Wireless Sensor Network for Electric Transmission Line Monitoring

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Genscape Inc., Louisville, KY
Background

- To date, little success obtaining real time grid situational awareness during emergency situations (brownouts/blackouts).
- Detailed information on grid status is controlled by regional grid owners/operators.
- Information is not shared due to public relations concerns, confidentiality agreements, competition.

Focus - Address lack of information available to Federal Agencies regarding grid status for use during actual or potential grid emergencies.
Objective

☐ Obtain electric power line (or grid) information in real time independent of owners/operators of grid assets.

☐ Provide source of information that Government can use to obtain situational awareness of the electrical grid.
Ongoing power monitoring capabilities — Genscape, Inc.

- Commercially owned and operated electric power line monitoring network
- Wireless monitors on lines into and out of power plants
- Non-Contact
- Utility Independent
- Private land use
- 1200 transmission lines monitored entering and leaving 400 of the larger US power plants
Genscape: Real-time Power Generation Visualization

- Plant generation output provided in real-time.
- Aggregated transmission line power flow data for certain strategic transmission pathways.
- Real-time alerts warn of breaks in power generation.
Challenges to Expansion of Genscape System

- Monitor placement too sparse to allow for detailed grid awareness.
- Existing monitors too big / expensive to greatly increase placement density.
- Monitors perform best in cases of simple line configurations.
- Use restricted to line measurements with large line separations.

Goals - Take advantage of newer technologies to optimize monitor form factor, power source and cost. Improve sensing capabilities for operation in high density, urban areas.
Project Tasks

- Design monitor to optimize form factor / function / cost
- Research alternate power sources
- Research and design of directional sensors
- Prototype development of alternate power module and directional sensor
- Embedded application development to manage power, communication, data acquisition and processing
- Field test and deployment of prototypes
- Server-side processing, viewing, alerting and dissemination application development
- Data viability and integration demonstration
Relevance to DOE Mission

Project Addresses 4 of 6 Key Activities for DOE Five-Year Program for Electric Transmission and Distribution Programs for Fiscal Years 2008-2012 (August 2006)

- **Sensors**
  Contributes to collection of “physical metrics across the grid”

- **System Monitoring**
  Measurement data provides “real-time information on grid operating conditions”

- **Visualization Tools**
  Provides data and visualization tools to enable “grid operators and federal agencies” access to global utility independent transmission line data “to identify disturbances before they cascade into serious problems”

- **Technology Transfer**
  Involves “field testing, technology showcases and learning demonstrations”
Form Factor/Cost/Function Optimization

- Utilize the Crossbow Mote processor platform – low cost, low power
- Reduce modem size to smallest available cellular network modem
- Test smaller flexible form solar panel technologies
- Implement small size 3-axis magnetic field meter chips to replace large magnetic solenoids
Form Factor Reduction

Genscape – Current Monitor

Proposed 1st stage size reduction using Mote processor

Modem

Processor
Research on Alternative Power Sources

**Objective:** Reduce and/or eliminate sensor dependency on high power (12V battery, 5W solar panel) large form factor power sources

- Research magnetic and electric field scavenging
- Research potential for vibration scavenging in urban areas
- Implement lower power communication modem
- Implement lower power processor
# Monitor Power Requirements

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CURRENT</th>
<th>PROPOSED</th>
<th>Potential Power Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication Modem and Antenna</td>
<td>3W (12V)</td>
<td>0.6 W (5V)</td>
<td>Solar, Permanent Battery</td>
</tr>
<tr>
<td>Microprocessor</td>
<td>660mW (12V) – processing mode</td>
<td>10mW (3.3V) - processing mode</td>
<td>Vibration, Magnetic/Electric Field Scavenging</td>
</tr>
<tr>
<td>Electric Field Sensor</td>
<td>Capacitive plate</td>
<td>Smaller form factor capacitive plate</td>
<td>Passive</td>
</tr>
<tr>
<td>Magnetic Field Sensor</td>
<td>Solenoid – Passive</td>
<td>Solid State Sensor 120mW(6V)</td>
<td>Vibration</td>
</tr>
<tr>
<td>Battery Source</td>
<td>12V</td>
<td>5V</td>
<td>NA</td>
</tr>
</tbody>
</table>
Electric or Magnetic Field Scavenging

Electric Scavenging Circuit

Magnetic Scavenging Circuit

Typical Fields at 25m
= 20-100V/m

Solenoid Output = 10mV/mG
Typical Fields at 20 meters
50-150mG at 20 m (0.5-1.5V)
## Power Scavenging from Ambient Vibrations

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>FREQUENCY (Hz)</th>
<th>AMPLITUDE (m/s²)</th>
<th>POWER OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footsteps on a wooden deck</td>
<td>385</td>
<td>1.3</td>
<td>45mW every 50 minutes</td>
</tr>
<tr>
<td>HVAC vents in office building</td>
<td>60</td>
<td>0.2-1.5</td>
<td>Not measured</td>
</tr>
<tr>
<td>Windows next to a busy street</td>
<td>100</td>
<td>0.7</td>
<td>Not measured</td>
</tr>
</tbody>
</table>

Vibration Scavenging: Urban Site Measurements

Street noise measurement

Measured Acceleration (m/s²)

Time (s)

Power Spectra Density (m²/Hz)

Frequency (Hz)
Vibration Scavenging: Cantilever-Based Design Ideas

Microfabricated cantilever for vibration energy scavenging

Magnetically modulated cantilever

- Tunable frequency response
- Possibility for nonlinear response

Example of microfabricated cantilever used for gas sensing
Cantilever Design: Energy Output Modeling

\[ \ddot{z} = -\omega_0^2 z + (\text{pkAcc}) \sin(2\pi ft) + \frac{1}{m} \left[ F(z_m - z) - F(z_m + z) \right] \]
Objective: Enable the monitor to target specific transmission lines in the presence of other lines and high 60Hz background noise

- 3-axis magnetic field sensor implementation

- Computational decomposition of superimposed magnetic field readings — separation of signal from noise via phase, EMF vector identification
Motivation for Directional Sensor

Accurate measurements of isolated transmission lines, but difficult to determine influence of individual lines in urban or congested setting.

Comparison between measured and modeled transmission line B-field

Computed power flow amplitude matches utility SCADA data to +/- 10%
3-Axis Magnetic Field Measurements

- With current 2 axis sensor - 3rd axis (z) needs careful alignment parallel to the line
- 3-axis gaussmeter chip allows smaller form factor and ability to allow signal de-composition from neighboring lines
Electromagnetic Field Modeling

**Simulation:** Suggests magnetic vector from 2 parallel lines forms an ellipse over one 60 Hz cycle whose axis is determined by the orientation of the power line.

**Proposal:** Test 3-axis magnetic field sensor to monitor the rotation of these axes to determine the source of any fluctuations in the signal strength.
Monitor applications will be written to deliver a range of reporting and power consumption profiles.

<table>
<thead>
<tr>
<th>REPORT INFORMATION</th>
<th>POWER CONSUMPTION PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-Time Power Flow Magnitude and Direction Data (Current Genscape Line Monitor Capability)</td>
<td><strong>Communication Modem/Antenna On:</strong> Depends on the frequency of data required (A single transmission requires power for approx. 20 secs*)</td>
</tr>
<tr>
<td>Alerts on Substantial Changes to Power Flow Magnitude Only</td>
<td><strong>Communication Modem/Antenna On:</strong> Only when exceptions occur plus one “heartbeat” message per 24 hours</td>
</tr>
<tr>
<td>Alerts on Substantial Changes to Line Voltage (Line ON/OFF) Only</td>
<td><strong>Communication Modem/Antenna On:</strong> Only when exception events occur plus one “heartbeat” message per 24 hours</td>
</tr>
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</table>
Field Test and Network Deployment

Field test sites have been identified for various test needs

<table>
<thead>
<tr>
<th>Measurement/Monitor Component Under Test</th>
<th>Suitable Test Site</th>
<th>Location</th>
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<tbody>
<tr>
<td>Varying Magnetic Field</td>
<td>Transmission Lines serving a Pump Storage Plant see varying power (magnetic field) on a daily basis</td>
<td>Rural Area in Bath County, Virginia</td>
</tr>
<tr>
<td>Varying Electric Field</td>
<td>Areas with high overnight humidity see predictable daily changes in electric field</td>
<td>Rural Areas in Jefferson and Trimble Counties, Kentucky</td>
</tr>
<tr>
<td>Vibration Power Sources</td>
<td>Urban location with high environmental background vibration levels</td>
<td>Urban Area in Louisville, Kentucky</td>
</tr>
<tr>
<td>High Line Density Sensor Arrays</td>
<td>Lines entering a substation, lines in an urban setting with lines in close proximity</td>
<td>Urban Area in Louisville, Kentucky</td>
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</table>
Available Line Types

The Genscape network contains a variety of transmission line types for field testing.
Server-side Applications

- Develop data processing algorithms to process new monitor data-types relating to transmission line specific parameters
- Develop alerting routines for a range of transmission line fault conditions (e.g. de-energized line, low/no power conditions, line power close to capacity etc)
- Develop transmission line visualization interface to provide real-time transmission line data
Transmission Line Visualization

- Transmission Line Corridor Views
- Individual Transmission Line Views
- Capability to import 3rd party line data
National Grid Demonstration Site

- Nationally recognized congestion corridors
- NERC identified regions of seasonal concern – Summer Report
- Hurricane or Forest-Fire Prone Regions

Data Viability and Integration

- Design optimized alerting and data delivery protocols
- Research current practices and protocols in the electric utility industry to define
- Demonstrate data integration possibilities with existing SCADA and EMS systems (collaboration with Louisville Gas and Electric)
- Develop 3rd party data dissemination methods for data delivery to federal agencies and/or utilities
Project Management

- Three functional teams
  - Research Team
  - Prototype Development Team
  - IT Applications/Infrastructure Team
- Weekly team meetings
- Shared access to UofL and Genscape facilities/resources
- Company work experience for students
UofL:

Bruce Alphenaar Ph.D. – PI

George Lin Ph.D. – Research Engineer

Bill Brown – Graduate Student
Genscape:

Deirdre Alphenaar Ph.D. - Co-PI
Chris Pettus M.Eng - Hardware and Embedded Application Engineering
Yang Xu Ph.D. – Research Engineer
Walter Jones Ph.D.,- Power Line Analytics/Modeling
Kevin Brown – IT Applications/Software
Mike Linahan – Logistics and Field Support

In addition members of IT and Logistics groups at Genscape support primary project participants above

Some of the Genscape people…
### Project Schedule Tasks 0-4
(one block represents one month of a 12 month project schedule)

### Project Schedule Tasks 5-8

(one block represents one month of a 12 month project schedule)

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<td>Task 5.1 Firmware Requirements Analysis and Design</td>
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<tr>
<td>Task 5.2 Firmware Development and Test</td>
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<th>Task 6: Field Test and Deployment</th>
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<td>Task 6.1 Identify/Prepare Field Test Sites</td>
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<tr>
<td>Task 6.2 Field Testing</td>
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<tr>
<td>Task 6.3 Identify/Prepare Grid Network Site</td>
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<tr>
<td>Task 6.4 Network Deploy</td>
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<th>Task 7: Server-Side Application Development</th>
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<td>Task 7.1 Data Center Requirements Analysis</td>
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<td>Task 7.2 Data Center Design / Implementation</td>
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<tr>
<td>Task 7.3 Basic Data Center Applications Development (Message Handling, Data Processing)</td>
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<td>Task 7.4 Advanced Data Center Development (Interface, Alerting, Datafeeds)</td>
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<th>Task 8: Data Integration</th>
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<tbody>
<tr>
<td>Task 8.1 Grid Fault and SCADA Integration Design</td>
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<tr>
<td>Task 8.2 Alert Protocol Design</td>
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<tr>
<td>Task 8.3 Alert Protocol Development</td>
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<tr>
<td>Task 8.4 Data Delivery Development and Test</td>
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