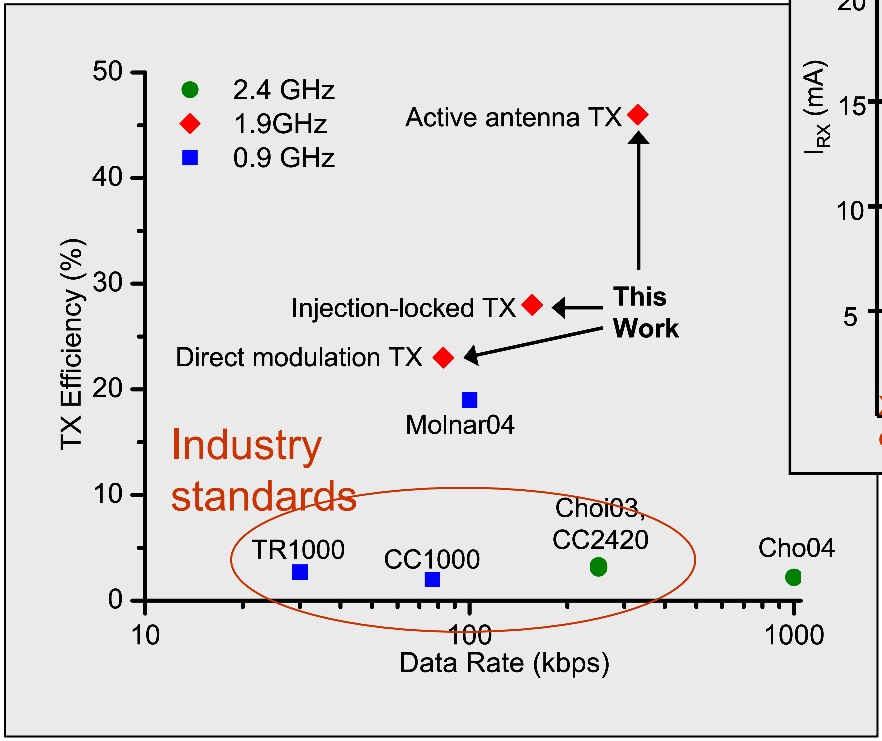
Why two radio projects both aiming at 10x10?

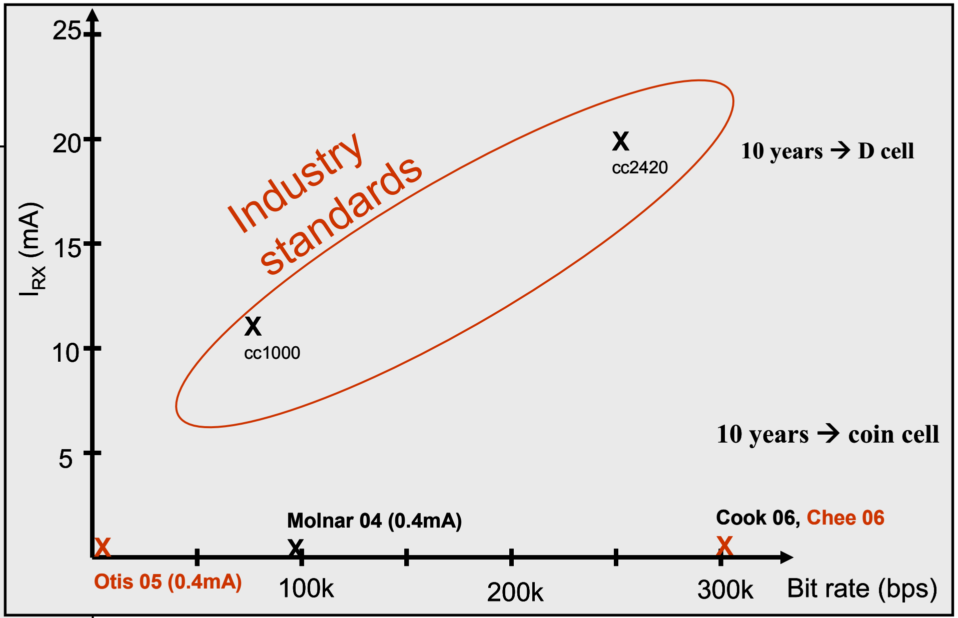
- **"FBAR route" explores new MEMS technology for design (uses OOK)**
- **Pros:**
  - Simple design with MEMS simplifies oscillator
  - Fixed at one frequency
  - Will get to lower power levels
- **"CMOS optimized" using passive gain thru LC network (uses FSK)**
- **Pros:**
  - Standard CMOS
  - Tuneable (1.9-2.4 GHz)
  - Robust with noise linearity similar to commercial devices
  - More flexible design

Courtesy: J. Rabaey, K. Pister

Radio Performance summary and the exciting year(s) ahead







Ultra Low Power Receivers

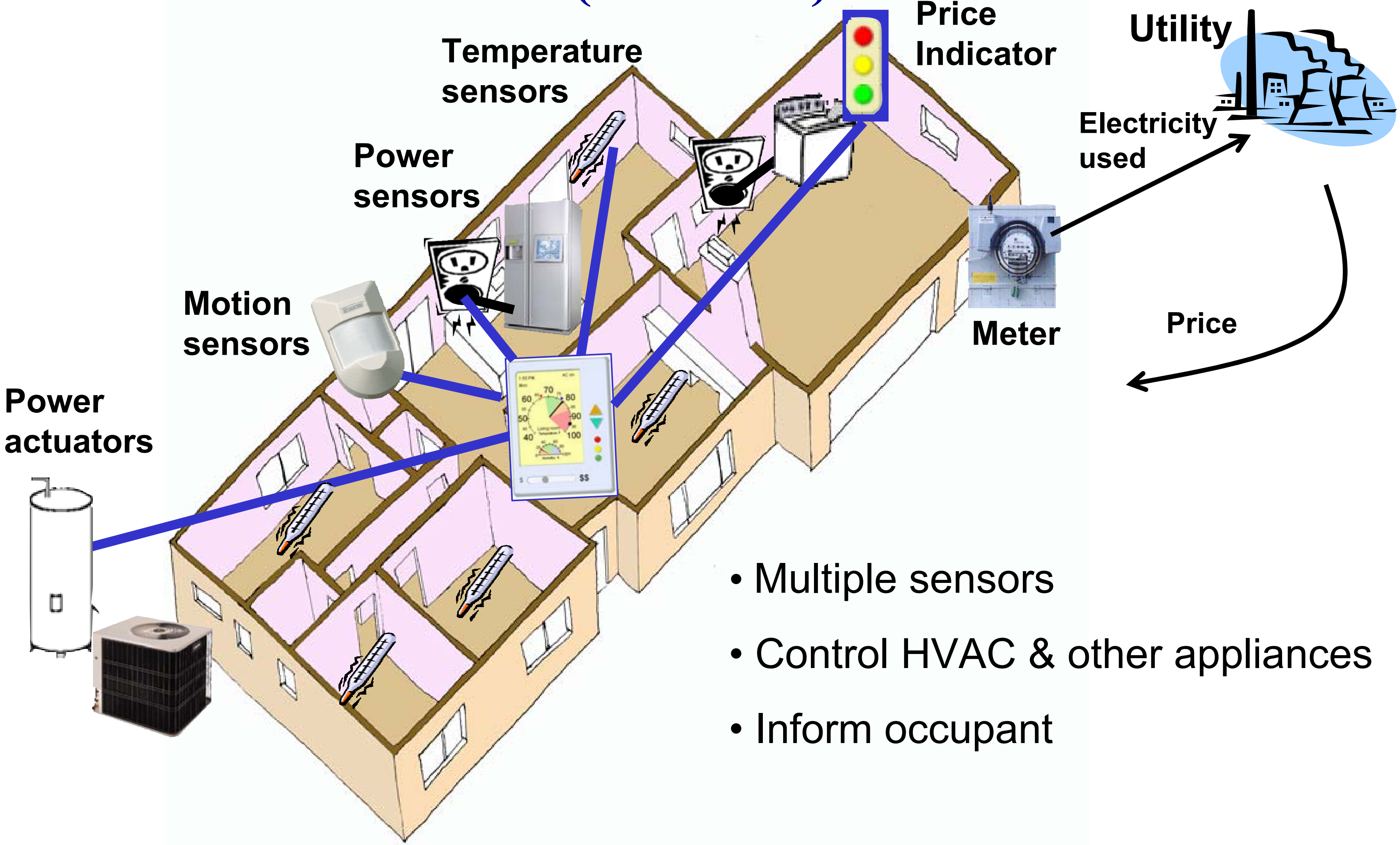
0 dbM Transmitters

Courtesy: J. Rabaey, K. Pister

Thermostat/Control Group

- **Control Design**
  - Demand Response Electrical Appliance Manager
  - Residential Energy Manager
- **Simulation**
- **Hardware & Network Testing**
- **Customer Implementation Issues**

Demand Response Electrical Appliance Manager (DREAM)



- Multiple sensors
- Control HVAC & other appliances
- Inform occupant

DREAM Goals

* Work out of box (built-in defaults)
* Simple to use
* Automatic control in response to price
* Guide occupant behavior
* Learn occupant preferences & house characteristics
* Educate & inform (energy use, price)

DREAM Control Code

Control of simulated, model, or real houses

Controller

Java

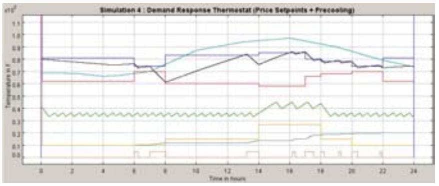
Sensor/ Actuator Module

Java

Interface

XML

Simulation



RF

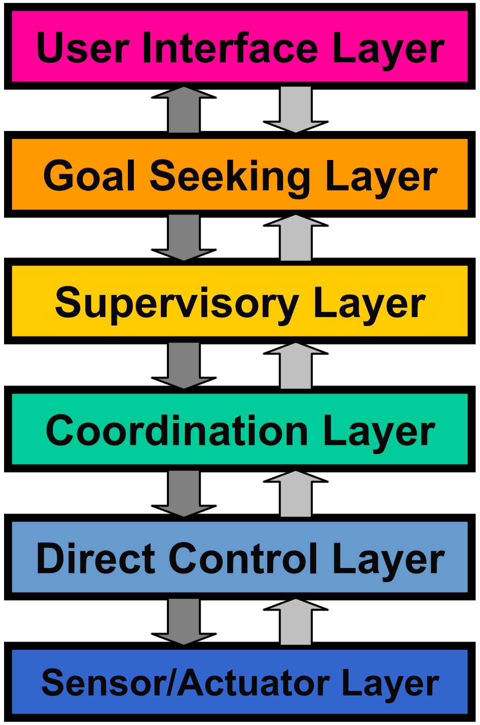
Physical Model

RF

Real House

System Control

- Layered control
- Used to build control software for experiments to-date
- Next challenge:
  - Autonomous behavior



Why Layering?

- **Advantages**
  - Modularity – design teams work on a layer
  - Interoperability – modules from various sources can interact
- **Disadvantages**
  - Optimization limited to layers (not global)
  - Interfaces between layers are fixed – hard to add functionality requiring new information

On Balance …

- Layered design has been very useful thus far
- A lot of software (Java) but few problems

Autonomy

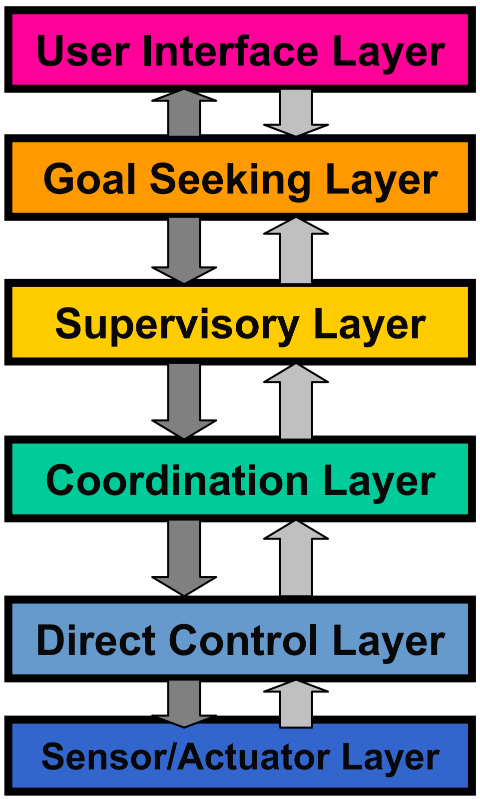
- Residential DR systems do not have professional management
- They must react reasonably to a price or reliability signal even if nobody is home
- They must work satisfactorily out-of-the-box (half of programmable thermostats aren't ever programmed!)

Widening The Control Hierarchy

- **Decision-making – the goal seeking layer**
  - A query path to lower layers
  - Adds to the signal flow path
- **Layered learning**
  - Each layer needs to learn what it needs to perform its own function well
  - Each layer needs to learn what it needs to respond to queries from other layers

Example of Query

Assessing potential for precooling



Q: What is user's temperature preference?
A : 75F

Q: How much power is required to sustain desired temperature in normal mode versus pre-cooling mode?
A : 2500W (pre-cooling mode), 800W (normal mode)

Q: Which device uses least power to sustain desired temperature in normal mode versus pre-cooling mode?
A : Whole house fan

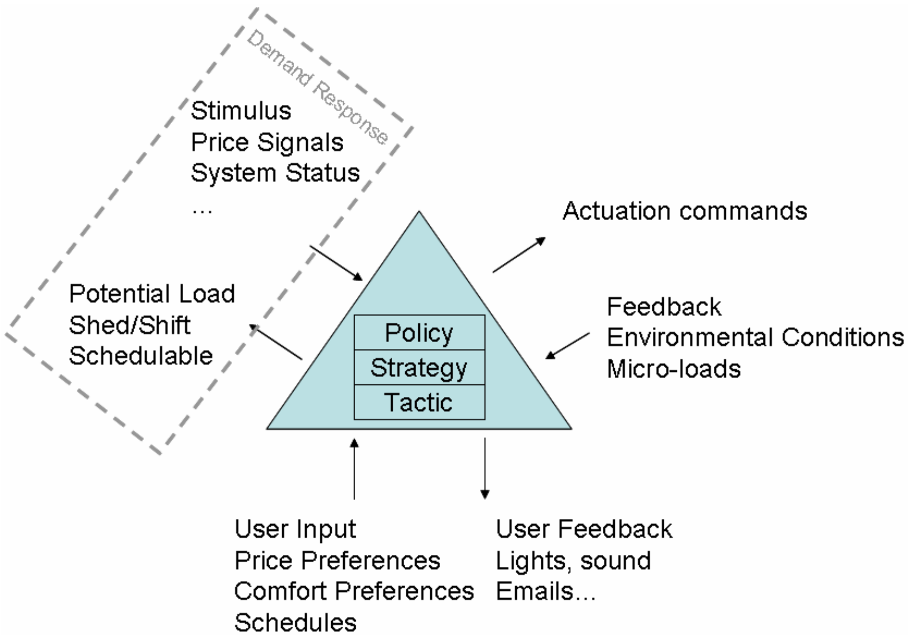
Q: How much power is required for each device to keep temperature at desired value?
A : 500W(whole house fan) , 2500W(AC)

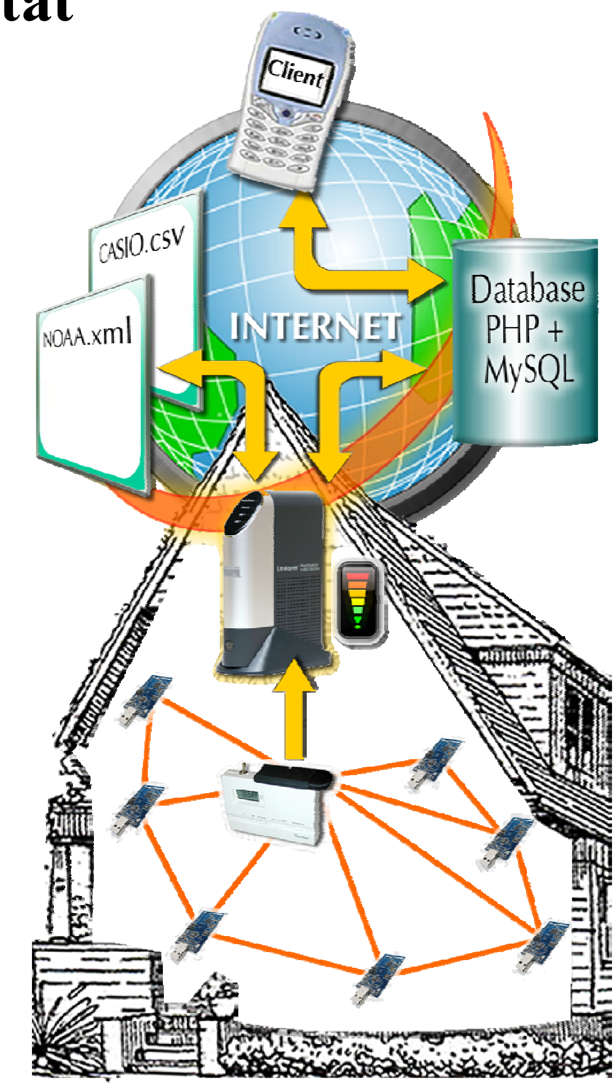
Single-zone Actuation with Multi-zone Sensing

- Reduce energy consumption
- Increase satisfaction

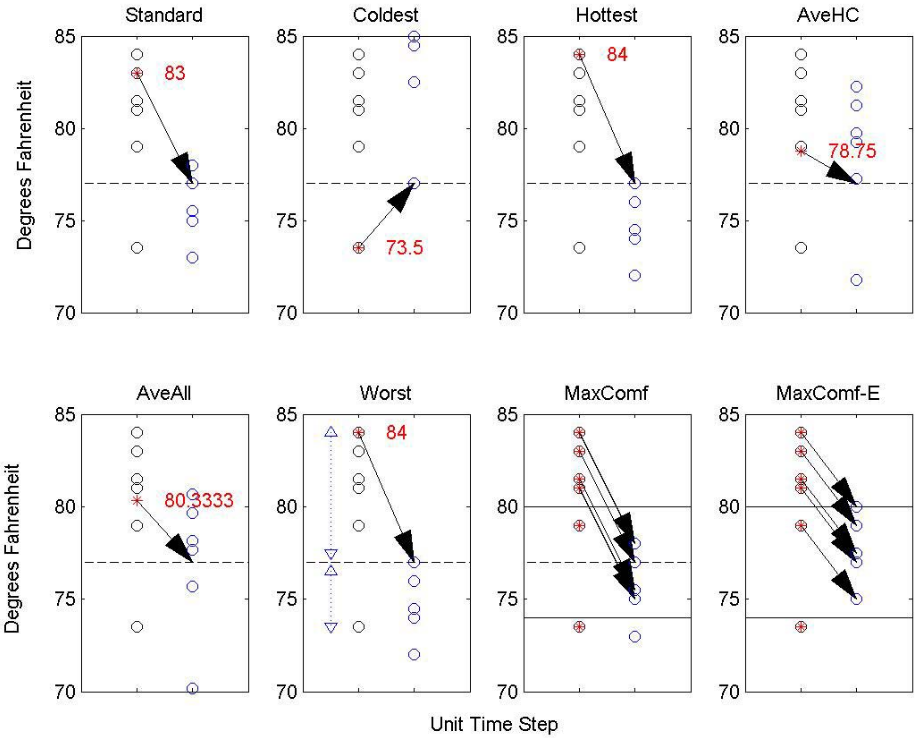
The Residential Energy Manager

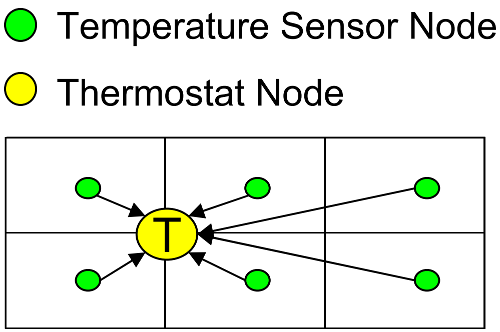
- Uses modified standard thermostat





HVAC Control with Distributed Sensing

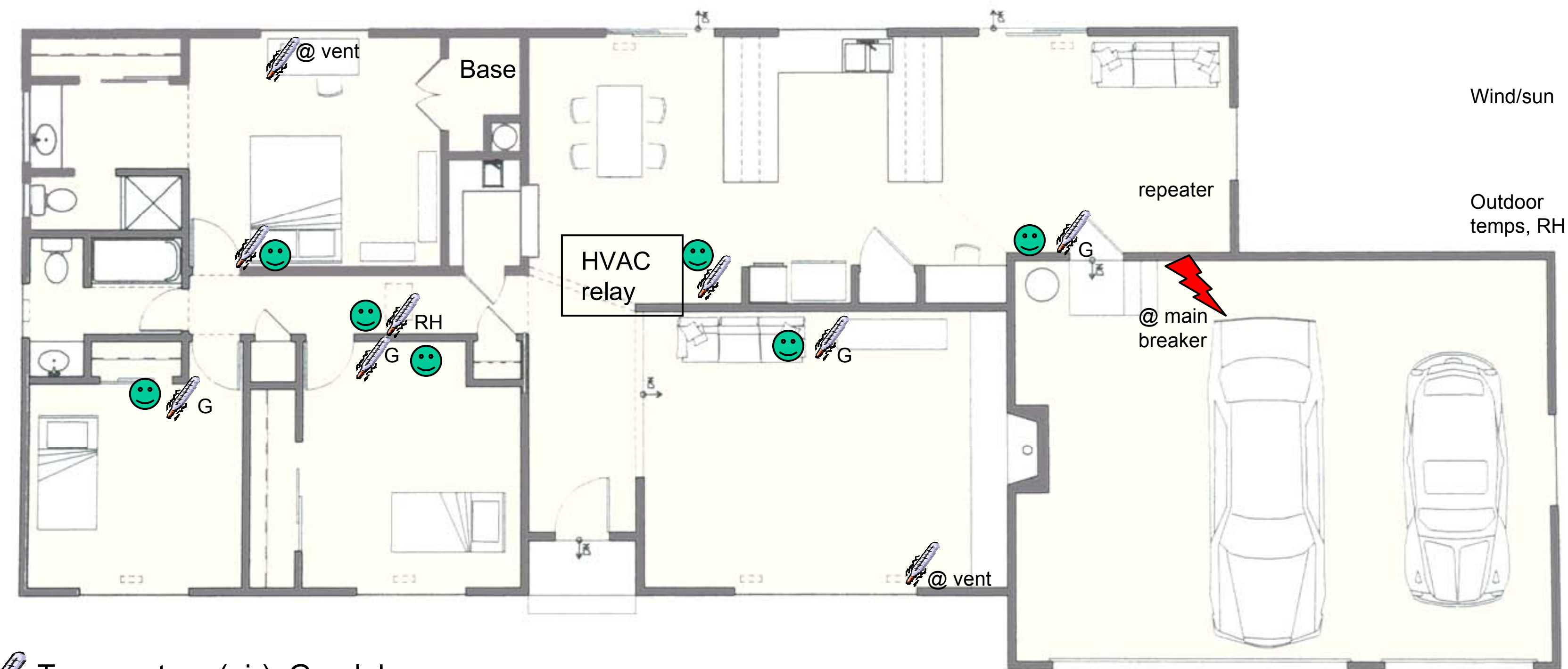




<u>Conclusion</u>: Simulations show that some work, some don't

Summer 2006 pilot deployments throughout California.

House Test 2005: System Integration



Temperature (air), G= globe
Temperature (air) + RH
Occupancy
Power sensing (breaker panel)

Weather station on roof (not shown)
Anemometer (wind direction and speed)
Pyranometer (total horizontal radiation and diffuse radiation)
Outside Temperature (exposed to night sky, not exposed)
Outside RH

HVAC Control

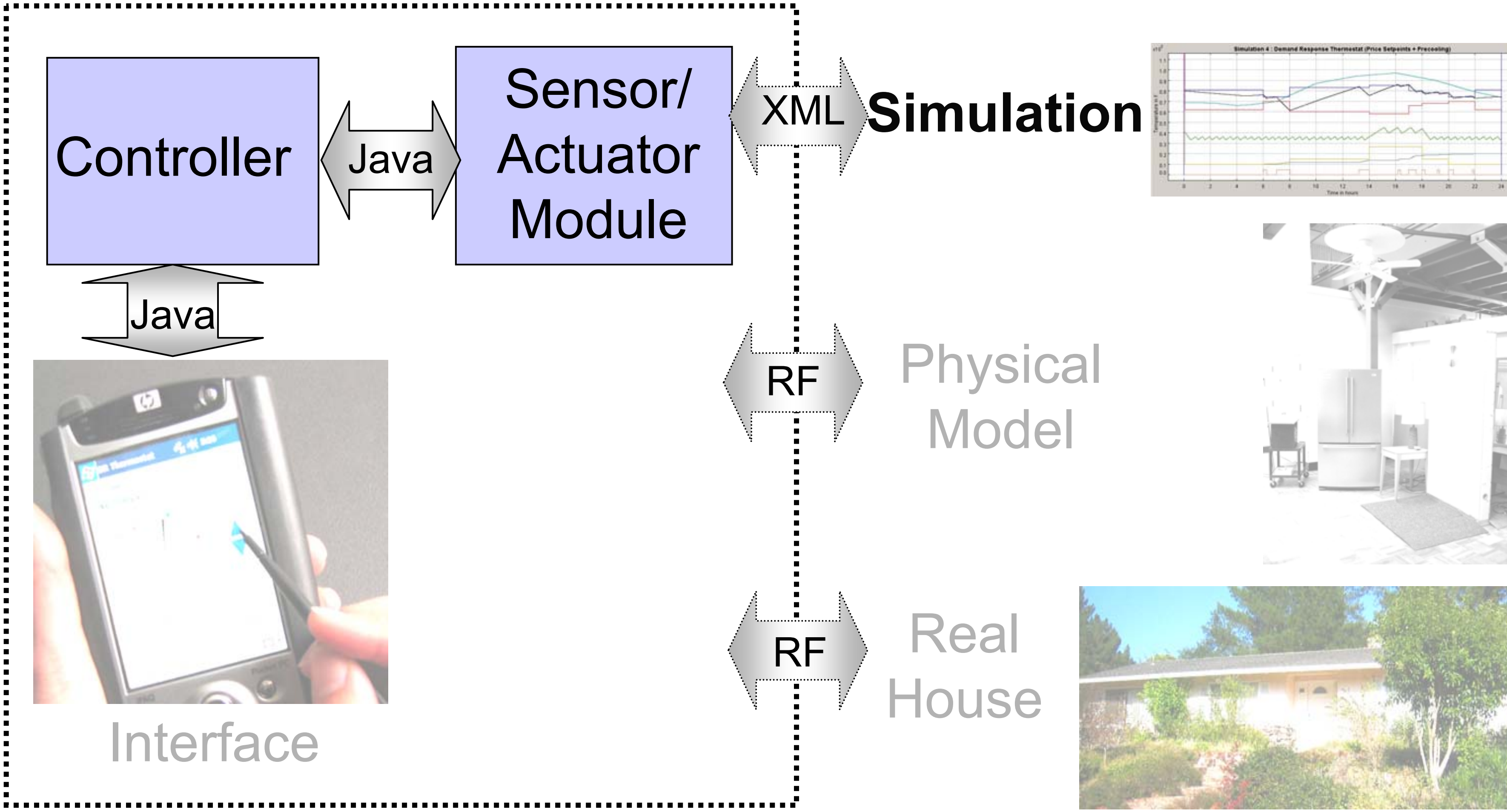
- Replace traditional thermostat with mote controlled relays

Price Indicator

- Transmit price information to residential customer
- Next step is to add sound

DREAM Control Code

Control of simulated, model, or real houses



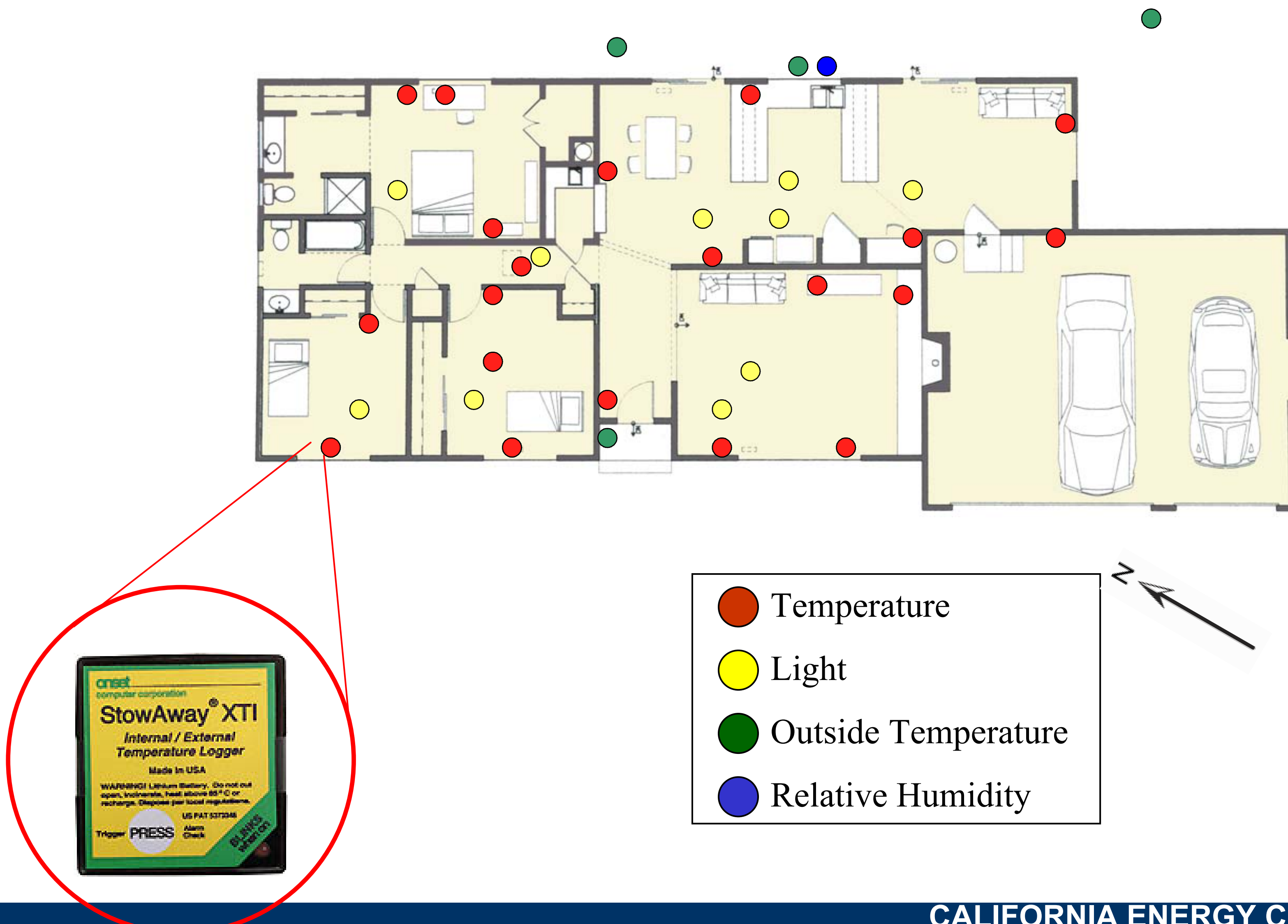
MultiZone Energy Simulation Tool (MZEST)

- Based on California Non-Residential Engine
- 5 minute time step
- Calculates temperatures for each room or zone

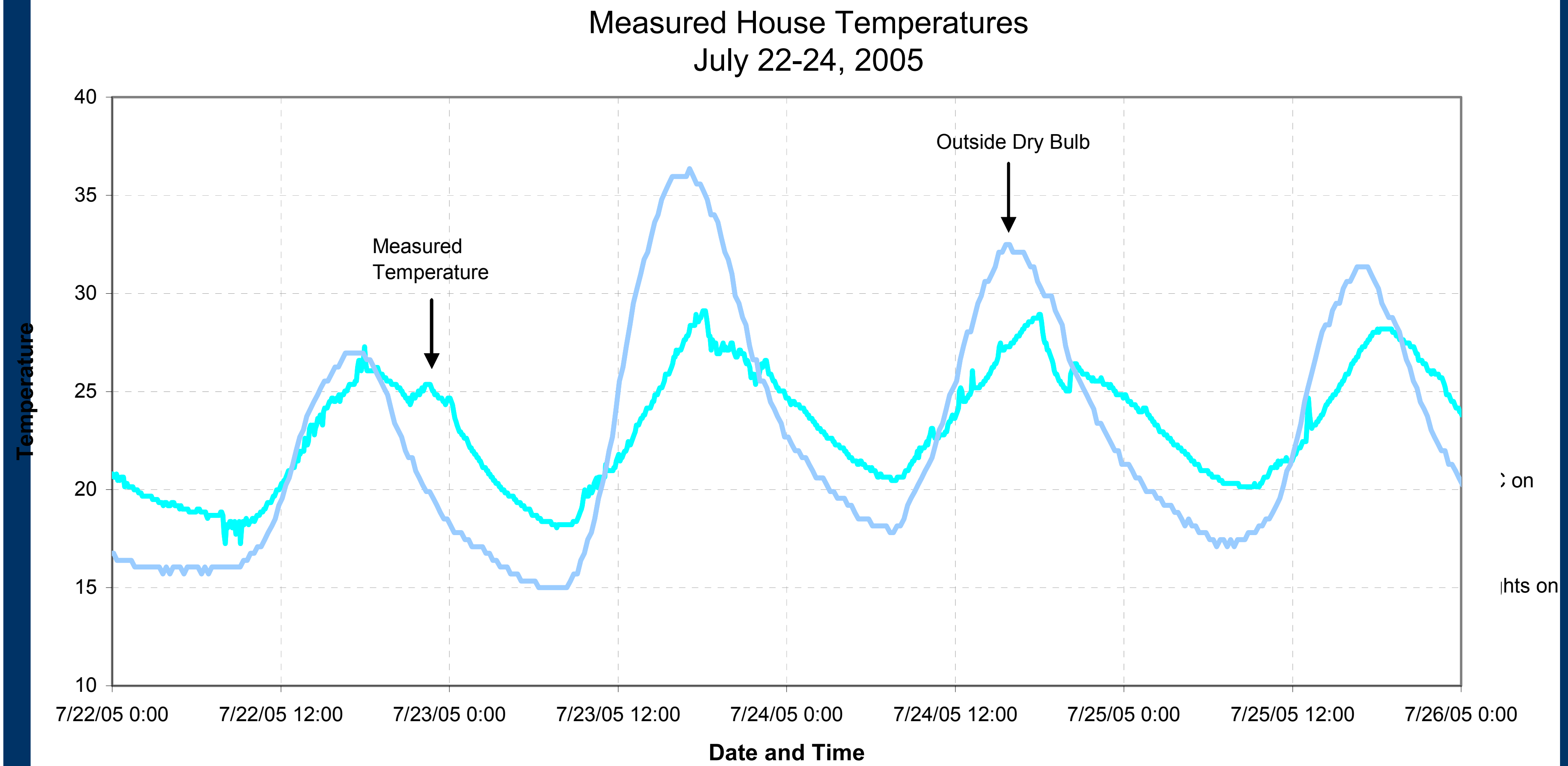
Simulation Tool Calibration

- Independent datalogger-based monitoring system used to validate mote sensors and to provide data for initial simulation model calibration
- Weather station measures site microclimate
- Mote sensor data used to refine the simulation model

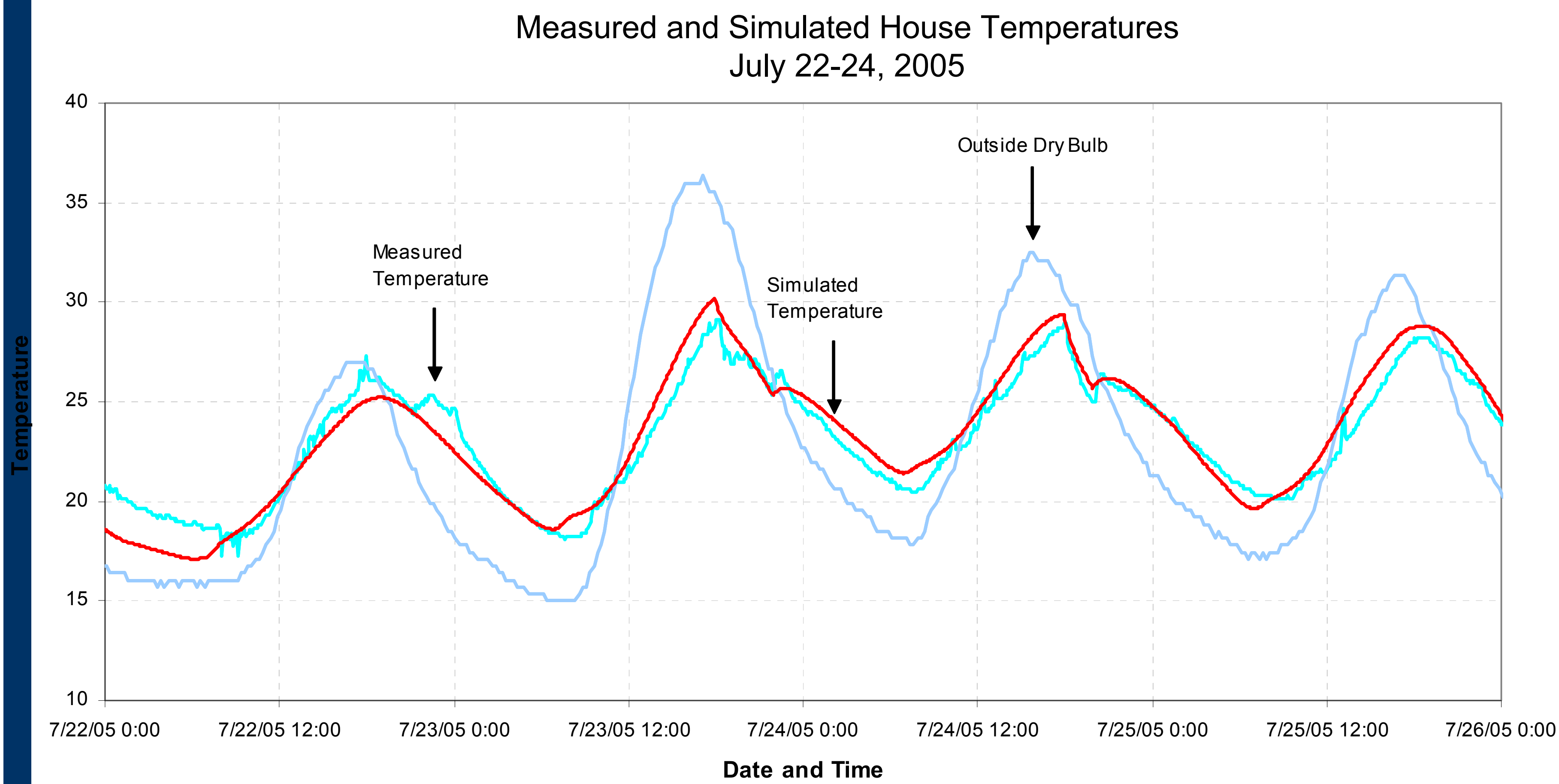
Datalogger Locations



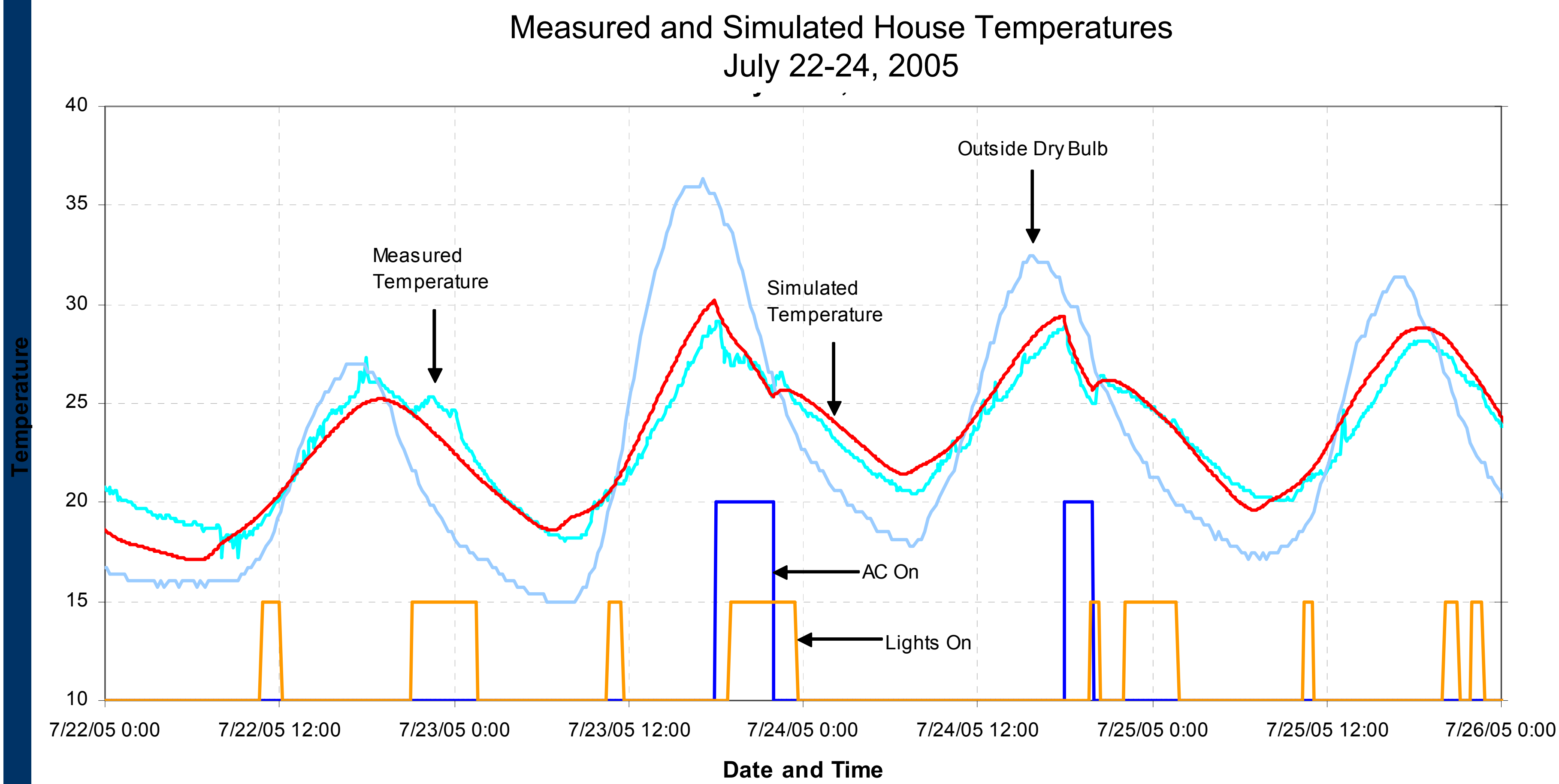
Measured Data



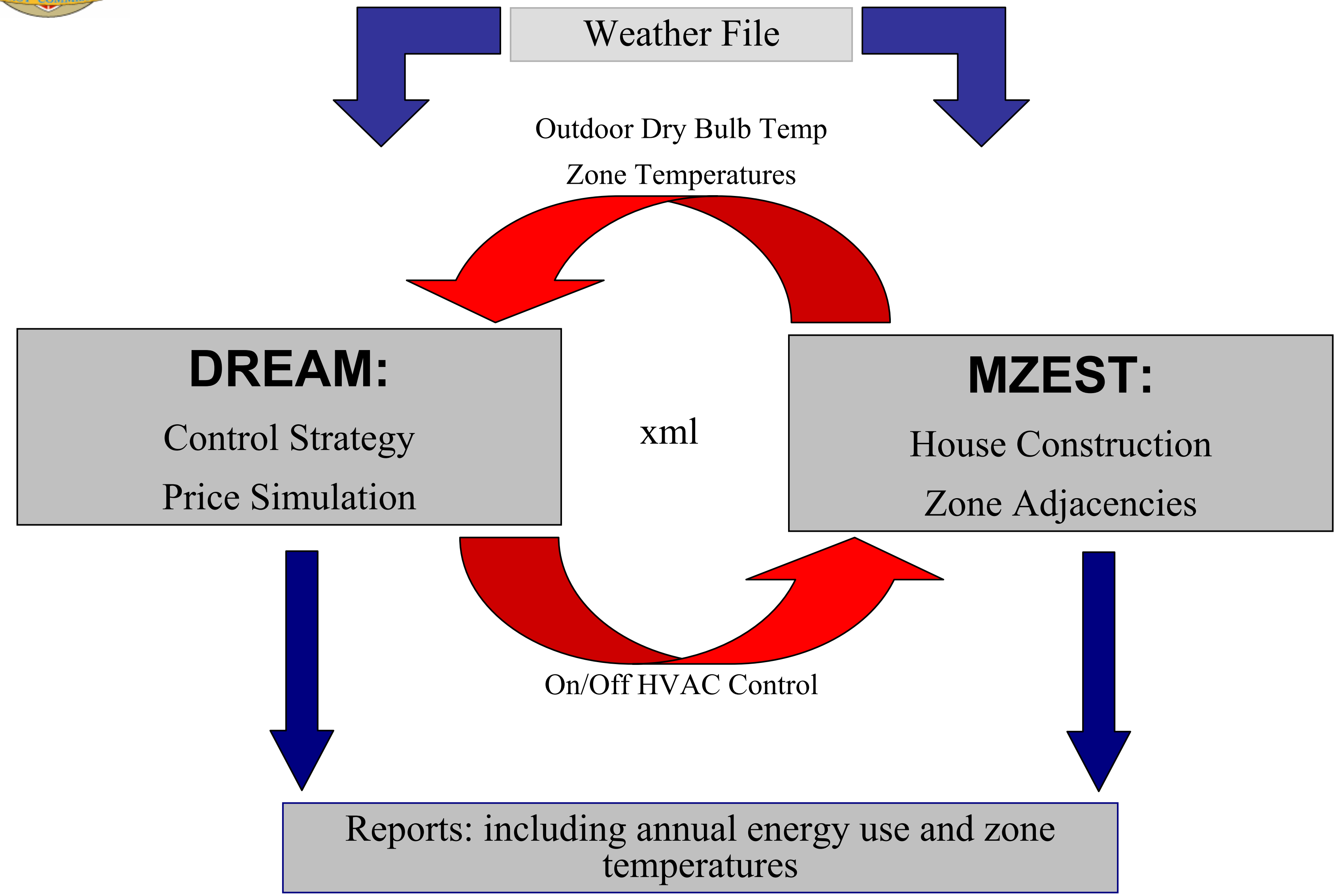
Simulation Results



Simulation Results



DREAM Controlling MZEST



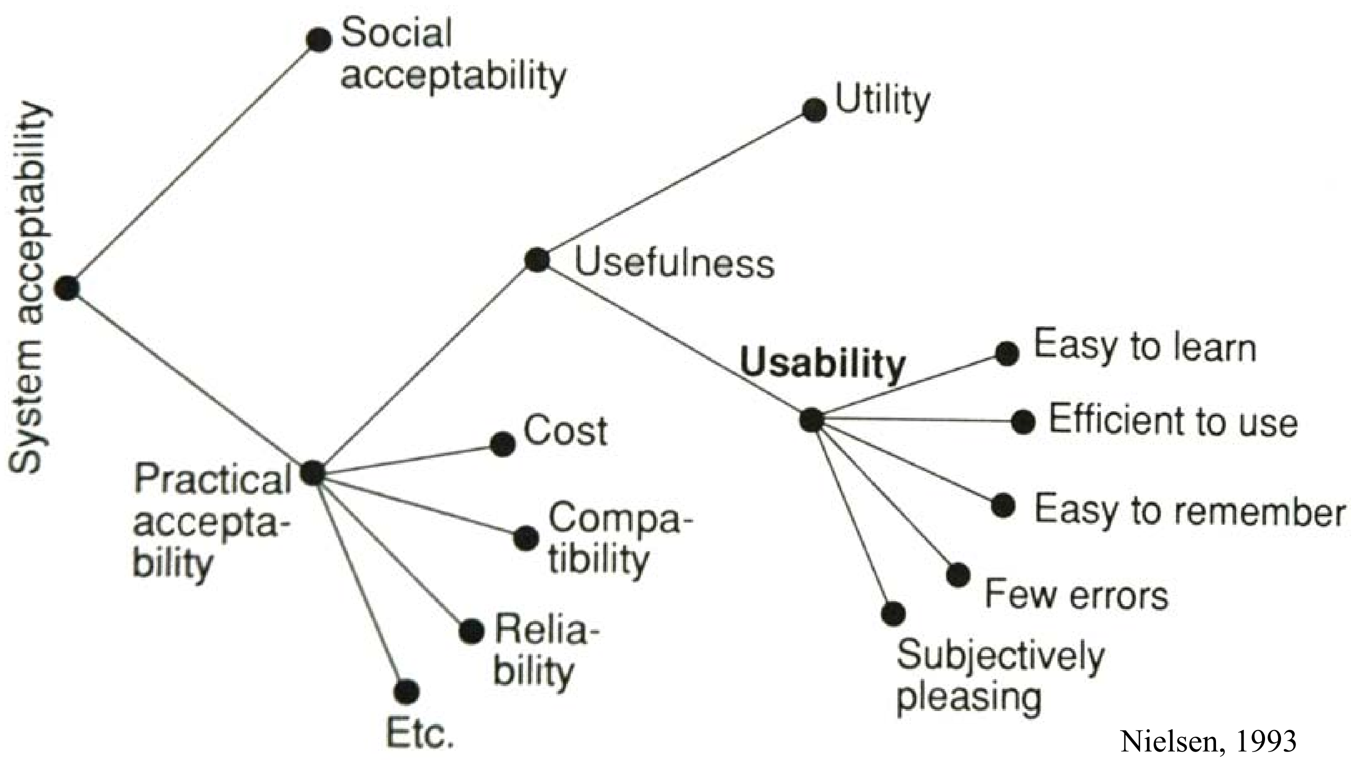
Customer Implementation Challenges

- **Technology and Infrastructure**
  - Communication
  - Control
  - Metering
- **Customer Participation**
  - Acceptance
  - Usability
  - Adoption

"Technology will be adopted only if the perceived return outweighs the effort required to understand the new technology" (Mozer, 2005)

Acceptance and Adoption

System acceptance of Demand Response technology occurs at many levels.



Nielsen, 1993

Social Acceptability

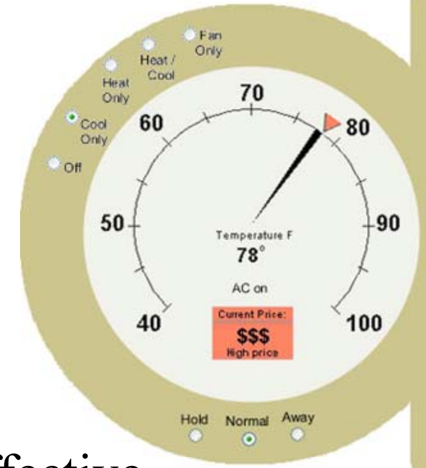
- **Programmable thermostats not well adopted and used: half CA households have them, about half of these are used in program mode**
  - Too difficult to program
  - Lack of understanding of how they work (myths)
  - Lack of need
    - Personal control increases sense of comfort
    - No energy savings
      - Occupant's attitude determines savings
- **In Statewide Pricing Pilot, 19% *increased* use during peak period**

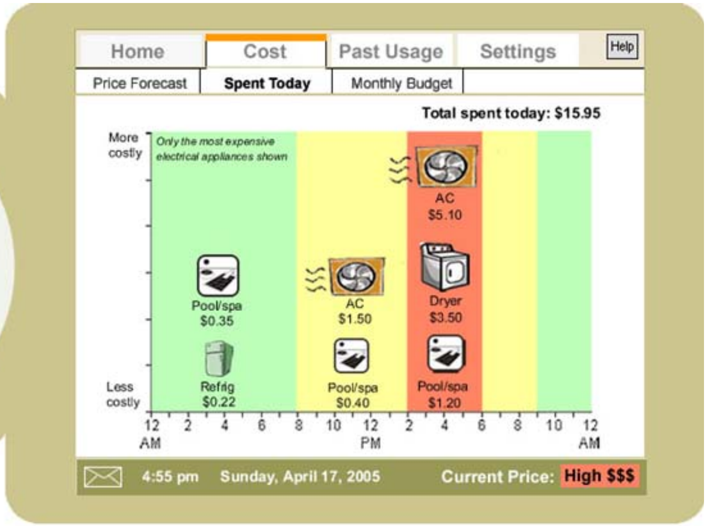
Stochastic Behavior

- **Residential energy end use highly variable**
  - 200-300% difference in energy between identical houses
- **Comfort models for commercial sector not applicable for residential sector**
  - Temperature preferences highly variable
  - Schedules, clothing levels, metabolic rate more flexible than office environment

Design of DREAM interface

- **Control:**
  - allow user to control
  - provide feedback





- **Information**
  - provide training
  - feedback + advice effective
  - humanized info
  - energy consumption per device effective
  - compare with neighbor

- **Next steps: heuristic evaluation and usability testing**

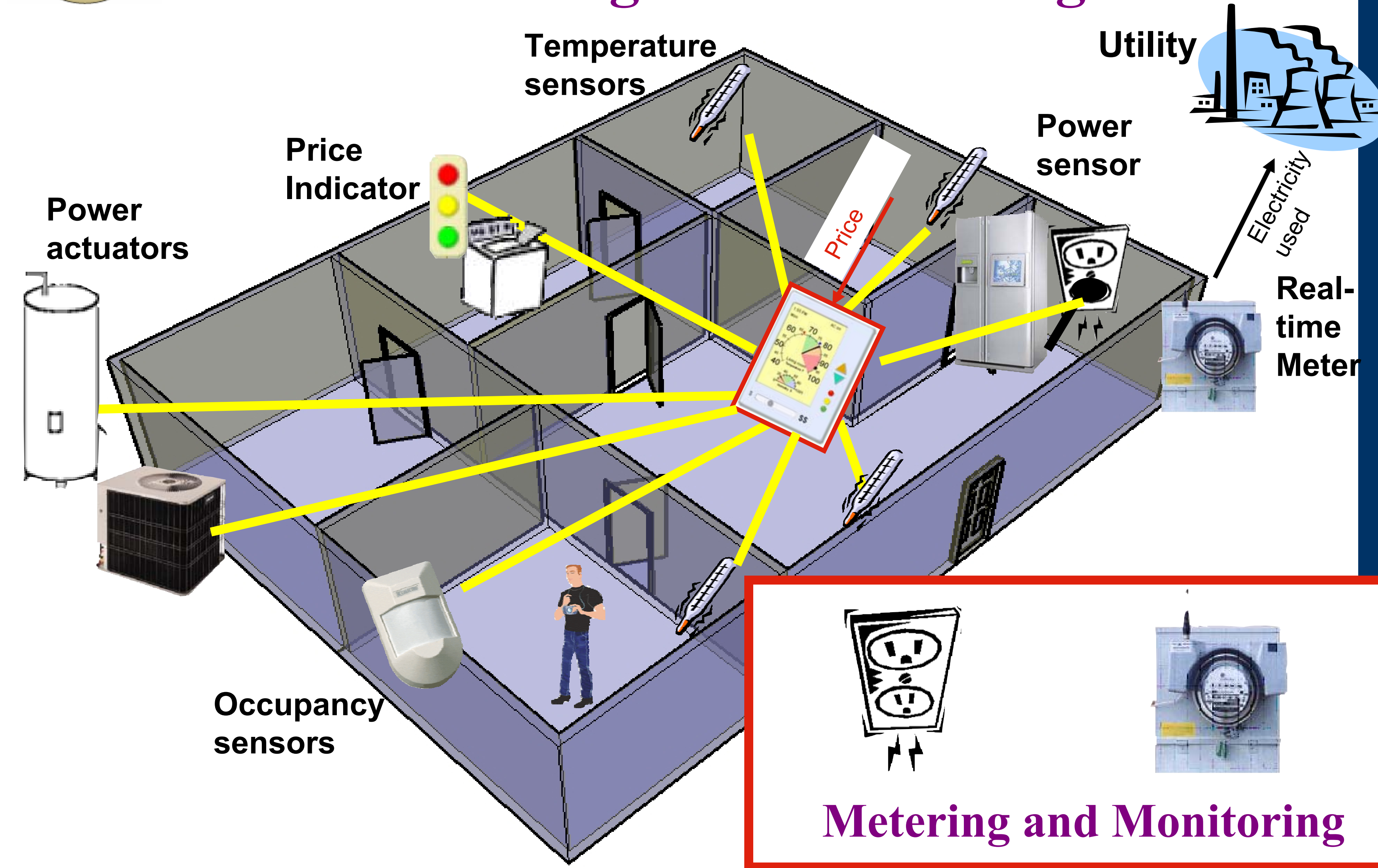
- Please visit our poster session for more details.

Electrical Sensor Work

Contributors:

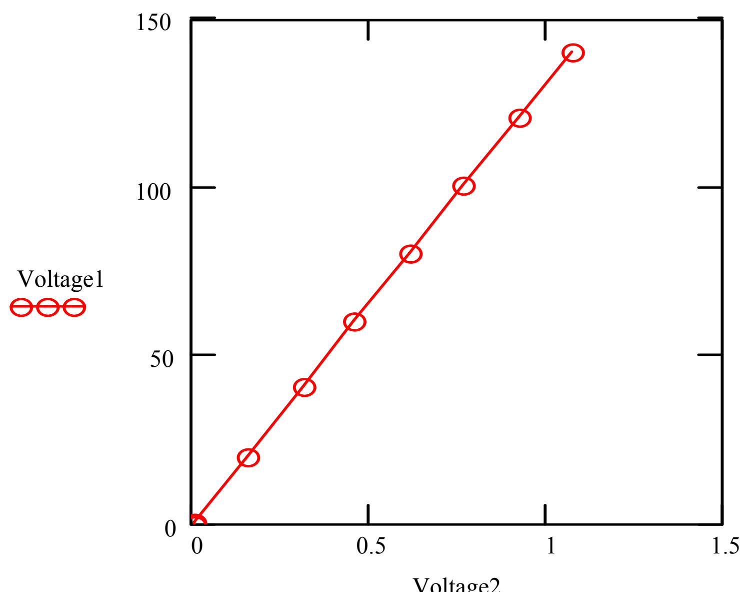
Eli Leland (Ph.D. student, with Prof. Wright);
Xin Yang (CS/Math graduate);
Tho Nguyen (engineer);
Dick White (Prof. in EECS and Founding Co-Director of BSAC)

Sub-team #3: Sensors for Metering and Monitoring

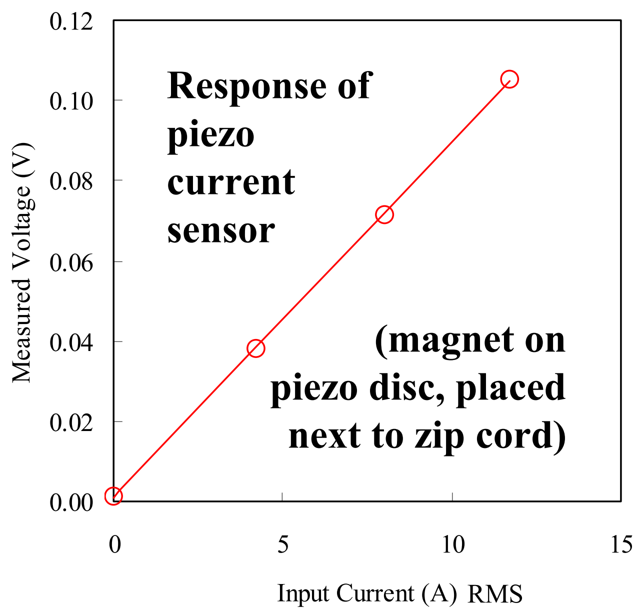


Challenge: Make sensors for AC voltage and AC current that are passive and operate in close proximity to insulated AC wiring?
Passive so they don't require DC power source (replaceable batteries)
Proximity so we don't have make conductive contact to wiring

AC Voltage sensor: Electrostatically couple electrodes near insulated wires and detect using analog/digital converter on wireless mote for transmission:

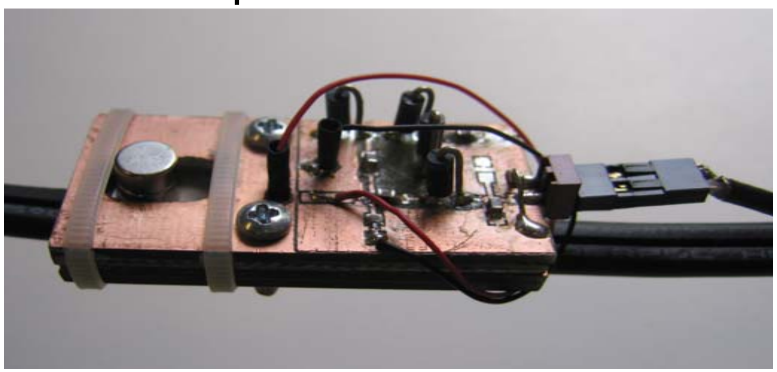


AC current sensor: Locate piezoelectrically-coated cantilever with attached magnetic material near current-carrying insulated wires. Output voltage is proportional to peak electric current.

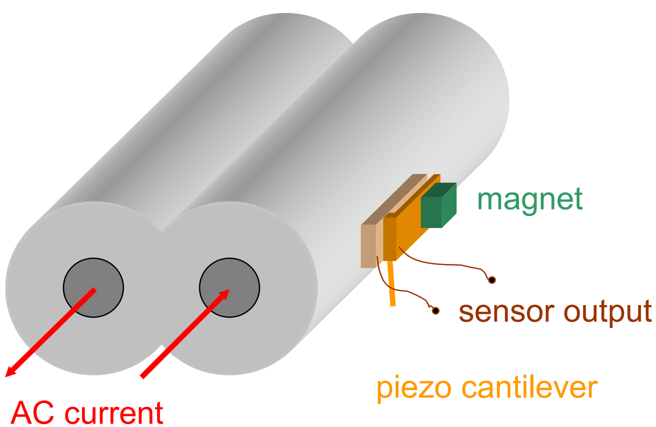


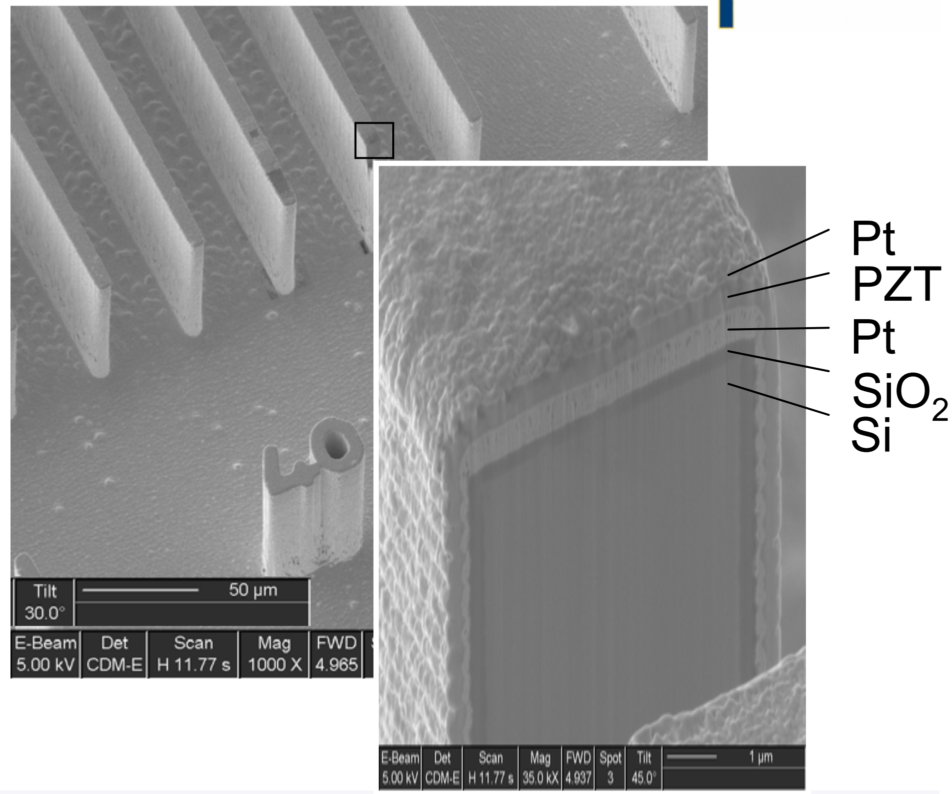
Proximity Current Sensor

Meso-scale current sensors on zipcord with permanent magnet on cantilever coated with piezoelectric



Proposed MEMS-based AC current sensor





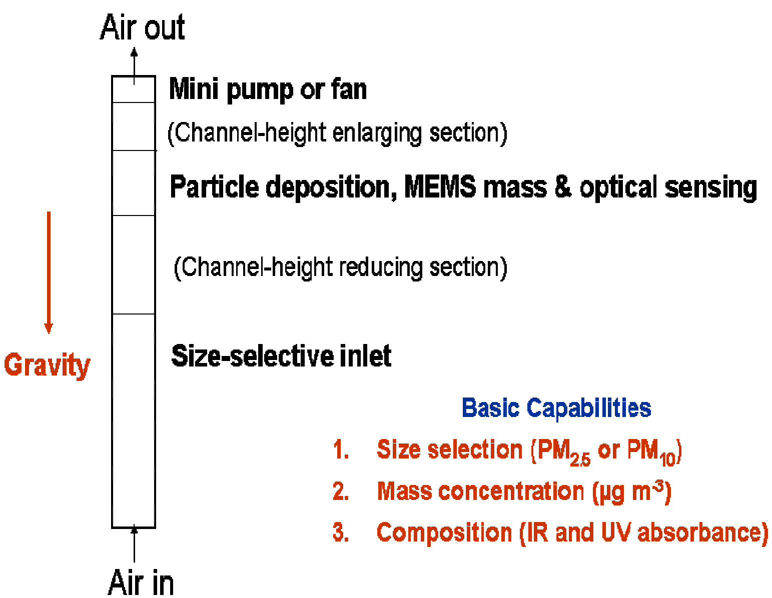
PZT film on sidewalls creates piezoelectric bimorph structure

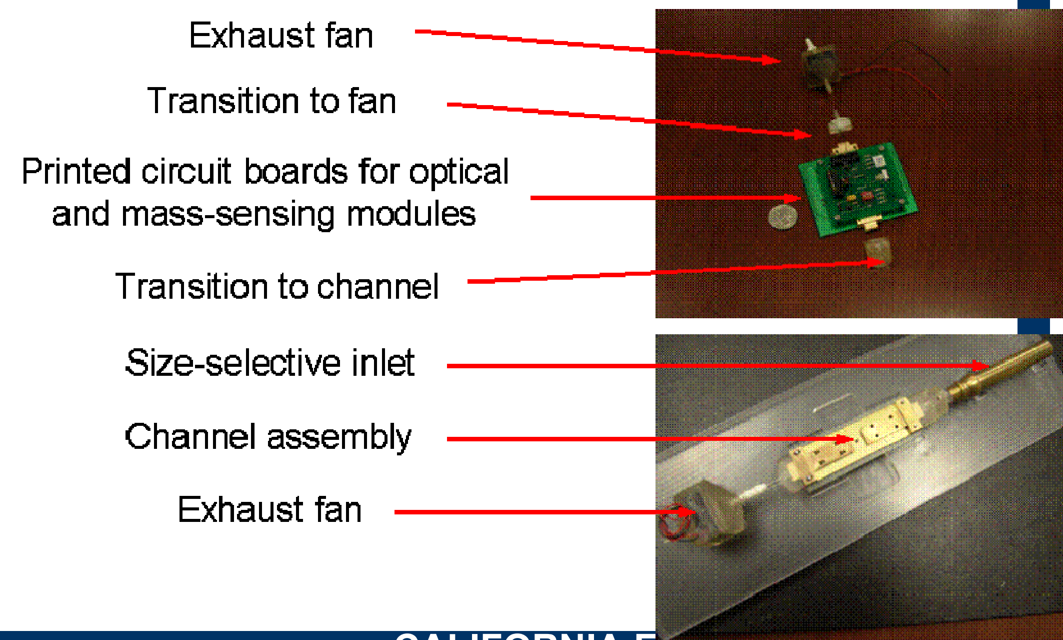
A BIT MORE ABOUT MEMS

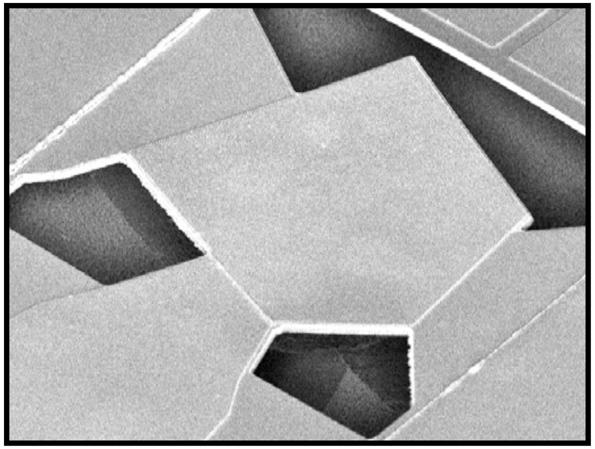
MEMS-based portable inexpensive particulate matter monitor (CEC+).

→It shows the advantages of using MEMS for small size, low cost, potential for battery operation, sensitivity, easy electronic control, etc.

→Such an instrument when coupled to a GPS unit or cell phone with localization capability, could be used in epidemiological studies of health effects of airborne particles such as diesel exhaust, environmental tobacco smoke (ETS), wood smoke, and power plant emissions



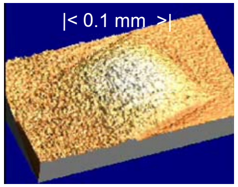




1.6 GHz film bulk acoustic resonator (FBAR) to measure deposited mass

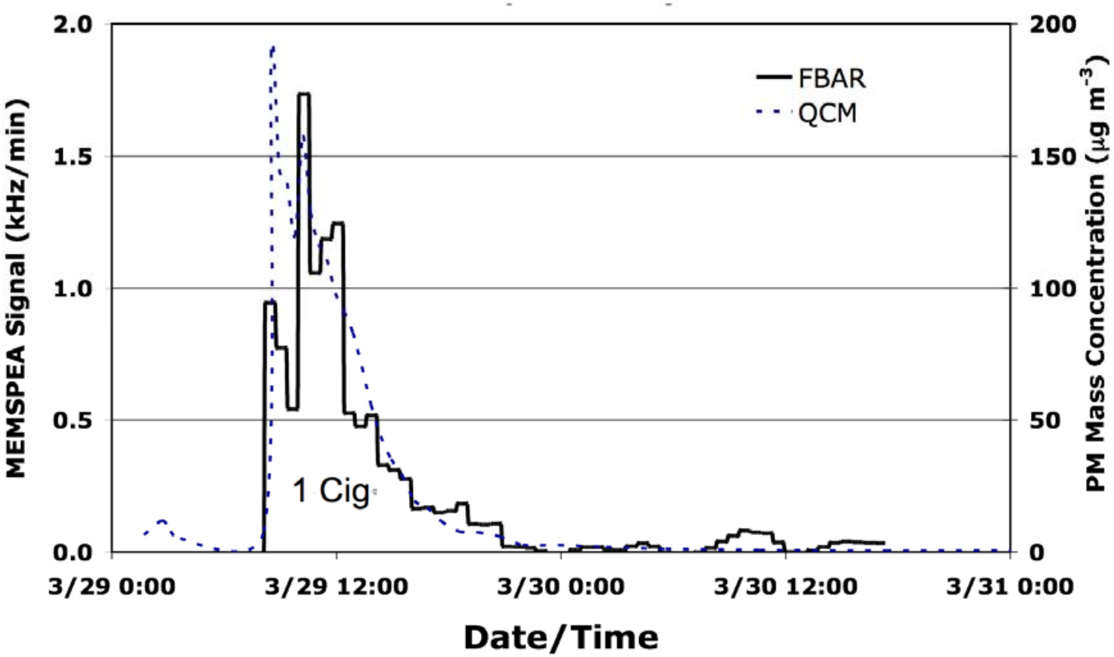
QCM

FBAR



Sensor	Device Description	Typical Operating Frequency (MHz)	Calculated Theoretical Mass Detection Limit (ng/μm^2)
Quartz Crystal Microbalance (QCM)	AT-cut Quartz	6	0.70
Surface Acoustic Wave (SAW)	ST-cut Quartz	100 -500	0.08
Flexural Plate Wave (FPW)	Micro-fabricated ZnO, SiN,Al	2 - 5	0.02
Film Bulk Acoustic Resonators (FBAR)	Micro-fabricated ZnO, SiN,Al,Au	1000 - 2000	0.01

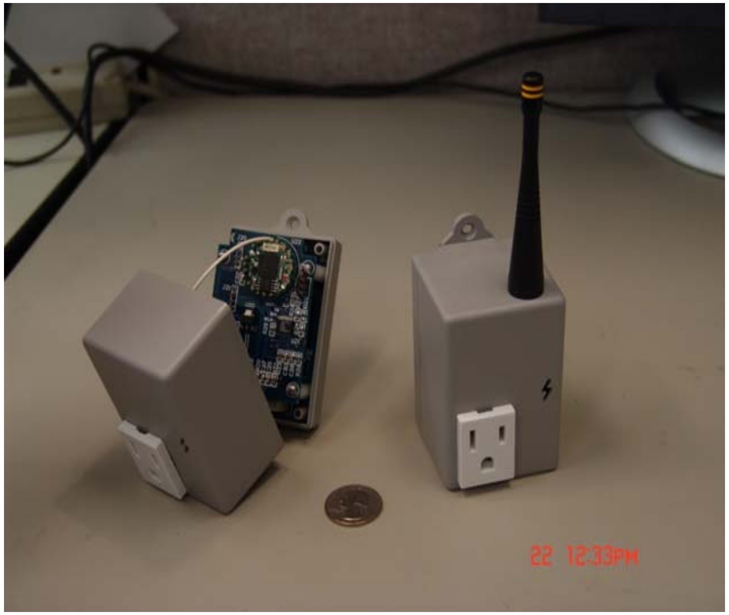
- FBAR: sensitive to ~ 1pg
- FBAR: capacity ≥ 1 ng
- Easy to micro-fabricate
- FBAR: arrays 2x2 to 10x10
- PM mass sensor on a chip



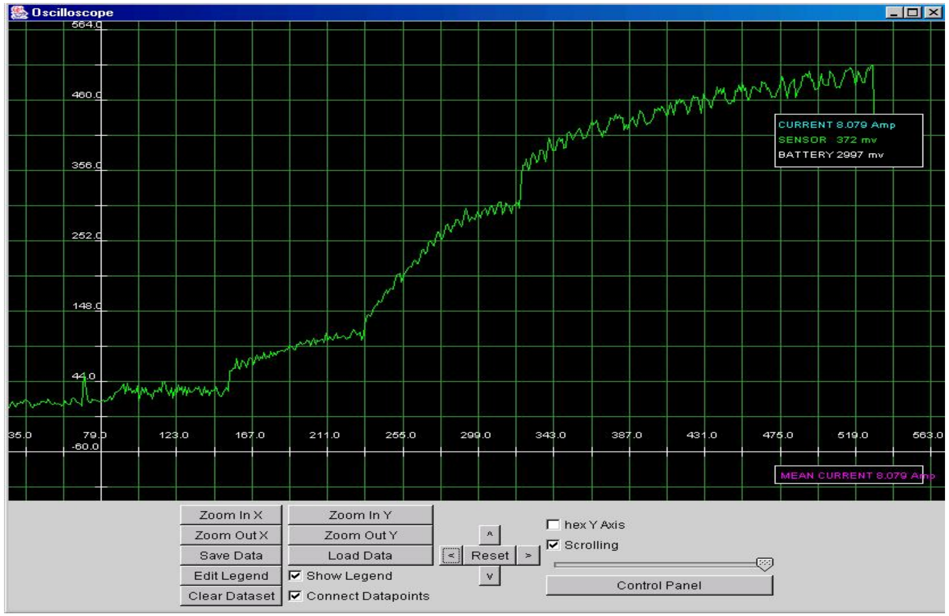
Response of improved FBAR mass sensor, taken in February, 2006, to ETS from one cigarette, agreeing well with commercial QCM mass-sensor data.

Monitor mass, volume and power consumption are 114 g, 250 cm^3, and no more than 100 milliwatts, respectively. Comparison with calibrated aerosol instruments in the field shows that mass concentrations as low as 10 μg/m^3 of PM2.5 particles can be monitored with the MEMS-based device over time periods as short as 30 min.

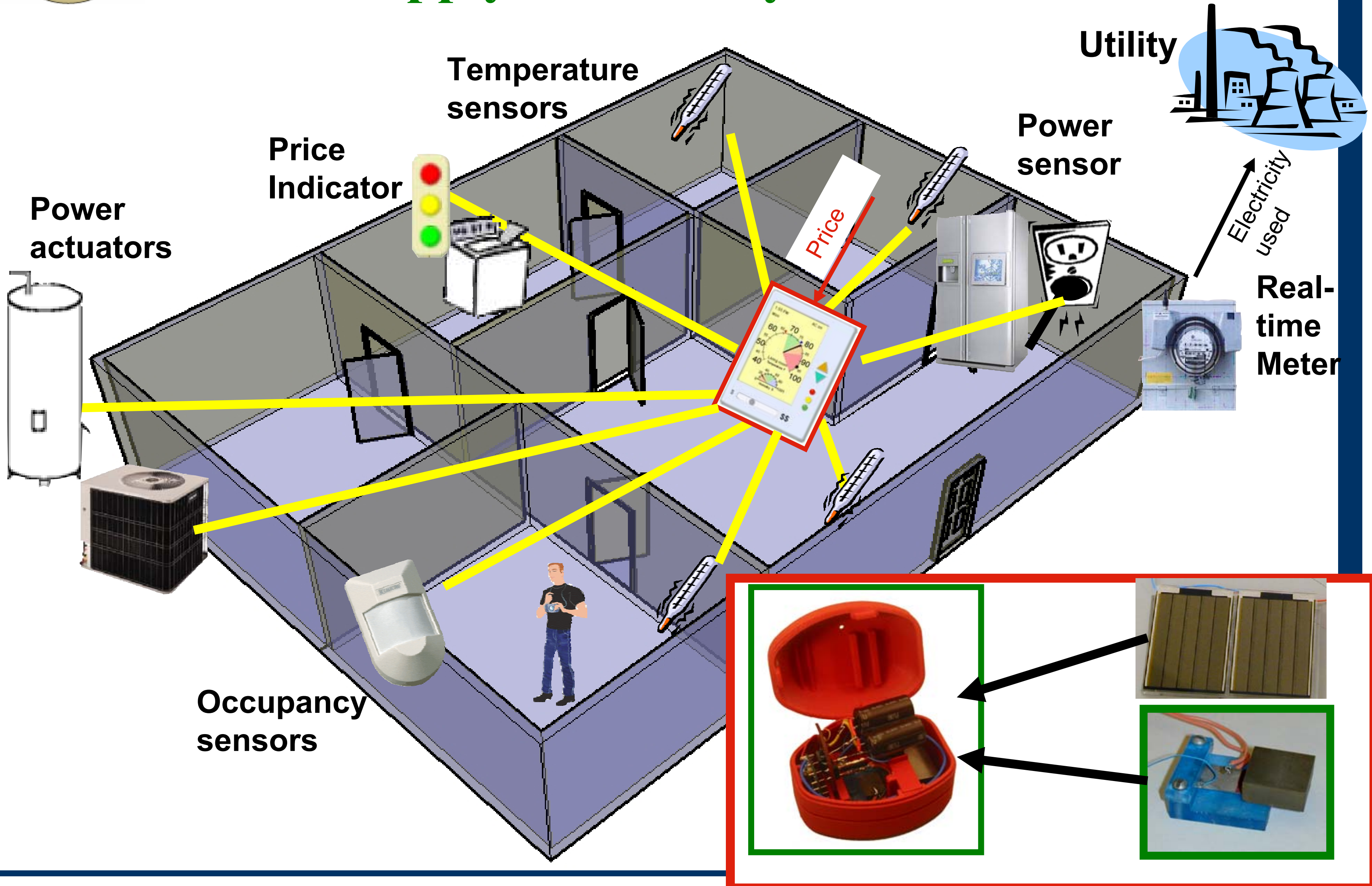
Wirelessly controlled metering outlet



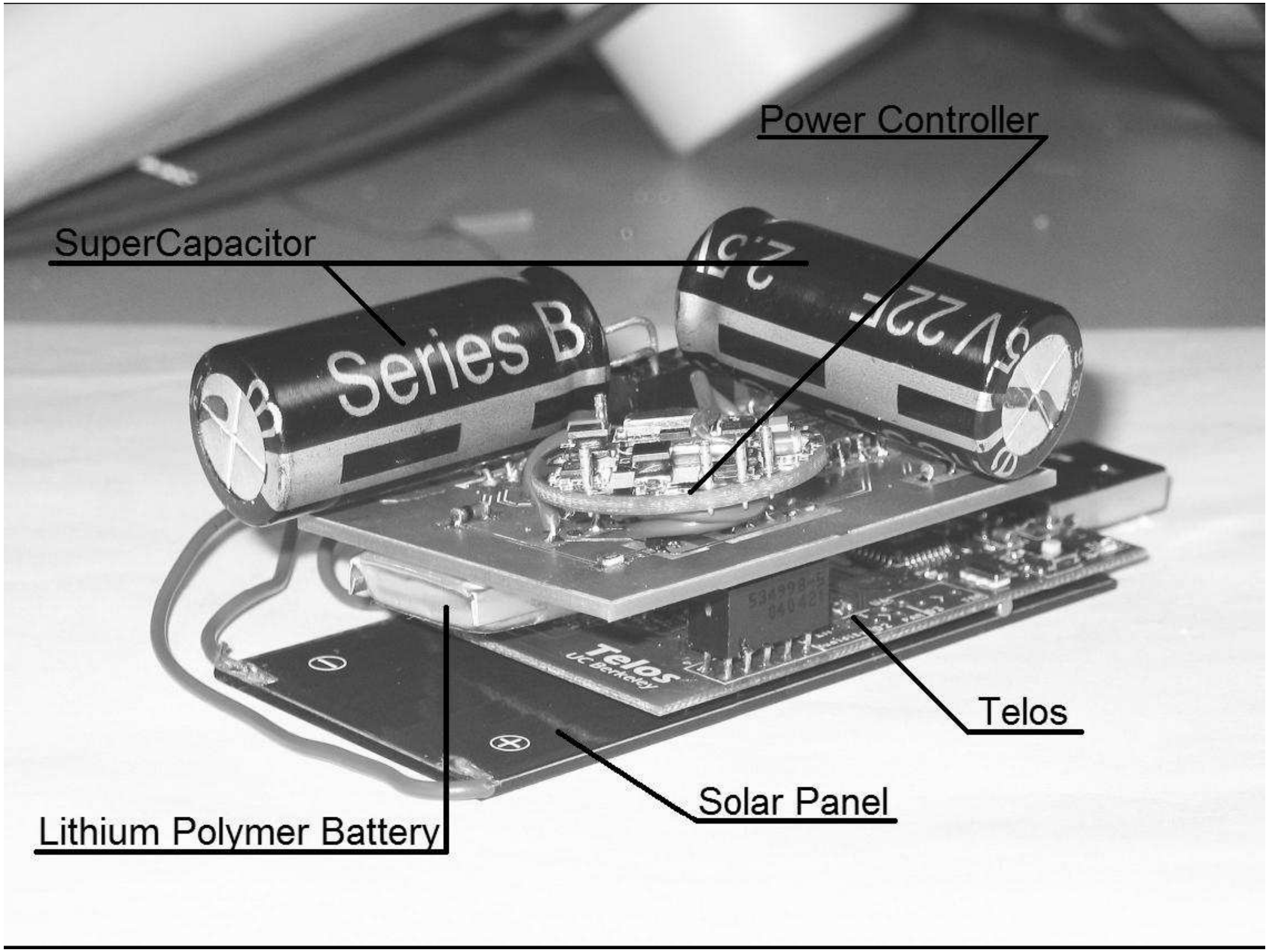
Sensor Data



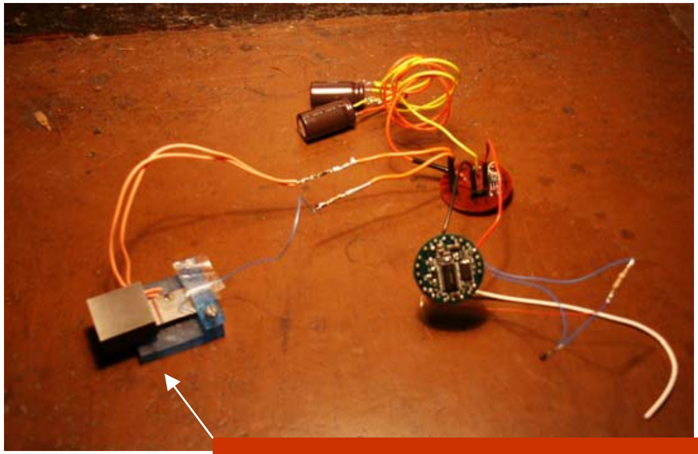
Sub-team #4: The power supply for the tiny devices



Environmental PV scavenging



Environmental vibrations

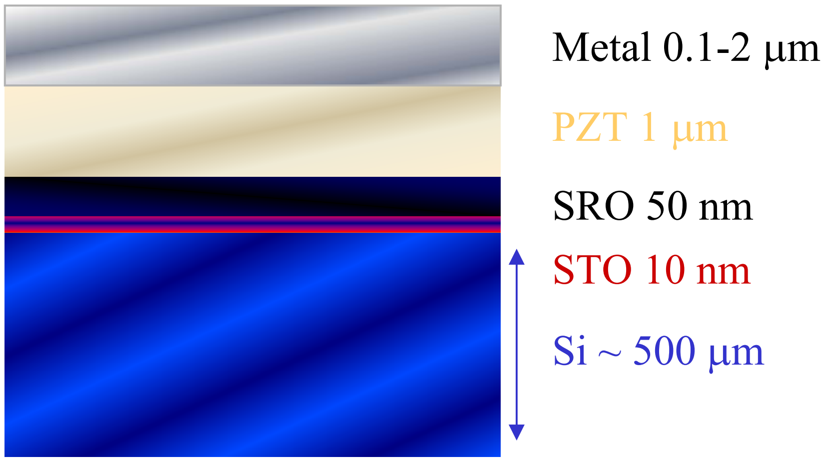


- Stair-Case Vibrations from Running Up and Down Stairs
- Piezoelectric: PZT
- Tungsten Alloy Mass: 52 g
- Beam Dimensions:
- 1.25” x 0.5” x 0.02”
- Resonant Frequency: 26.8 Hz
- Power Output: 450 μW

Piezoelectric “diving board” with tungsten mass

Cost reduction @ MEMS scale

Piezoelectric and Elastic Layers



1. $SrTiO_3$ (STO) coated (10 nm) single crystal Silicon **[Motorola, Inc.]**

2. Deposition of $SrRuO_3$ (SRO) bottom electrode, and PZT with pulsed laser deposition.

3. Deposition of metallic elastic layer via e-beam evaporation/thermal evaporation

Elastic Layer Deposition Methods

*__Pt-__ electron beam evaporation, Ti adhesion layer

*__Ni-__ thermal evaporation

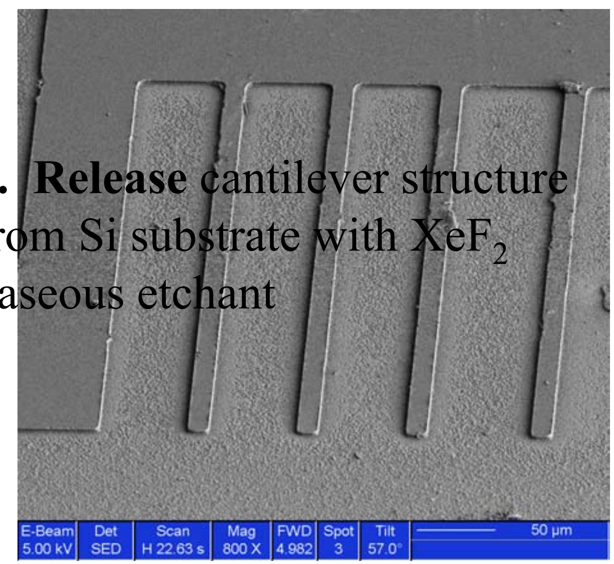
*__Au-__ electron beam/thermal evaporation, Cr adhesion layer

MEMS scale

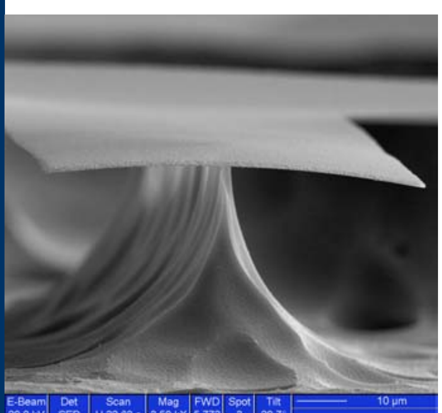
Cantilever Array Structures

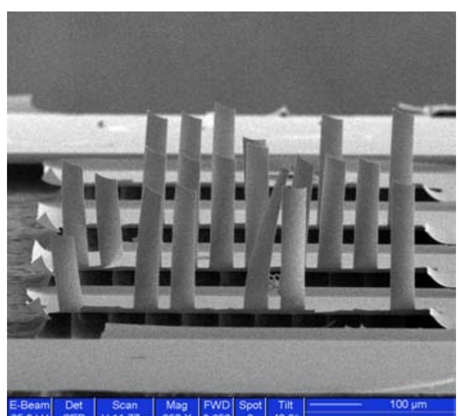
4. Definition of devices using photolithography

5. Etch heterostructure with Ar ion milling to expose Si substrate

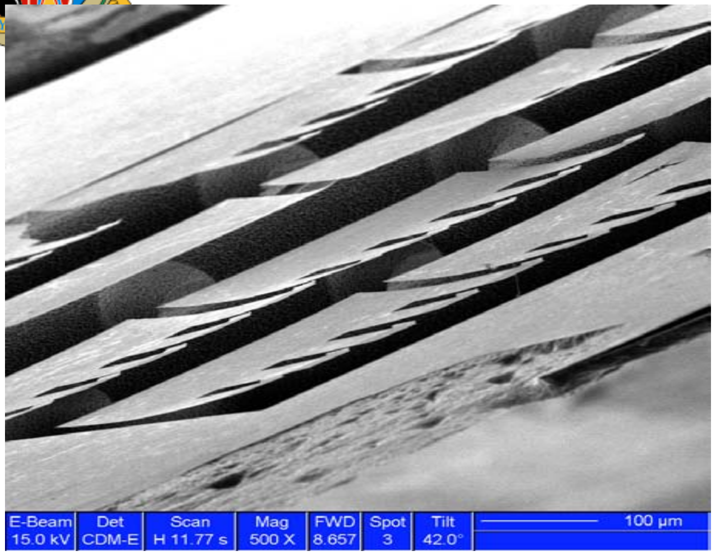


6. Release cantilever structure from Si substrate with XeF_2 gaseous etchant

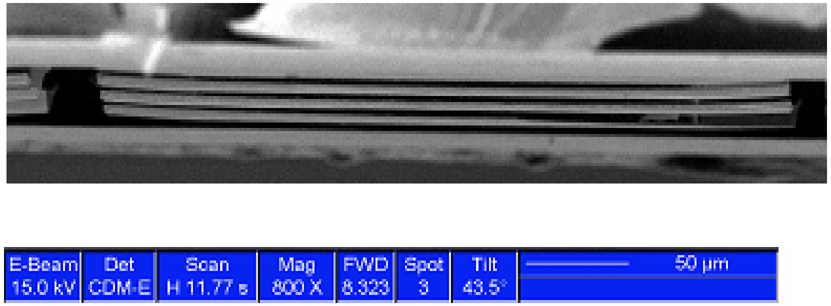


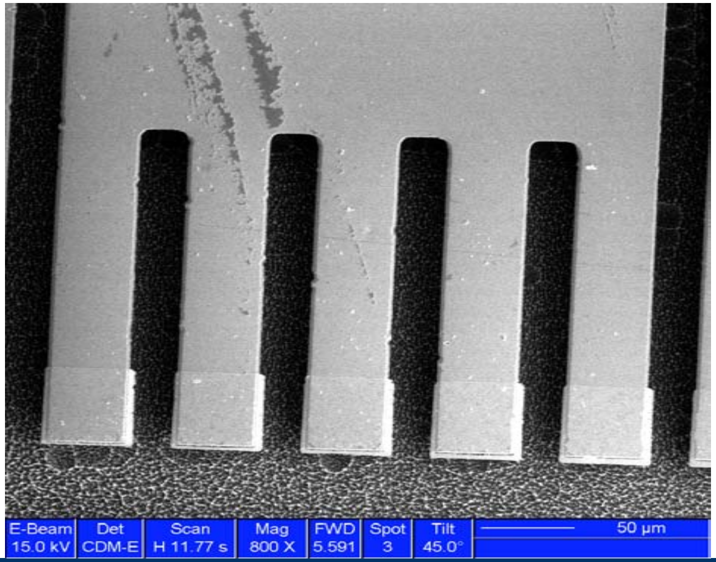


Current Results

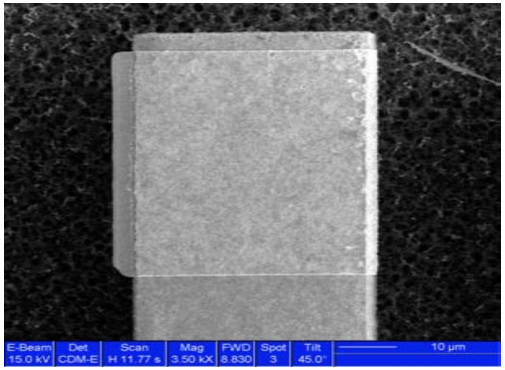


Cantilever array lies completely in-plane



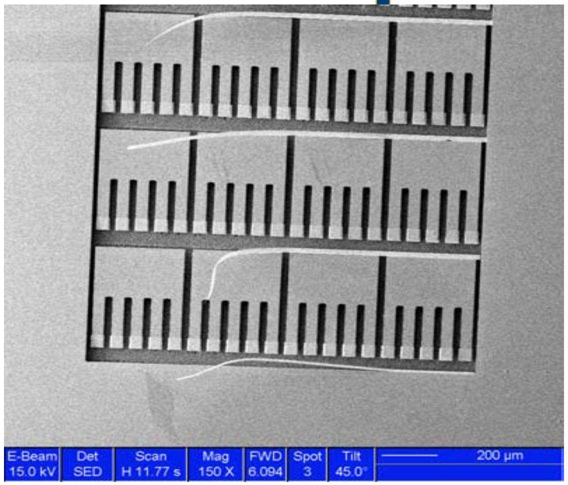


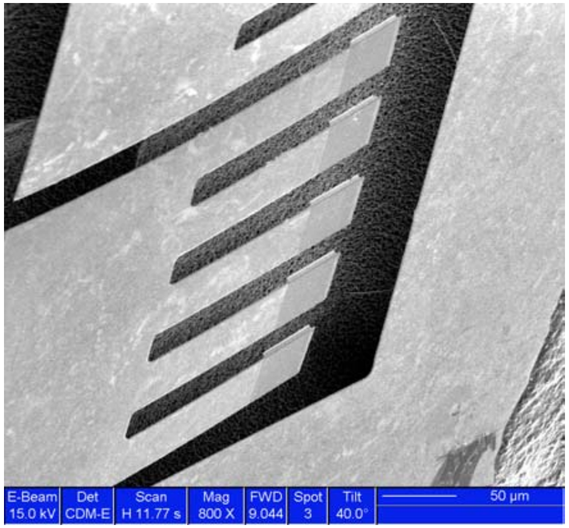
Proof mass design



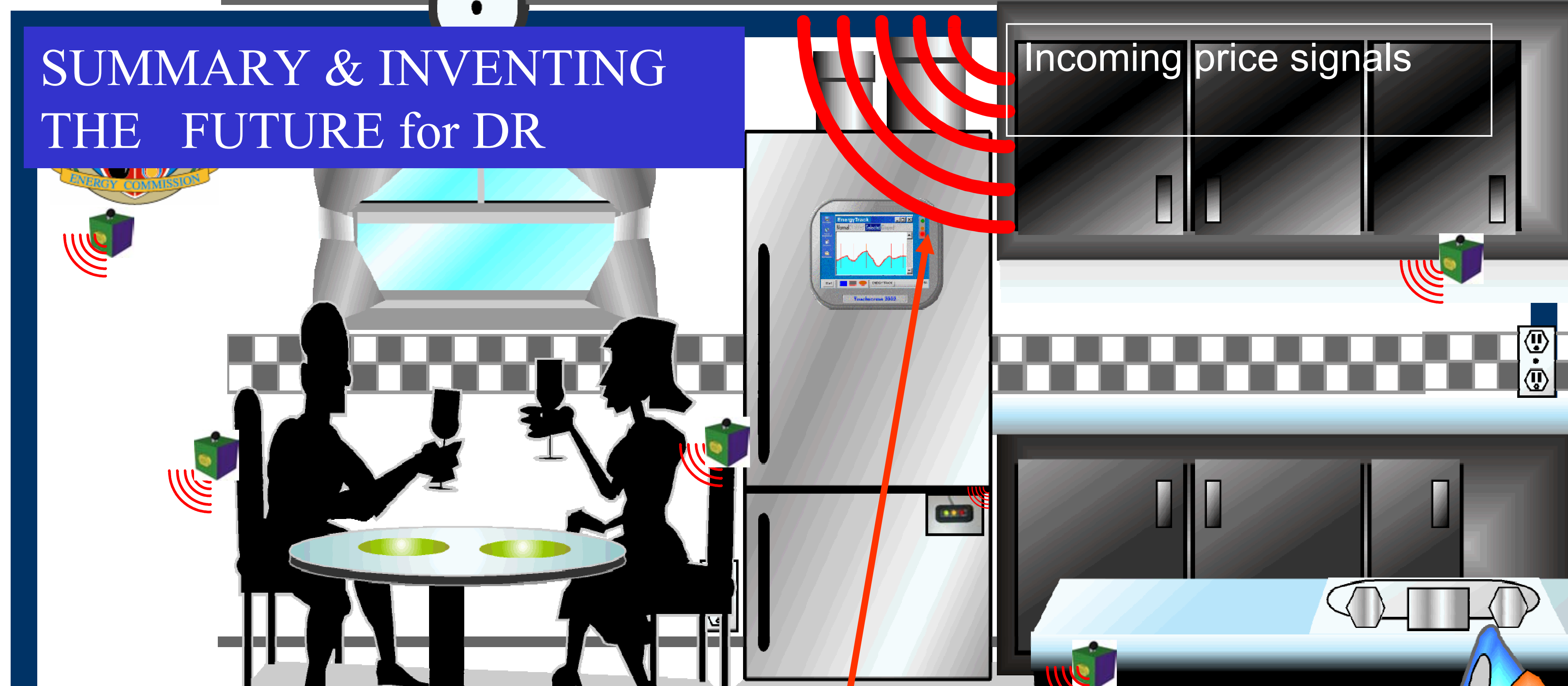
MEMS Findings for Power Supply

- Pulsed laser deposition can be used to grow epitaxial PZT films on Si substrate
- Thin film piezoelectric coefficient approaches bulk values, shows good switching capabilities
- Microscale cantilever resonant frequency 250-2500 Hertz, alternative design increase frequency
- Power modeling indicates a power density approaching 200 $\mu W/cm^3$
- Cantilever arrays fabricated and released using standard-CMOS compatible processes
- Residual stresses in film reduced





SUMMARY & INVENTING THE FUTURE for DR



Putting everything together@ 10x10x10

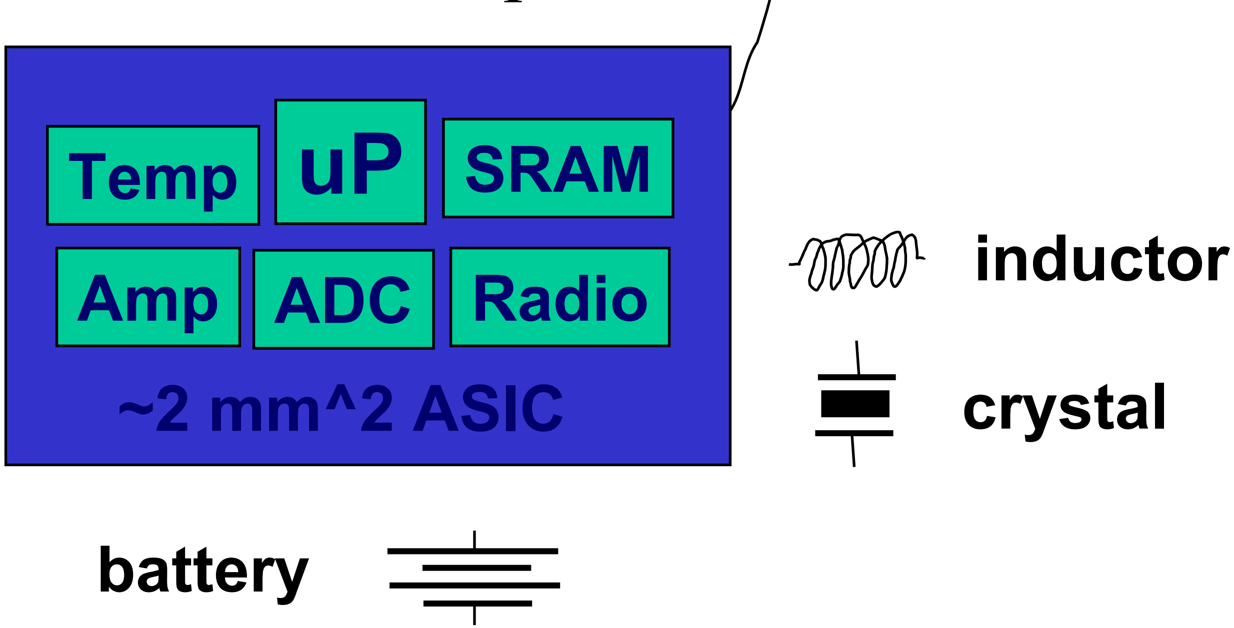
1. **New Thermostat** with touchpad shows price of electricity in ¢/kWhr + expected monthly bill.
   *Automatic adjustment of HVAC price/comfort.
   *Appliance nodes glow-colors based on price.
2. **New Meter** conveys real-time usage, back to service provider
3. **Wireless beacons** throughout the house allow for fine grained comfort/control

Appliance lights show price level & appliances powered-down

Mote on a Chip?

(circa 2000/1 Kris Pister and Jan Rabaey)

- **Goals:**
  - Standard CMOS (or MEMS resonators)
  - Low power
  - Minimal external components

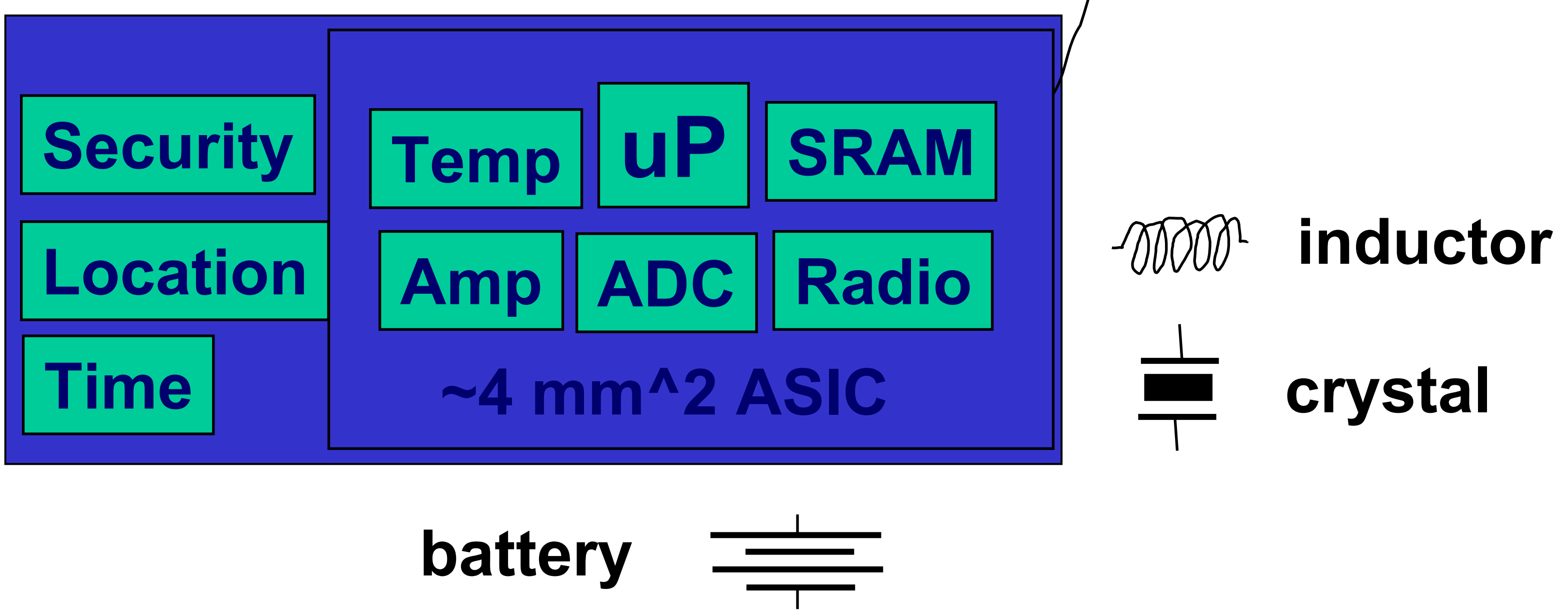


Hardware directions:

- Standard CMOS (or MEMS resonators)
- Low power
- ~~Minimal~~ external components

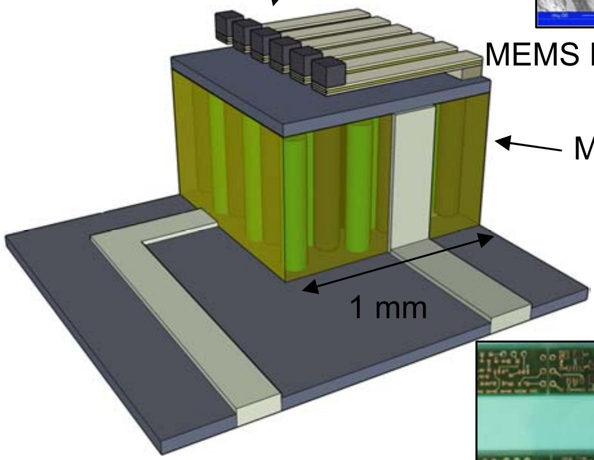
  Zero

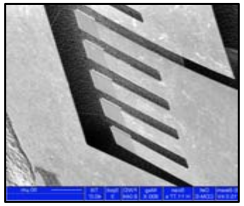
antenna



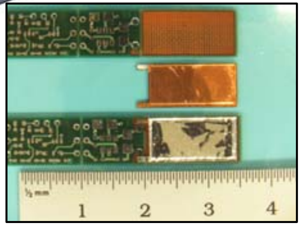
FIREPower

- **Objective**
  - Electrical energy generation, storage and delivery at the microscale – cubic millimeter
  - Device tailored to achieve 350 Wh/L and 100 - 800 W/L
- **Key innovation**
  - Direct write printing for varied form factors
    - Ink-jet printing for high resolution nano - structured batteries
    - Pneumatic dispenser for meso-scale batteries
    - Laser direct write for topographically rich structures
  - Extensive use of nano-structured inks to maximize active volume
  - CMOS integratable thin-film piezoelectric geometries for energy scavenging
- **Impact**
  - On-chip integration of power with sensing, actuation and communications

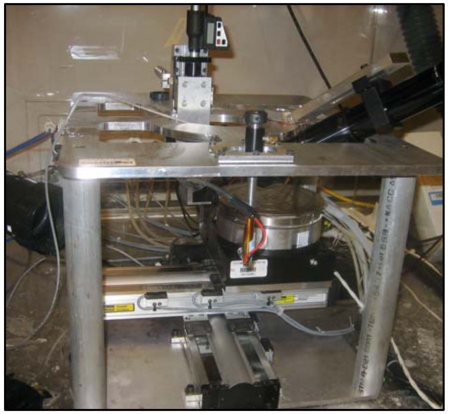




MEMS Piezo Structures

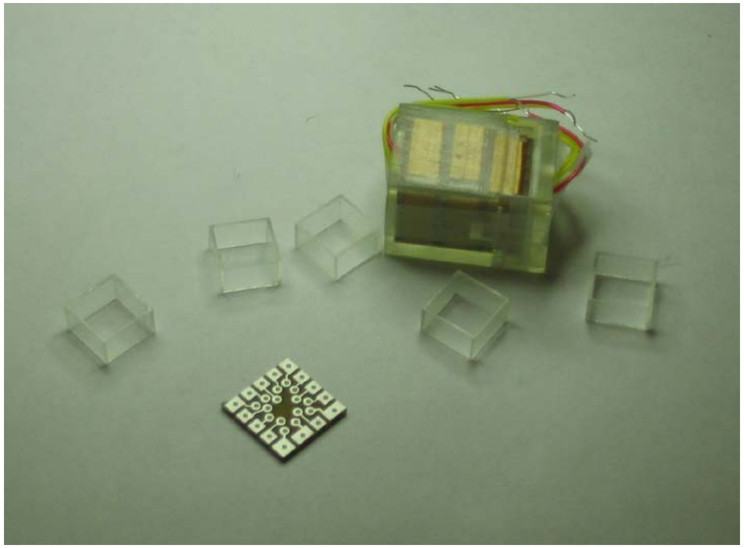


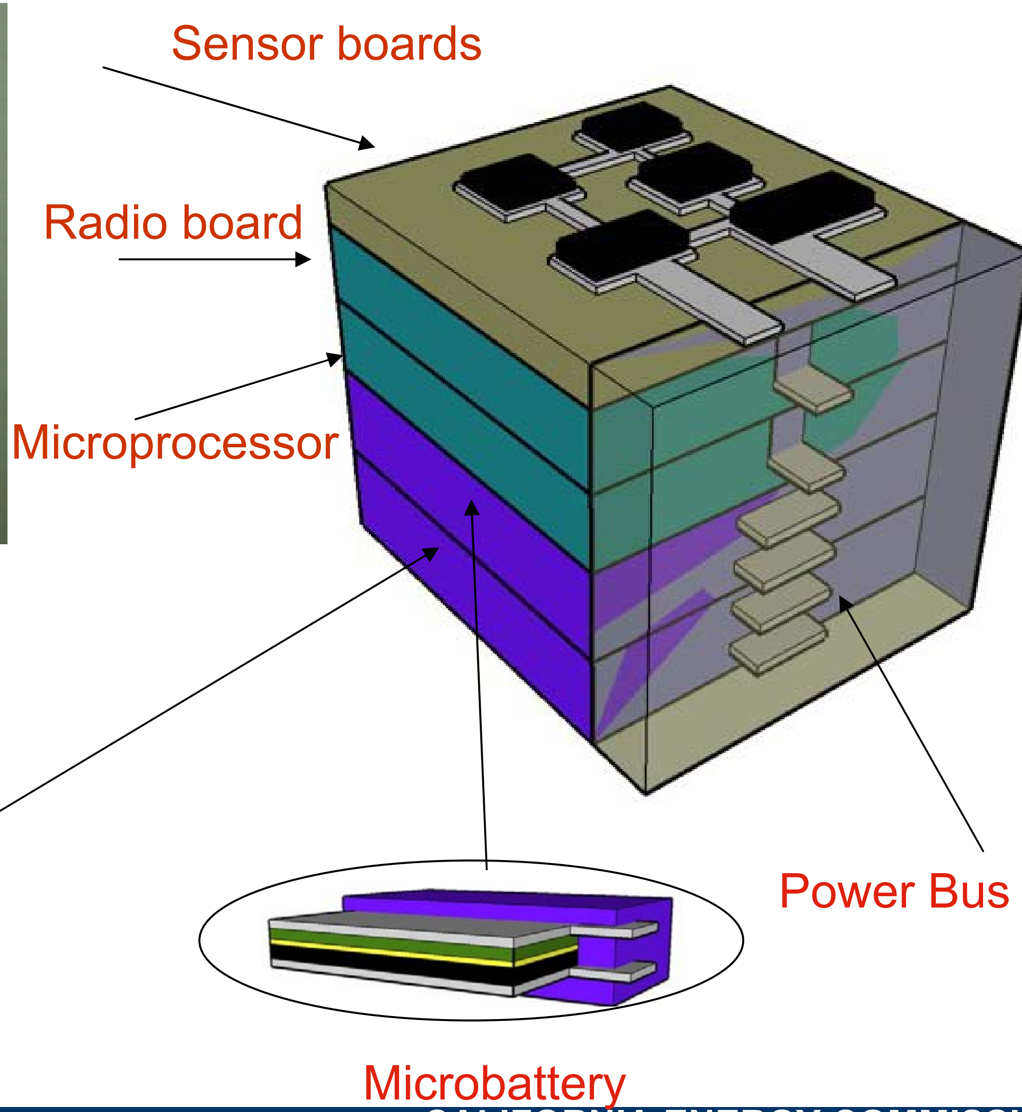
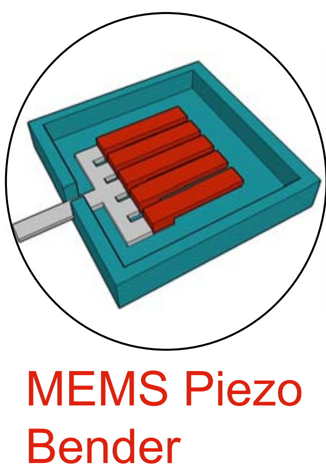
PCB Embedded Li-Ion Cell



Ink-jet Printer

Beginning micro-integration and miniaturization to reduce DR's cost



DR Summary

- **Managing our summer peaks today is as big a job for society as was managing our per capita energy (kW-hr) needs in the last quarter of the 20th century**
- **However, this problem is different in that it involves complex information exchange and advanced communication systems**
- **Such communication needs the micro-integration of**
  - Low-power radios,
  - Mesh-networking,
  - MEMS-scale sensing,
  - MEMS scale power supplies, and
  - Micro-packaging-integration
  - All at "about a couple of dollars BOM per platform" range.
- **Such micro-integration will enable DR control and learning, for integration into meters, thermostats, temperature nodes**