Eaton Wireless Sensor Network for Advanced Energy Management Solutions
Phase 2: Advanced Pervasive Wireless Energy Sensing

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Problem Statement

Need: Increase *Energy Savings in Industrial Electric Motors Across IoF*

U.S. Department of Energy (DoE) research has shown that industrial motor energy use could be reduced by 11 to 18 percent if proven methods typically used on larger motor systems could be widely deployed. DoE estimates that electric motor-driven systems used in industrial processes consumed 679 billion kWh, or 23 percent of all electricity sold in the United States.

Implementation of advanced energy management monitoring and diagnostic systems in large electric motor (>200 HP) applications has proven dramatic energy savings, economic benefits, and reduced environmental impacts.

*To achieve improvements on a broad scale, energy management solutions will need to be extended widely across the energy distribution systems within the process plant*
Project Summary

Eaton Wireless Sensor Network for Advanced Energy Management Solutions (CPS# 14225)

Goal: Enable significant energy savings for Advanced Energy Management Solutions (AEMS) in the Industries of the Future (IoF).

Novel/Transformational Elements:

• Create open architecture, low-cost, robust, self-configuring Wireless Sensor Network (WSN) that will gather relevant data in the industrial environment for the IoF
• Create online/non-intrusive energy management and condition based monitoring sensors for electrical motors and connected loads

Benefits: The wireless-enabled power management system is broadly applicable to all 8 IoF. Deploying WSN to the electrical distribution and power control system enables quantifiable energy savings. Estimated energy savings greater than 279 trillion Btu/year in 2020 for targeted IoF

Participants:

Red Wing Technologies
Eaton
Georgia Institute of Technology
Eaton Electrical
bp
International Paper
Weyerhaeuser

DOE Sensors & Automation 2005 Annual Portfolio Review
Core Technology

Drivers
Energy Savings
Environmental Concerns
Industrial Productivity

Core Technologies
Smart Sensors/Intelligent Algorithms
• Novel on-line & non-intrusive electrical motor energy estimation algorithms

Wireless Sensor Networks
• Self-Configuration
• Low-Cost
• Robust
• Secure
Parasitic Power

High Impact Solution

Wireless → Low Installation Cost → Pervasive Measurements
Measure → Quantify Value → Knowledge Enables Actions → Save Energy!
**Barrier and Pathways**

**Barriers**

- Lack of robust, secure, and cost-effective communication networks to enable collection of critical monitoring and diagnostic information in energy management solutions
- Lack of cost effective electrical motor energy sensing methodologies that minimize intrusiveness, while providing required accuracy
- Lack of standards that promote interoperability

**Pathways**

- Development of robust, self-configuring, low cost wireless sensor networks for advanced energy management solutions
- Advanced modeling to design and develop on-line electrical motor energy monitoring systems using distributed data
- Eaton’s industry leadership in IEEE802, WINA, ISA/SP-100, IEEE1451 and the ZigBee Alliance
Closing The Loop on Energy Savings

Eaton’s WSN enables continuous energy savings!
Initial Industrial Application

Energy Management and Condition-based Monitoring

Wireless communication also enables a wide range of cost effective conditions based maintenance features and capabilities.
Original Project Structure

<table>
<thead>
<tr>
<th></th>
<th>Kickoff</th>
<th>Progress Reviews</th>
<th>Baseline Demo</th>
<th>Phase II Interim Demo</th>
<th>Phase II Concept Demo</th>
<th>Phase III Interim Demo</th>
<th>Final Demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kickoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Final Demo at End-User Facility</td>
</tr>
<tr>
<td>2,4,6,8,10</td>
<td>Progress Reviews</td>
<td></td>
<td></td>
<td>Lab-based demo of Advanced Wireless Network</td>
<td>Lab-based demo of On-line Energy Monitoring Estimators</td>
<td></td>
<td>Final Report: Tests results &amp; Commercialization Plan</td>
</tr>
<tr>
<td>3</td>
<td>Baseline Demo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Phase II Interim Demo</td>
<td></td>
<td>Lab-based demo of Advanced Wireless Network</td>
<td>Lab-based demo of On-line Energy Monitoring Estimators</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>Phase II Concept Demo</td>
<td></td>
<td>Lab-based demo of Advanced Wireless Network</td>
<td>Lab-based demo of On-line Energy Monitoring Estimators</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Phase III Interim Demo</td>
<td></td>
<td>Demonstration of Phase II system in end-user plant. Annual Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Final Demo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key:  = Major Milestone or Decision Point

Accomplished!

DOE Sensors & Automation 2005 Annual Portfolio Review
Project Status—2004

Deliverables and Timeline Macro View

Phase I

- Q1: Requirements Specification
- Q2: Technology Assessment
- Q4: Development of Baseline WSN Test-bed

Phase II

- Advanced WSN
- Performance Testing
- Validation and Field Testing
- Commercialization Plan

Phase III

- Energy Management

2004 2005 2006 2007 2008
Project Status—2005

Deliverables and Timeline View

- Phase II
  - Advanced WSN
  - Performance Testing
  - Validation and Field Testing
  - Advanced Energy Management
- Phase III
  - Commercialization Plan
  - QoS, Industrial Perf., Power-Aware Network
  - Online Energy Monitoring
  - Commercialization Planning
  - Alpha Test Site

Commercialization plan and field validation were accelerated!
Project Roadmap—Revised

Phase II—Concept Feasibility

- Advanced WSN
- Enhanced Security Features
- Online Energy Management
- Power-aware Mgmt.
- Industrial & Environ. Adaptation
- Demonstration/Testing in Industrial Environment (Partner Facility)

Phase III—Concept Validation

- Alpha Test Site Demonstrations
- Implement Design Improvements
- Commercialization Plan
- Develop Product Intro Plan
- Marketing Plan

2005 2006 2007 2008
Energy Savings for Industrial Manufacturing Applications

Distribution of Motor Size for US Manufacturing

<table>
<thead>
<tr>
<th>Motor Size</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5 HP</td>
<td>3288035</td>
</tr>
<tr>
<td>6-20 HP</td>
<td>1129527</td>
</tr>
<tr>
<td>21-50 HP</td>
<td>220908</td>
</tr>
<tr>
<td>51-100 HP</td>
<td>86836</td>
</tr>
<tr>
<td>101-200 HP</td>
<td>28047</td>
</tr>
<tr>
<td>201-500 HP</td>
<td>28047</td>
</tr>
<tr>
<td>501-1000 HP</td>
<td>10958</td>
</tr>
<tr>
<td>1000+ HP</td>
<td>7306080</td>
</tr>
</tbody>
</table>

Distribution of number of motors vs. horsepower rating (Department of Energy estimate)

Electric Motor Driven Process in U.S.
- Accounts for 23% of all US electricity sold
- 98% of motors are <200hp
- Consumes 71% of electrical energy used in industrial process plants

Application of Mature Technology
- Improving motor rewinding practices
- Reducing system load requirements
- Reducing or controlling motor speed
- Matching component size to load
- Upgrading component efficiency
- Improving maintenance
- Properly sizing motors to applications

WSN removes cost barriers enabling application of proven technology realizing 11% to 18% energy savings in industrial process systems

Eaton’s Energy Savings Approach

Conservative Estimates

- Savings related to electrical energy management only
- Based on 10% energy savings (vs. DOE est. of 11% to 18%)
- Realized savings based on capitalization schedule
  - Assume 6 to 10 yr motor life
  - 100% R&R by 2020
- DOE OIT report based data
  - Fuel Consumption tables per industry segment (SIC)
  - Industry segment growth rates
- Calculation using DOE/ Energetics tool set

Using conservative DOE-based data yields significant electrical energy savings of 279 Trillion Btu’s year

<table>
<thead>
<tr>
<th>Industry</th>
<th>Petroleum</th>
<th>Aluminum</th>
<th>Chemical Products</th>
<th>Forest Products</th>
<th>Glass</th>
<th>Casting</th>
<th>Mining</th>
<th>Steel</th>
<th>Total Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Growth</td>
<td>4.8%</td>
<td>-0.8%</td>
<td>2.4%</td>
<td>1.6%</td>
<td>2.7%</td>
<td>-0.8%</td>
<td>6.4%</td>
<td>-0.8%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>Curve</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
<td>10 Year</td>
</tr>
<tr>
<td>Saving</td>
<td>10%</td>
<td>5%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Production (x000,000) ton</td>
<td>990</td>
<td>4.6</td>
<td>364.2</td>
<td>88.1</td>
<td>20</td>
<td>14.1</td>
<td>5570</td>
<td>107</td>
<td></td>
</tr>
</tbody>
</table>
### Project Evaluation Tool

**User Inputs**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Natural Gas Energy Savings Natural Gas</th>
<th>Electricity Energy Savings Electricity</th>
<th>Coal Energy Savings Coal</th>
<th>Fuel Oil Energy Savings Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>100.0%</td>
<td>10.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

**Inputs Based on DOE and Other Reports**

**Calculations Based on Inputs Above**

### Energy Impacts for Petroleum

**(Based on the input provided above, this technology will have the following impacts.**

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARKET PENETRATION</td>
<td>N/A</td>
<td>21.1%</td>
<td>70.7%</td>
<td>95.6%</td>
</tr>
<tr>
<td>MARKET (Million tons)</td>
<td>N/A</td>
<td>340</td>
<td>1,456</td>
<td>2,611</td>
</tr>
<tr>
<td>ENERGY SAVINGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Energy Savings (million Btu)</td>
<td>N/A</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Electricity Energy Savings (million Btu)</td>
<td>N/A</td>
<td>4.01</td>
<td>17.31</td>
<td>29.63</td>
</tr>
<tr>
<td>Coal Energy Savings (million Btu)</td>
<td>N/A</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fuel Oil Energy Savings (million Btu)</td>
<td>N/A</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TOTAL ENERGY SAVINGS</td>
<td>N/A</td>
<td>4.04</td>
<td>17.31</td>
<td>29.63</td>
</tr>
</tbody>
</table>

### POLLUTANT REDUCTIONS (lbs)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (MMTCF/yr)</td>
<td>N/A</td>
<td>0.0783</td>
<td>0.3290</td>
<td>0.5977</td>
</tr>
<tr>
<td>Nitrogen Oxides (NOX)</td>
<td>N/A</td>
<td>1,433,378</td>
<td>6,129,772</td>
<td>18,578,037</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO2)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>N/A</td>
<td>180,307</td>
<td>613,840</td>
<td>1,494,507</td>
</tr>
<tr>
<td>Volatile Organic Compounds (VOCs)</td>
<td>N/A</td>
<td>20,245</td>
<td>68,570</td>
<td>149,418</td>
</tr>
<tr>
<td>Particulates</td>
<td>N/A</td>
<td>40,491</td>
<td>173,157</td>
<td>298,031</td>
</tr>
<tr>
<td>Other (million lbs)</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**User Explanations**

- **Technology Description:** Develop a wireless network for DOE’s IoT
- **Market Penetration:** 5 to 10 year life on 0 to 300 HP motors, upgrade to energy management when R&R
- **Introduction Year:** Beta test in 2 years, product introduced 1 year after beta
- **Energy Impacts Percentage:** The major impact will be on electrical. Not sure how to include wellness in this calculation
- **Other Wastes and Pollutants:** Possible reduction of non-combustion pollutants on restart.
Critical Metrics

• 11% to 18% energy reduction in industrial motor energy consumption by 2020

• 80% cost saving in the deployment of wireless vs. wired sensors

• Creation/adoption/development of wireless industrial communications standard

• **Successful product launch**

<table>
<thead>
<tr>
<th>Benefits (est.)</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Savings</td>
<td>&gt;279 trillion Btu</td>
</tr>
<tr>
<td>Cost Savings</td>
<td>$1300 millions</td>
</tr>
<tr>
<td>Pollutant Reduction</td>
<td>116 Million lbs</td>
</tr>
</tbody>
</table>
Accomplishments to Date

• Requirements – Completed 2004
• Technology assessment – Completed 2004
• Baseline network – Completed 2004
• Online Energy Management
  – Online energy monitoring algorithm designed (Jan-05)
  – Georgia Tech Wireless Energy Lab (on-going)
• Advanced WSN
  – Wireless sensor architecture completed (Feb-05)
• Alpha Testing
  – BP refinery industrial wireless environment characterization performed with Oak Ridge National Labs (Dec-04).
  – Wireless sensor alpha test conducted at BP’s Whiting refinery (May-05)
• Commercialization Plan
  – Eaton Electrical Steering Committee Created– Lead by EE’s CTO (Feb-05)
  – Value proposition tool (on-going)
    • Baseline design completed (May-05)
Online Energy Management

No speed and torque sensors needed → Inferential, non-intrusive, low-cost!
Online Energy Management (cont)

**Online Stator Resistance and Rotor Speed Estimation**

**DC Signal Injection Stator Resistance Estimation**

DC is injected every 30 sec. for a short period (0.25 sec)

Estimation error less than 0.5%

**Speed Estimation using Stator Current Spectrum**

Estimation error less than 0.5 rpm
### Inferential Online Motor Efficiency Estimation

**Motor Efficiency Testing Methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>No Load</th>
<th>Full Load</th>
<th>Un-power</th>
<th>Variable Volt/Freq</th>
<th>Speed</th>
<th>Torque</th>
<th>Nameplate Info</th>
<th>Stator Resistance</th>
<th>Intrusiveness</th>
<th>Anticipated Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORMEL96 Method</td>
<td>No</td>
<td>No</td>
<td>Optional</td>
<td>No</td>
<td>Measure</td>
<td>No</td>
<td>Yes</td>
<td>Optional</td>
<td>Low</td>
<td>4% [1]</td>
</tr>
<tr>
<td>OHME Method</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Measure</td>
<td>No</td>
<td>Yes</td>
<td>Measure</td>
<td>Medium</td>
<td>2.3% [1]</td>
</tr>
<tr>
<td>Modified AGT Method</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Estimate</td>
<td>No</td>
<td>Optional</td>
<td>Estimate</td>
<td>Non</td>
<td>1.2% [1]</td>
</tr>
</tbody>
</table>

**Modified Air-Gap Torque Method**

\[
\eta = \frac{T_{\text{air-gap}} \cdot \left( 2\pi \frac{\omega_r}{60} - W_{F_r} - W_{LL_r} \right)}{P_{\text{input}}} \times 100 \%
\]

- \( T_{\text{air-gap}} \): Calculated from integral of stator voltages subtracting stator IR drop
- \( \omega_r \): Estimated from current spectral analysis
- \( W_{F_r} \): Estimated from IEEE Std-112
- \( W_{LL_r} \): Estimated from IEEE Std-112
- \( P_{\text{input}} \): Directly calculated by multiplying stator voltages and currents

**Tests and Measurements/Estimations Required**

- Shaft Torque
- Efficiency

**Performance**

- Stator Voltage, Currents, Rotor Speed, and Stator Resistance
Online Energy Management (cont)

**Inferential Online Motor Condition Monitoring**

Detection of Rotor Unbalance

Possible Motor Faults:
- Winding turn faults
- Broken rotor bar
- Air-gap eccentricities
- Winding overheating
- Load torque oscillation
- Worn bearings
- Rotor unbalances
- Shaft misalignment

Detection of Shaft Misalignment

**All motor faults can be detected using only stator voltages and currents → non-intrusive!**
Advanced Wireless Sensor Network

- Robustness
- Self-configuration
- Standard based
- Secured
- Low-cost
Alpha Testing

BP, Eaton Electrical, Eaton Innovation Center and Oak Ridge EMC$^2$ at BP’s Whiting Refinery

Time, Spectrogram and Frequency Plots

Wireless Energy Sentinel

The Plot of Noise-level vs. Frequency

Dual Radio Industrial Wireless Sensor Node
Next Project Steps

• Implement wireless network performance improvements for robust operation in the industrial environment

• Actively participate in standards efforts, to maximize the benefits from interoperability → Emphasis in collaboration in new ISA SP-100 standard

• Enhance the energy estimation algorithms, including development of a payback tool to effectively convey the results to decision makers

• Develop and implement product introduction plan covering the manufacturing, marketing, and introduction of the WSN into an energy management system optimization product

FY06 Activities—This phase will address issues critical to field installations of a robust wireless energy monitoring network: Security, RF propagation in the industrial environment, application independent wireless stacks, QoS routing, energy efficiency, energy usage and online electrical motor monitoring system
Commercialization Plan

• **End Use Application:** The technology will enable retrofit of overload relay/meter in a motor control center application

• **Implementation Plans:** Eaton is presently developing a motor wellness relay with that will provide the overload relay, metering, power quality monitoring, and motor prognostic capabilities. The technologies developed in this program will become part of this product platform.

• **Product:** A hybrid of an overload relay and power meter with added features of power quality monitoring and inferential-based prognostics and diagnostics for the motor and connected loads

• **Value Proposition:** Tools are being developed to quantify for the end customer the value of energy savings and the commercial payback period of deploying the products resulting from this project
Commercial/Technical Risks Remaining

- **Commercial**
  - Quantifiable energy savings must be proven
    - IoF partners will help
  - Insufficient business justification could stall rollout
    - IoF partners will help
  - Wireless applications in the IoF plant environment must build on a common backbone to ensure success
    - Adoption of industrial communications standards can be low if multiple vendors provide competing rather than complimentary solutions
    - Mesh network will be made all the more robust when all vendors build on same backbone
    - Challenge is that many manufacturers see themselves as being best provider of backbone
    - Providing excellent installation/commissioning tools will be critical for easy deployment

- **Technical**
  - Performance of online energy management system effectively integrated with embedded architecture.
  - Communication robustness in the industrial environment
  - Effective balance between performance, level of security and cost
Value Proposition For End User

Energy Management Systems are Currently Deployed for Business Reasons

Reasons EM or CBM Deployed (ranked, 1 is most important)

- Highest priorities for system deployment involve increased revenue and profit
- Energy management (e.g., savings) is not the top reason for deployment

but…
Value Proposition For End User

- Current barriers to broader energy management system usage
  - Wiring costs—up to $1000/foot
  - Information overload—any system must present alternative recommended actions rather than simply more data
  - Daunting cost/benefit analysis—especially for small motors

*It is the difficulty of calculating return on investment that currently prevents broader deployment of energy management systems. Wireless Sensor Networks enables quantification of ROI.*
Research and team expertise will permit development of engineering/business tools justifying broader usage of energy management system in IOF plants.
Continuation After ITP-Sponsored Project

... in the future

DOE and Eaton Corp. unveiled new technology to enable dramatic energy savings in the industry

Eaton Corp, a developer of highly engineered industrial solutions, announced the launch of the first pervasive sensing energy management and condition based monitoring solution for electrical motors. The offering enables the Industries of the Future to save significant amount of energy with a return of investment of 18 months.

It is expected that after current R&D activities, the technology will be transferred to Eaton Electrical for the Advanced Product Development Phase

Industrial energy news

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DOE Sensors & Automation 2005 Annual Portfolio Review
Concluding Remarks

• Eaton’s Innovation Center Team continues its leadership in the wireless sensing area for energy management
  – ISA/SP-100 and WINA—Quality of service for industrial networks and WSN industrial awareness
  – ZigBee Alliance—Profile for industrial networks with focus in energy management
  – IETF—New standard for industrial wireless sensor networks
  – IEEE 802—Enhancement of the current WAN standard

• Eaton’s IC and Georgia Tech are making significant advances in online non-intrusive energy estimation technology
  – Testbed being built currently at GT energy management labs

• Eaton’s IC is working closely with EE to produce a successful Eaton product from this project
  – EE CTO created Wireless Technology Platform Steering Committee formed by marketing, engineering and product managers of the six major division groups
  – Eaton has business units serving IoF that are well positioned to bring products and solutions to market

• Eaton’s IC and EE are working closely with our application partners with the purpose of testing technology for energy savings in their facilities
  – Deployment at BP on Q2/05
  – Deployment at Weyerhouser on Q3/05
Sensors for Manufacturing Efficiency Workshop

DOE Sensors & Automation
2005 Annual Portfolio Review

It’s all about energy!!

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