
Energy Consumption Monitoring using Wireless Sensor Networks

Coalton Bennett, Steven B. Wicker, Judith Cardell
Cornell University

Presentation Outline

1. Energy Consumption Monitoring
 2. Need for sensors
 3. Sensor Design
 4. Looking Forward
 5. Conclusion
-

Reason/Purpose for Energy Consumption Monitoring cont...

- a. During times of low demand, only the lowest marginal cost power plants will operate, while at peak times, almost all available power plants run to meet demand
 - b. Electricity providers and their customers are concerned with load demand, in general, because of the effects that it has on both the environment and the cost to continue to sustain the increase in capacity of the electric system
 - c. Relevant environmental concerns
 1. Coal plants are some of the dirtiest and tend to be baseload (running all the time), and intermediate (running much of the time).
 2. Gas turbines provide the peak load, and they are relatively clean.
 3. Energy consumption and the relevant environmental concerns can be addressed by conserving energy whenever possible
 4. This would correspond with relying less heavily on coal plants--reducing demand.
-

Reason/Purpose for Energy Consumption Monitoring cont...

- c. The value of this mechanism has been summarized by the Peak Load Management Alliance as having the following impacts on both providers and customers/consumers:
 - i. Reliability of the electricity system
 - ii. Reducing costs associated with generation, transmission, and distribution
 - iii. Creating efficient markets
 - iv. Reducing suppliers' and customers' risk in the market
 - v. Reducing environmental impact by reducing or delaying new power plant developments
-

Reason/Purpose for Energy Consumption Monitoring cont...

d. Demand Response

- i. Demand response refers to the modification of customer electricity consumption during times of peak usage in order to help address system reliability, reflect market conditions and pricing, and support infrastructure optimization or deferral.
 - ii. Demand shedding is a dynamic temporary reduction, or curtailment of peak load when dispatched and refers to strategies that can be possibly implemented within a shorter period of response time.
-

Reason/Purpose for Energy Consumption Monitoring cont...

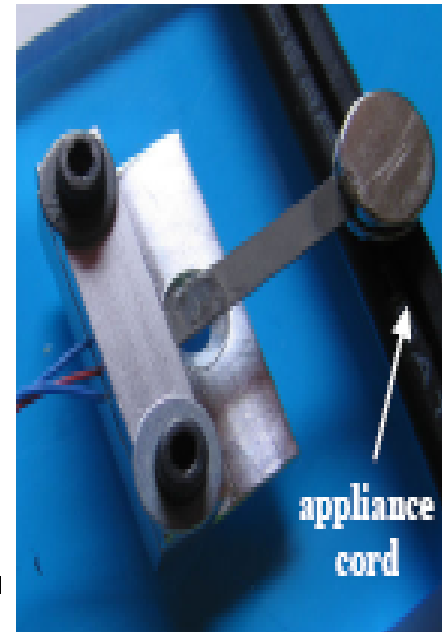
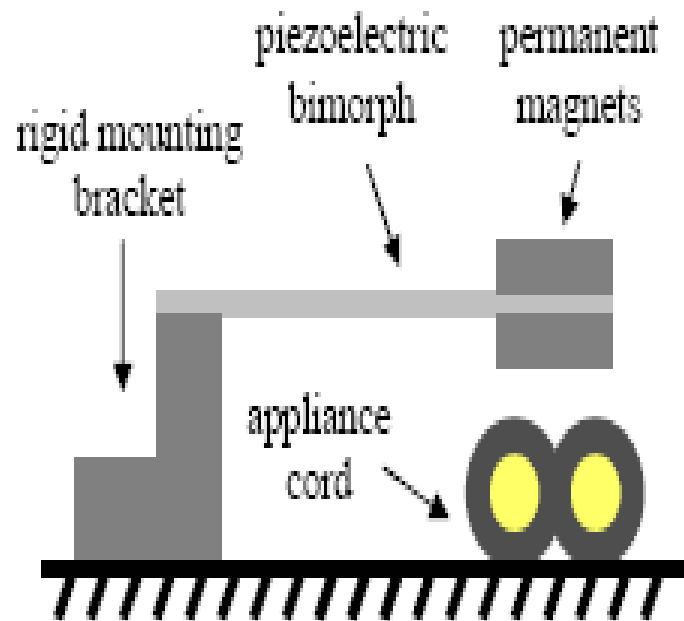
- e. Types of Demand Response
 - i. Manual Demand Response: Involves a labor intensive approach such as turning off unwanted lights or equipment
 - ii. Semi-Automated Response: Involves the use of controls for DR, with a person initiating a preprogrammed DR strategy
 - iii. Fully-Automated Demand Response: Does not involve human intervention, but is initiated at a facility, in our case a PC, through receipt of an external communications signal
-

Need for Sensors

- a. Little to no detail about the end-users consumption of electric power is made available to customers and utilities besides the information provided by the meter attached to the actual dwelling.
 - b. Provides a: cheap, accurate, and reliable way to implement the demand response technologies that were discussed above.
-

Sensor Design

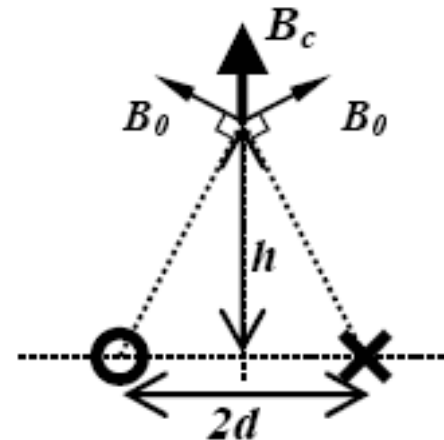
- a. A device which directly couples to an appliance cord and interacts with the alternating magnetic field produced by the current passing through the cord
- b. This device consists of a cantilever-mount piezoelectric bimorph with magnets attached to the free end



Sensor Design cont...

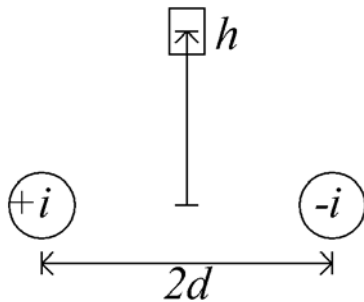
- The AC currents in the two wires are 180° out of phase
- The magnetic fields resulting from the two currents are equal in magnitude and opposite in sign
- The centers of the two conductors are separated by a distance of 2*d

$$B_c = \frac{\mu_0 i}{\pi} \left(\frac{d}{h^2 + d^2} \right)$$



Sensor Design cont...

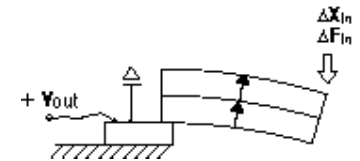
- Neodymium Disc Magnets
 - Dimensions: 3/8" dia. X 1/16" height
 - Material: NdFeB
 - Energy Product: $Bh_{max} = 42$ MGOe
 - Located a distance h above the two wires



Voltage and Force Relations for Triple-morph Cantilever Bender

The relationship between the force applied at the end of the bender and the output of the piezoelectric material is explained in the following equation.

$$V_o = F_{in} \left[\frac{a_3 c_p d_{31} t_p}{a_2 k_2 m \varepsilon \left[(j\omega)^2 + 2\zeta_m \omega_n (j\omega) + \omega_n^2 \left(1 - \frac{c_p d_{31}^2}{\varepsilon} \right) \right]} \right]$$



Variable	Comments
V_o	voltage out of sensor
F_{in}	input force on magnet
k_2	constant relating tip displacement to avg. strain in piezo material
m	mass of magnet
a_p, a_2, a_3	constants specifying unimorph, series bimorph, parallel bimorph
ε	dielectric permittivity of piezo material
c_p	elastic modulus of piezo material
d_{31}	piezoelectric coefficient
t_p	thickness of piezo layer in the sensor
ζ_m	dimensionless damping constant
ω_n	natural frequency of sensor beam

Voltage and Force Relations for Triple-morph Cantilever bender

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Magnetic Field and Force Relations for Cantilevered Bender

$V_{out} = F_{in} K(d_{31})$ Where F_{in} is the force on the magnet due to the magnetic field

$$V_{out} = F_{in} K(d_{31})$$

$$F_{in} = I\beta$$



$$V_{out} = I\beta K(d_{31})$$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

1. The force-current, and hence voltage-current, relationship is linear.
2. Thereby making the computations as performed by the mote less intensive
3. This in turn reduces the amount of battery power spent performing calculations, thus reserving the majority of it's power for sending and receiving communication signals

Crossbow Wireless Mote Specifications (Micaz)

Coupling the magnetic sensor to the Micaz 2.4 GHz wireless module provides the communication, computational, and analytical aspects of the network.

- i. Wireless Platform for Low-Power Sensor Networks
- ii. 2.4 GHz, IEEE 802.15.4 compliant
- iii. 250 kbps, High Data Rate Radio
- iv. Batteries are not needed
 - A. Energy scavenging mode
- v. 725 samples per second
- vi. Output voltage of bender is sampled by Micaz's ADC (Sampling Capability)



Note: The voltage values were computed with a multimeter in the experiment. However, we are considering, in future works, the inclusion of proximity voltage sensors [1] in hopes of creating a fully autonomous network.

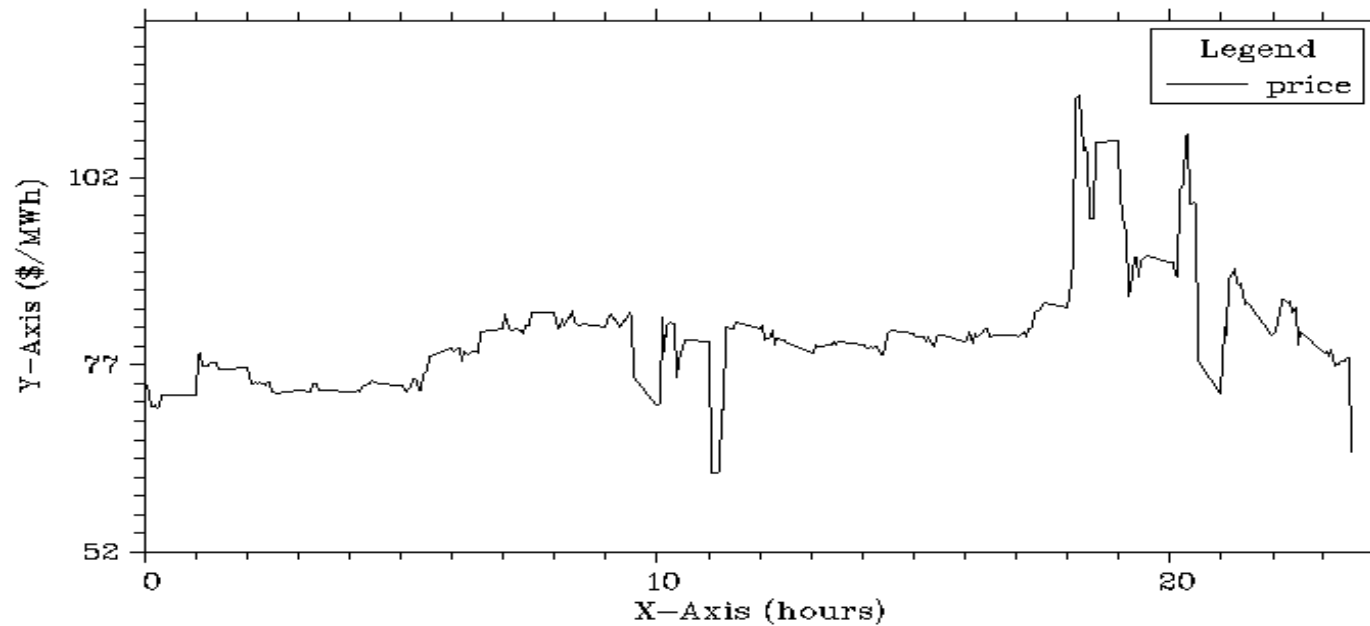
Customer Notification

- Once the power has been computed for an appliance, the computer queries the Independent System Operators website for pricing information.
 - Using this information the program executes an algorithm, based on the customer's preferences, that determines whether or not the appliance should be left on[2].
 - The customers are then notified via SMS when the cost to run a certain appliance has gone above a personal predefined threshold.
-

Customer Notification

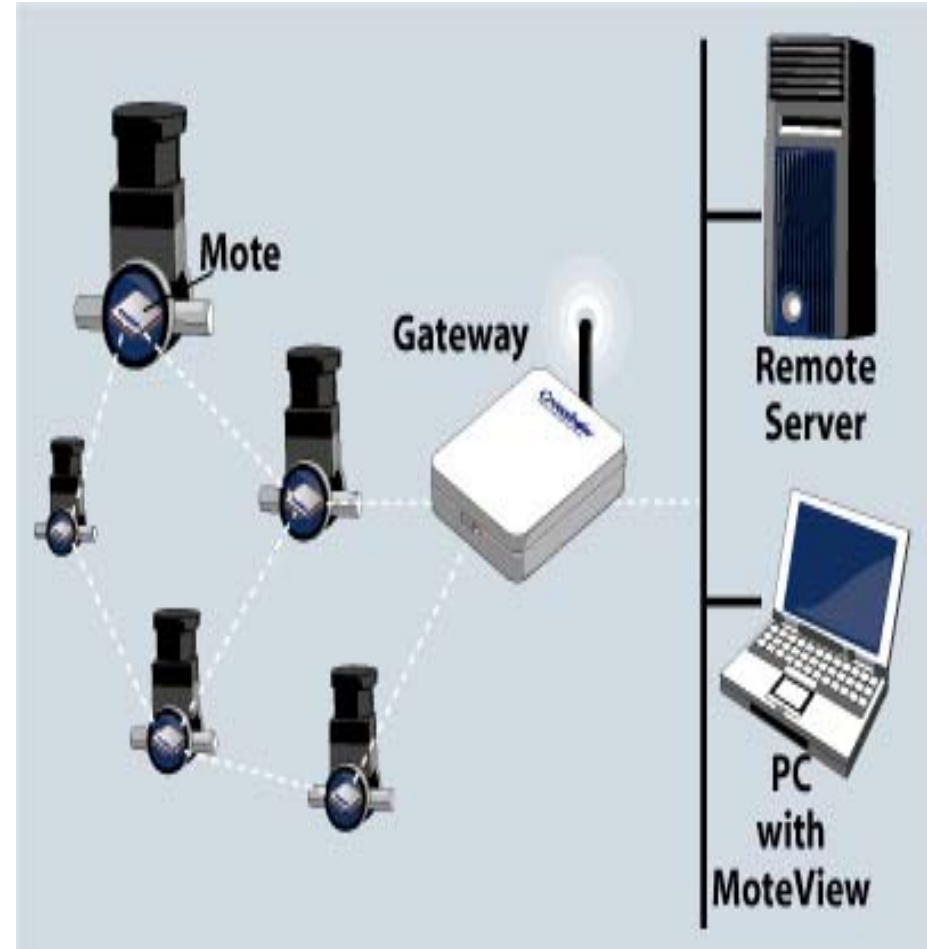
- Pricing information as provided by the New England ISO

5-minute Industrial Electricity Prices on 03/08/07



Looking Forward

- 1) Coupling several such devices to different appliances creates a mesh network
- 2) The information received at the PC/server, given predefined thresholds for pricing and the amount of power being consumed, will give the mote the ability to toggle the state of the device
- 3) Possibility of scaling current sensor downwards to a MEMS level of $500\mu\text{m}$



Looking Forward

- With the advent of smaller wireless radio modules like the mica2dot, shown here, the goal of scaling downwards to the mems level, with all of the aforementioned capabilities, is completely attainable within the next decade.
- Thus allowing manufactures to incorporate this relatively--*cheap*--technolgoy, in their appliances, for energy conscience customers.

QuickTime™ and a decompressor are needed to see this picture.

Conclusion

- Questions?
 - Comments?
-

References

- [1] http://www.cjatc.org/Knowledge_Base/Tick_Tracers/tick_tracers.html
 - [2] Bennett C., Trutoiu L., Wicker S., Cardell J., “Energy Consumption Management in Response to Price Change using Wireless Sensor Networks,” *TRUST Conference 2007.*, Berkeley, California, 2007
-