Wireless Sensor Network for Electric Transmission Line Monitoring

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Background

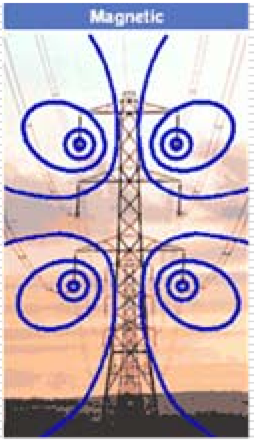
- To date, little success obtaining real time grid situational awareness during emergency situations (brownouts/blackouts).
- Detailed information on grid status is controlled by regional grid owners/operators.
- Information is not shared due to public relations concerns, confidentiality agreements,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

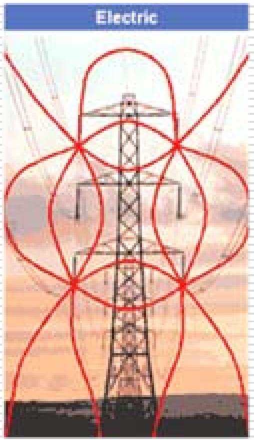
Focus - Address lack of information available to Federal Agencies regarding grid status for use during actual or potential grid emergencies.

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.

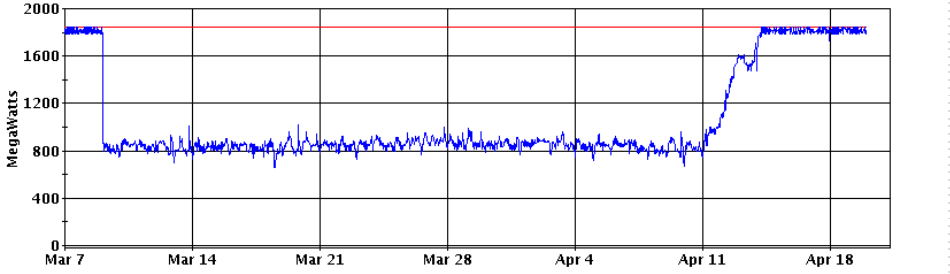




- Commercially owned and operated electric power line monitoring network
- Wireless monitors on lines into and out of power plants
- Non-Contact
- Utility Independent
- Private land use
- 1200 transmission lines monitored entering and leaving 400 of the larger US power plants

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)

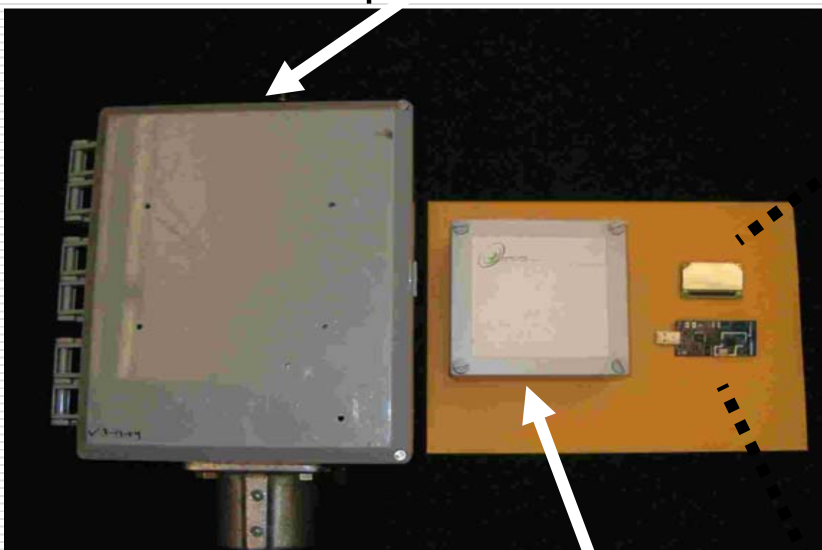
- *Sensors*
  Contributes to collection of "*physical metrics* across *the grid*"
- *System Monitoring*
  Measurement data provides "*real-time information on grid operating conditions*"
- *Visualization Tools*
  Provides data and visualization tools to enable "*grid operators and federal agencies*" 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

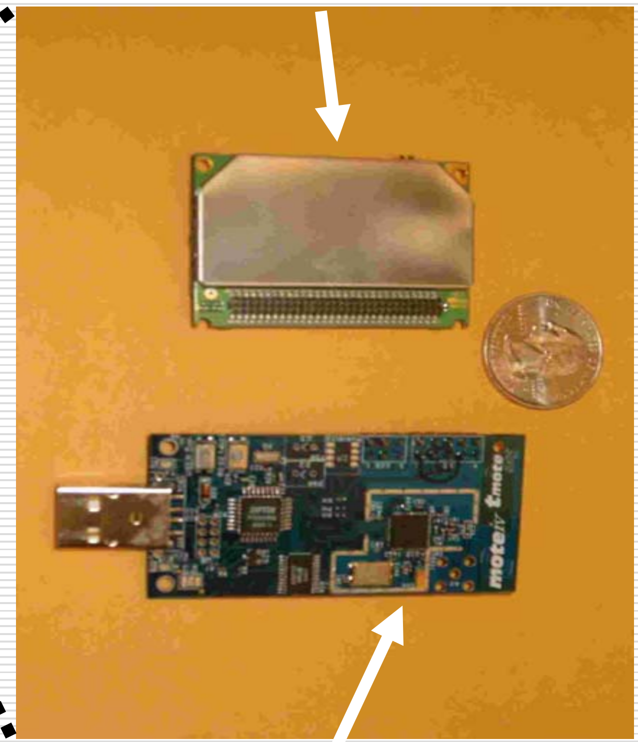
Form Factor Reduction

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

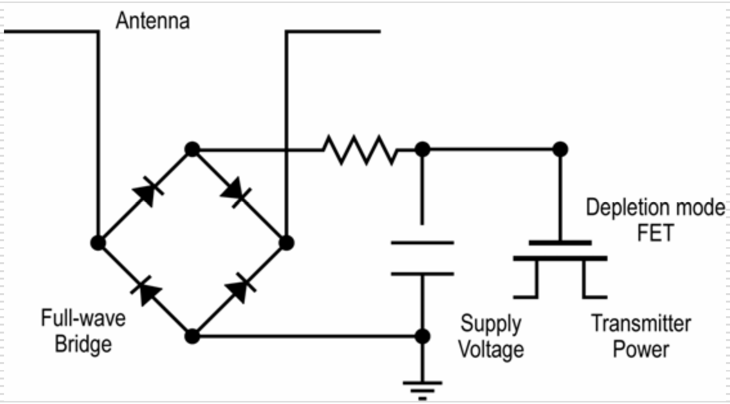
- Research magnetic and electric field scavenging
- Research potential for vibration scavenging in urban areas
- Implement lower power communication modem
- Implement lower power processor

Monitor Power Requirements

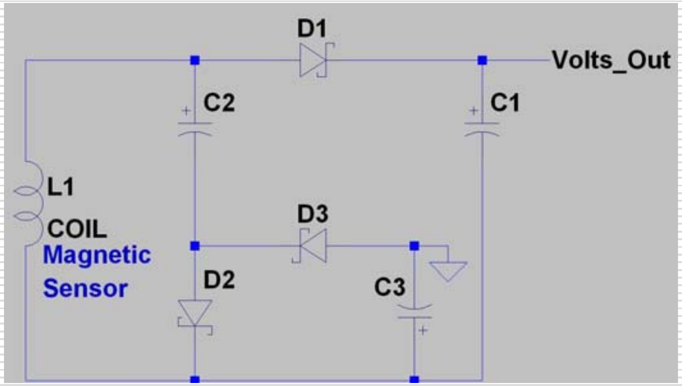
COMPONENT	CURRENT	PROPOSED	Potential Power Sources
Communication Modem and Antenna	3W (12V)	0.6 W (5V)	Solar, Permanent Battery
Microprocessor	660mW (12V) – processing mode	10mW (3.3V) - processing mode	Vibration, Magnetic/Electric Field Scavenging
Electric Field Sensor	Capacitive plate	Smaller form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

Electric or Magnetic Field Scavenging

Electric Scavenging Circuit



Magnetic Scavenging Circuit



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

Solenoid Output = 10mV/mG

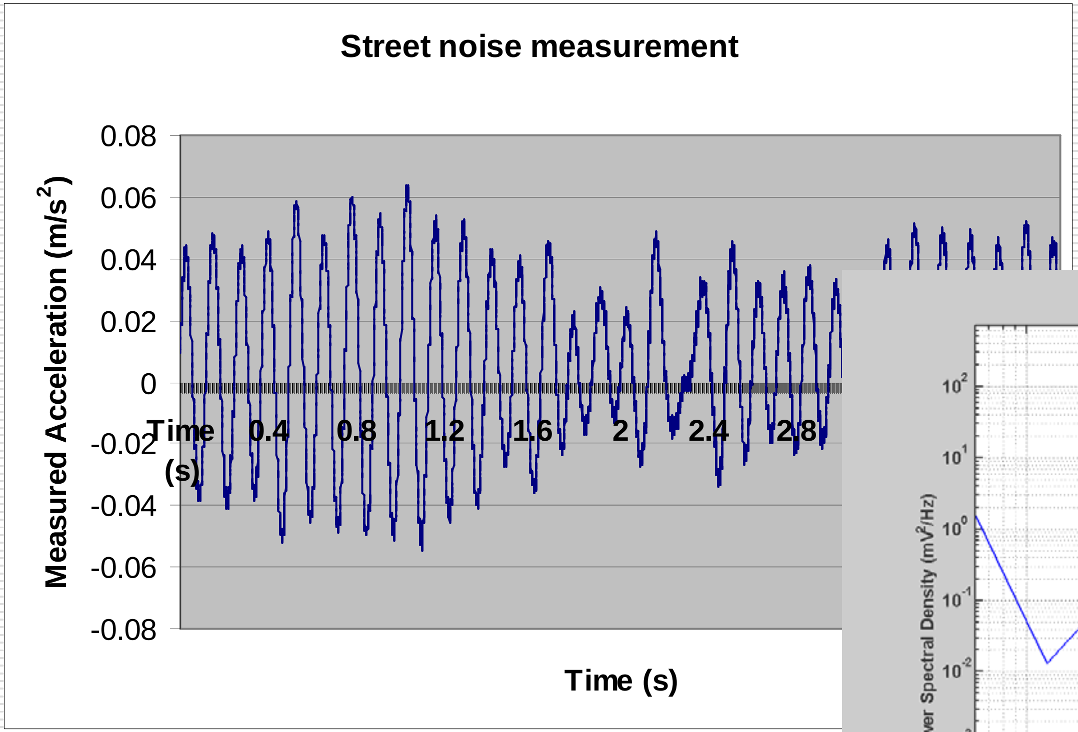
Typical Fields at 20 meters 50-150mG at 20 m (0.5-1.5V)

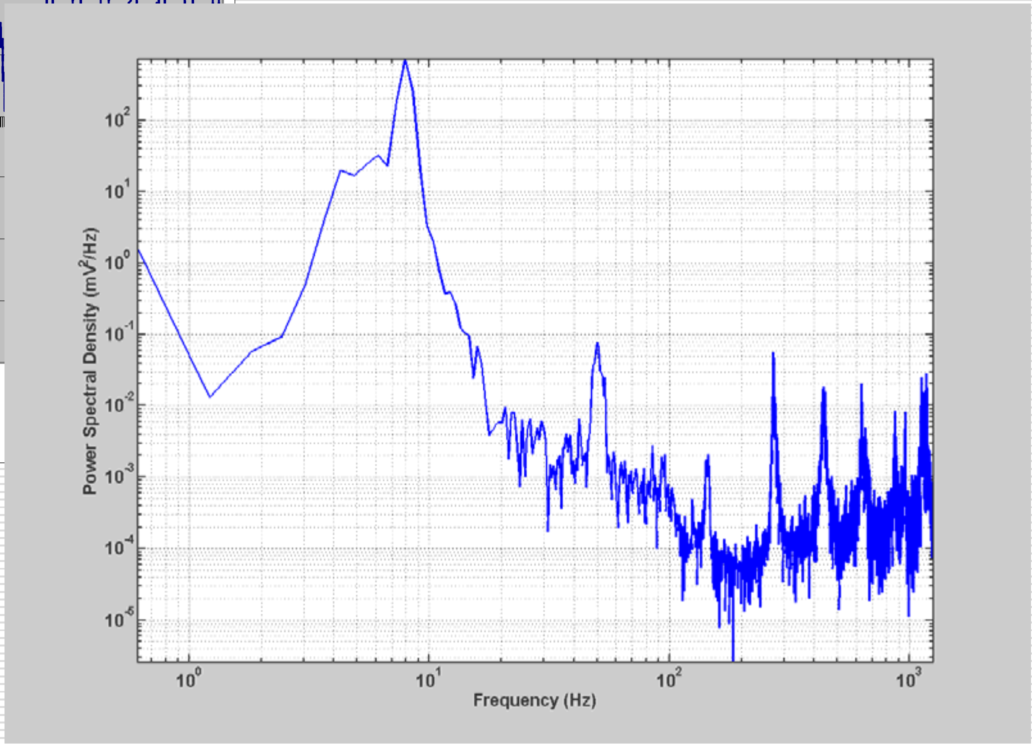
Power Scavenging from Ambient Vibrations

SOURCE	FREQUENCY (Hz)	AMPLITUDE (m/s^2)	POWER OUTPUT
Footsteps on a wooden deck	385	1.3	45mW every 50 minutes
HVAC vents in office building	60	0.2-1.5	Not measured
Windows next to a busy street	100	0.7	Not measured

Reference:"Energy Scavenging for Wireless Sensor Networks with Special Focus on Vibrations" Roundy, Wright, Rabaey 2004 (Kluwer Academic)

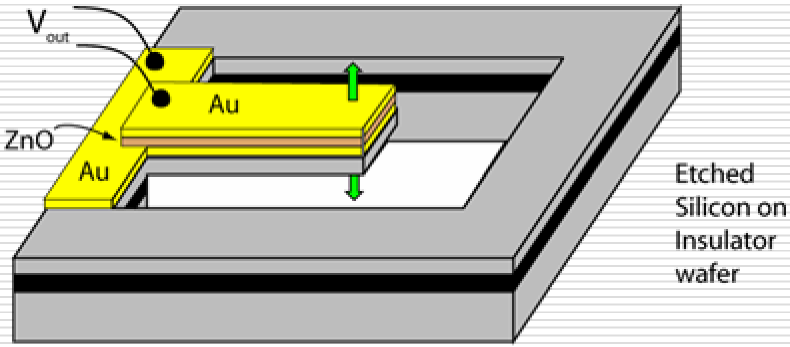
Vibration Scavenging: Urban Site Measurements





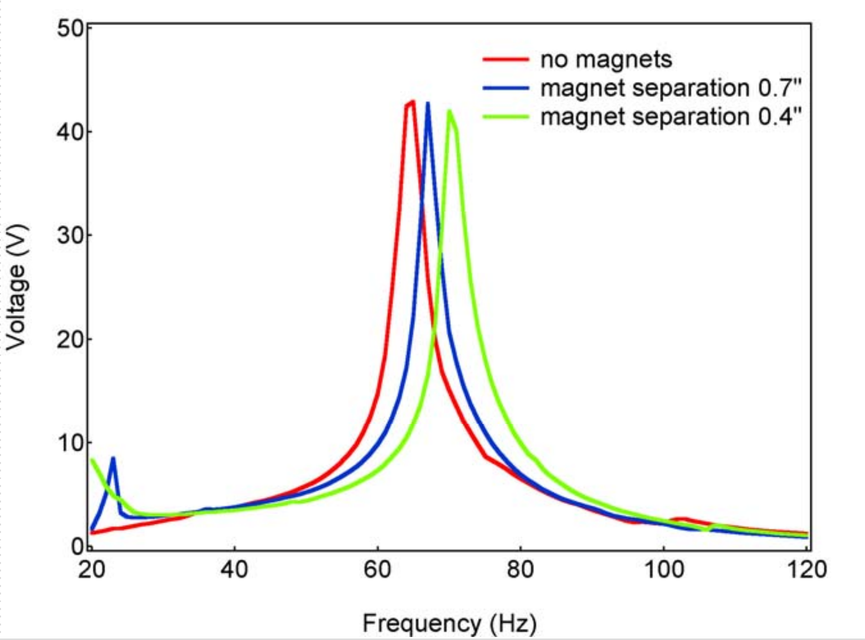
Vibration Scavenging: Cantilever-Based Design Ideas

Microfabricated cantilever for vibration energy scavenging



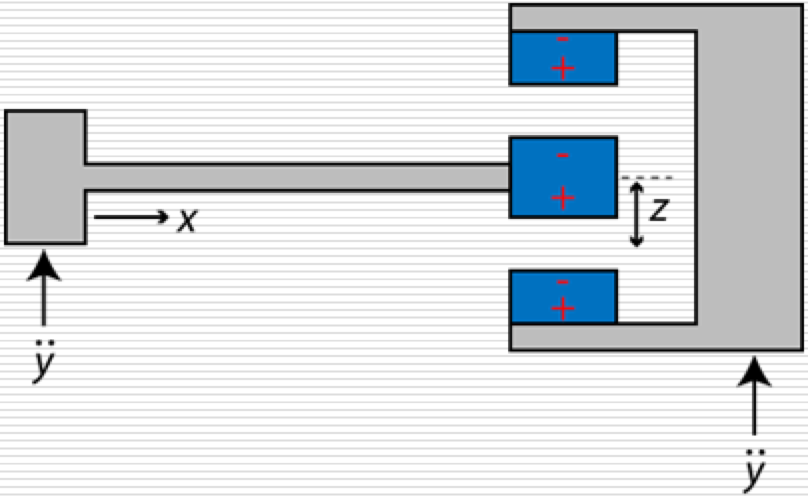
Example of microfabricated cantilever used for gas sensing

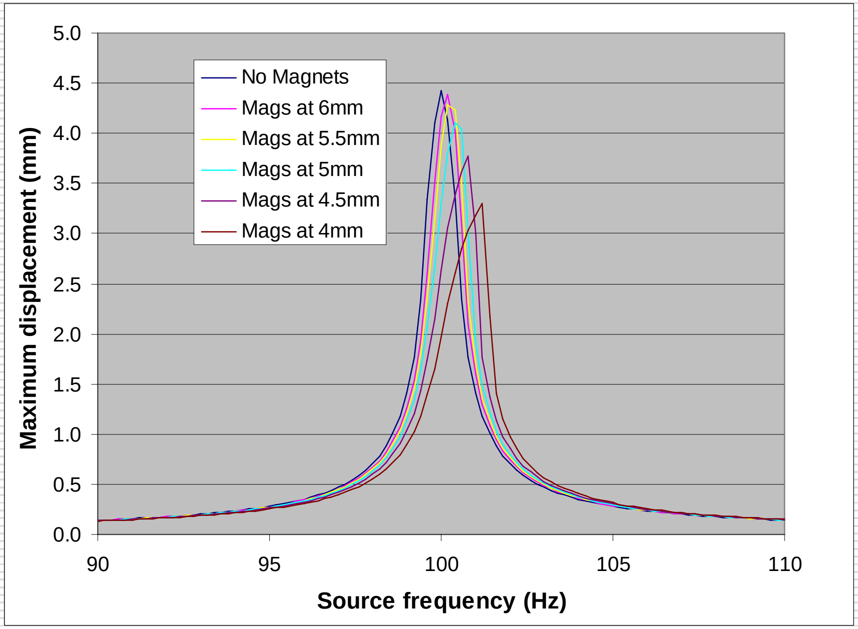
Magnetically modulated cantilever



- ❑ Tunable frequency response
- ❑ Possibility for nonlinear response

Cantilever Design: Energy Output Modeling





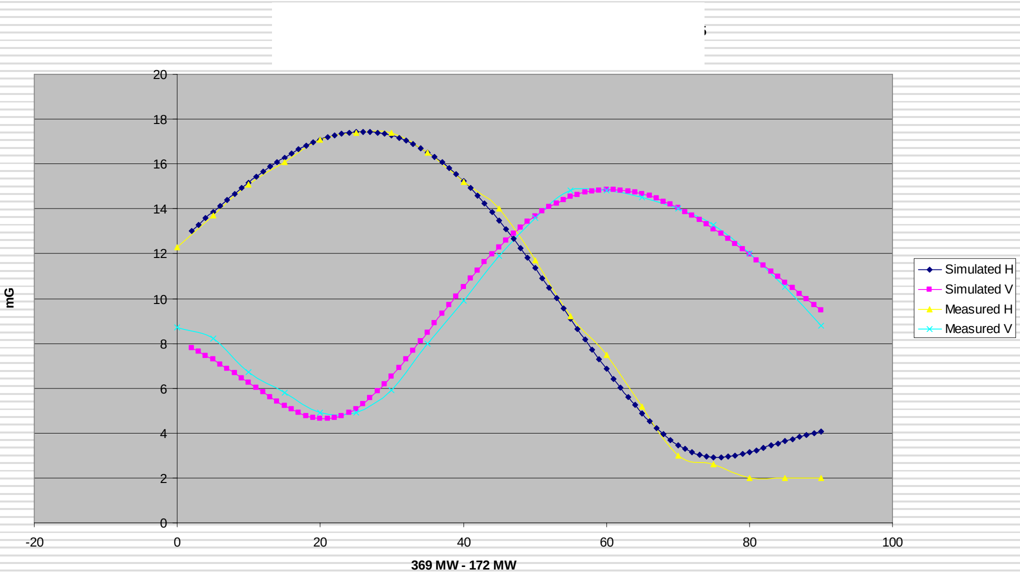
$$\ddot{z} = -\omega_0^2 z + (\text{pkAcc}) * \sin(2\pi ft) + 1/m\left[F(z_m - z) - F(z_m + z)\right]$$

Research/Design of Directional Sensors

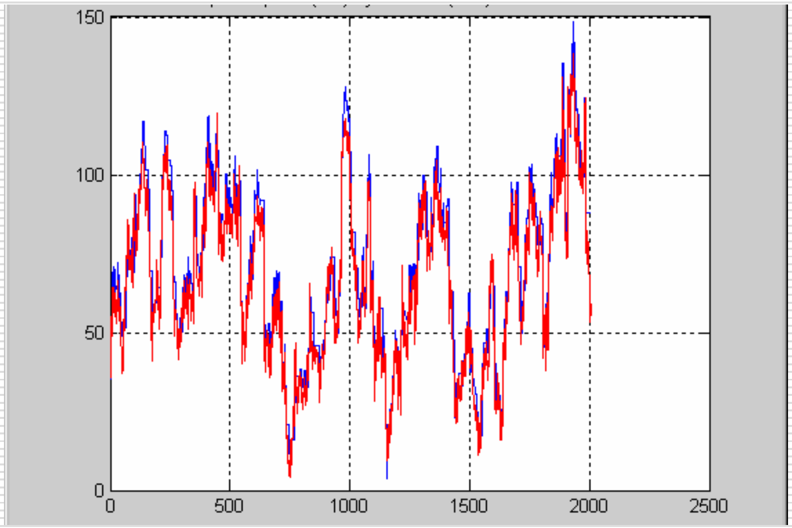
Objective: Enable the monitor to target specific transmission lines in the presence of other lines and high 60Hz background noise

- 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



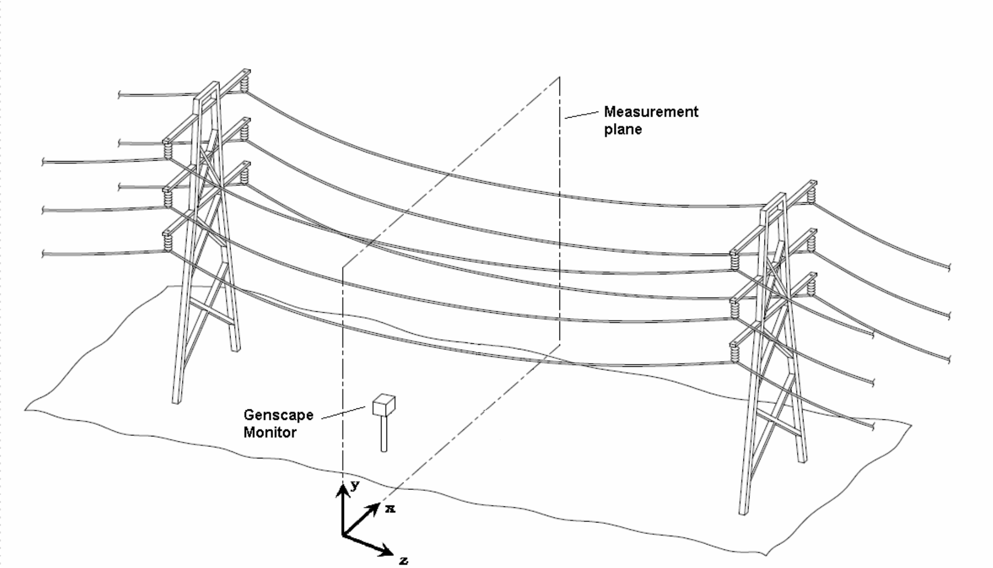
Comparison between measured and modeled transmission line B-field

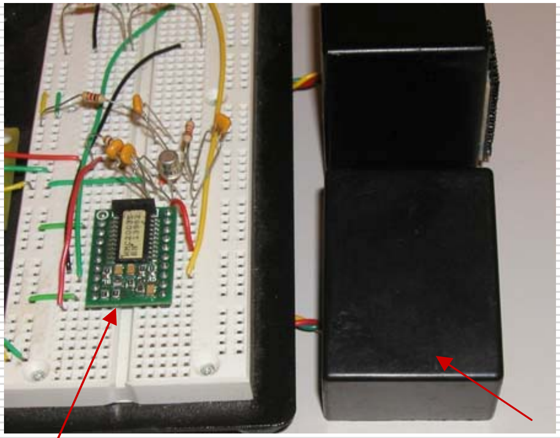


Computed power flow amplitude matches utility SCADA data to +/- 10%

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

3-Axis Magnetic Field Measurements





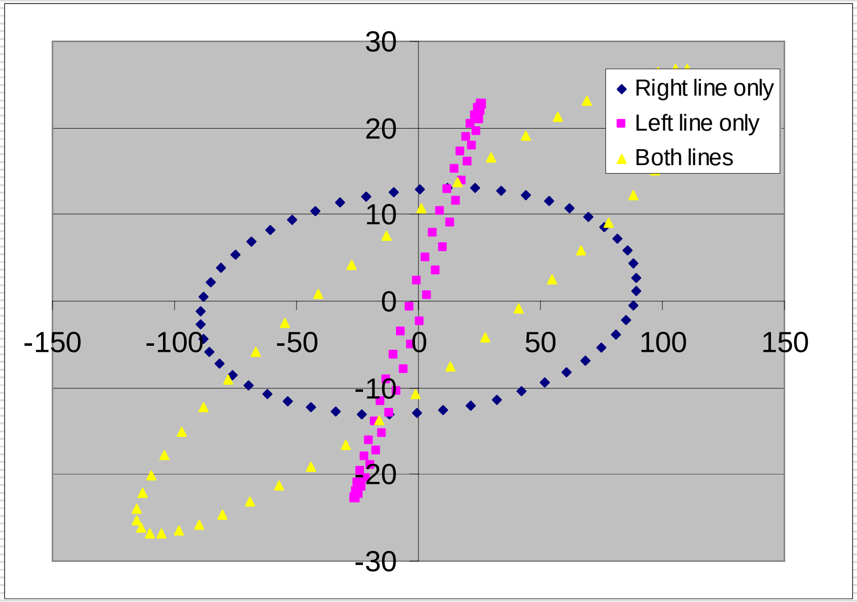
3-axis chip

solenoid casing

- 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

Embedded Application Development

Monitor applications will be written to deliver a range of reporting and power consumption profiles.

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

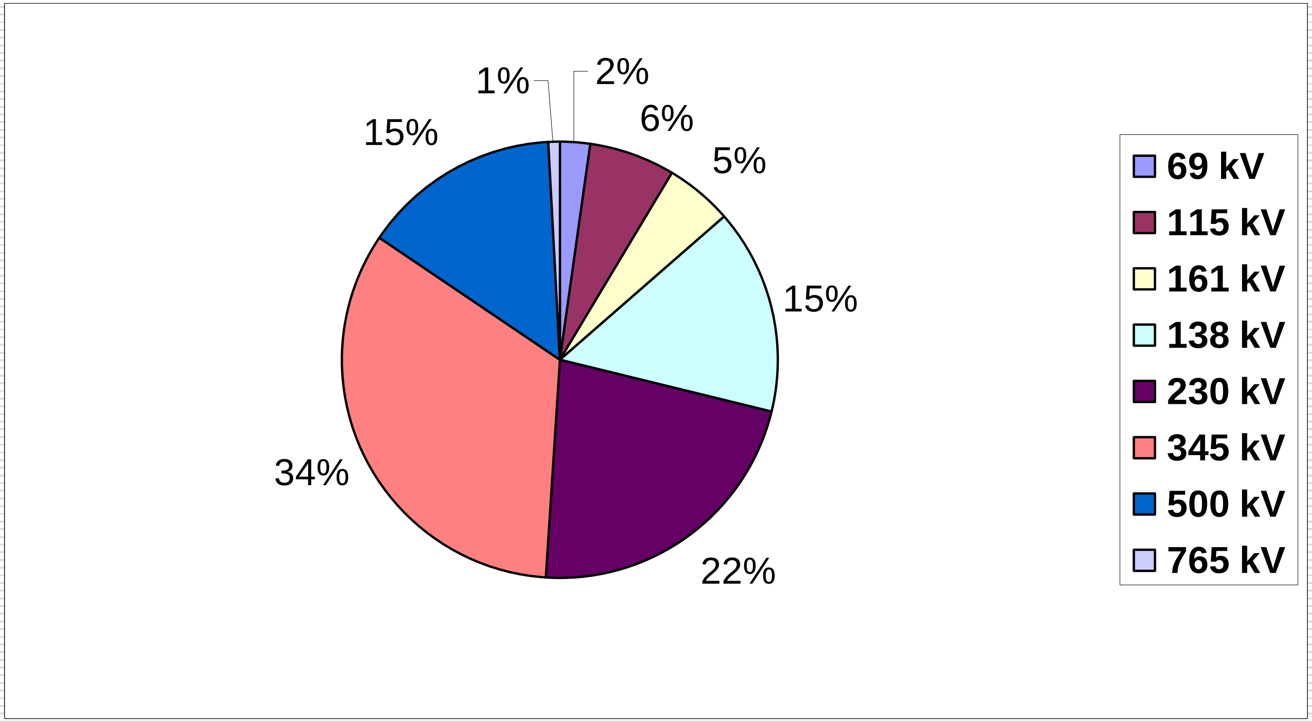
Field Test and Network Deployment

Field test sites have been identified for various test needs

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

Available Line Types

The Genscape network contains a variety of transmission line types for field testing.

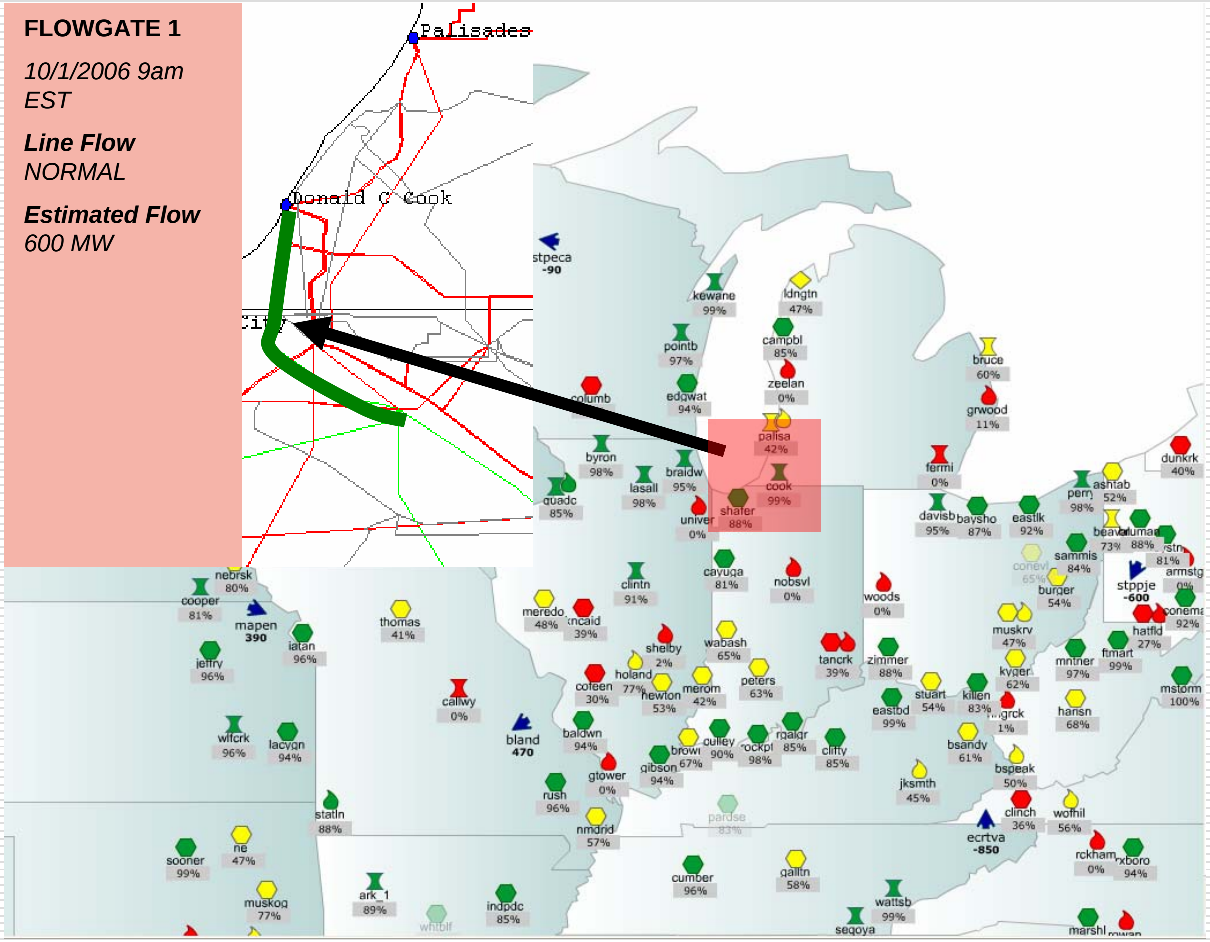


Server-side Applications

- 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

National Congestion Corridors - *National Electric Transmission Congestion Study* DOE (August 2006)

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

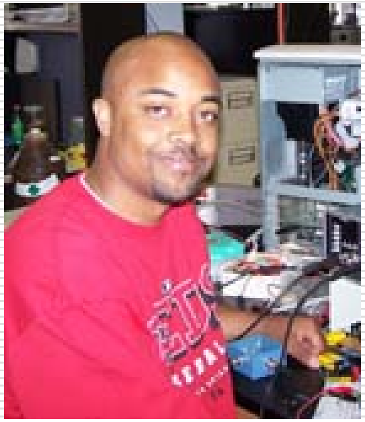
- Three functional teams
  - Research Team
  - Prototype Development Team
  - IT Applications/Infrastructure Team
- Weekly team meetings
- Shared access to UofL and Genscape facilities/resources
- Company work experience for students

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

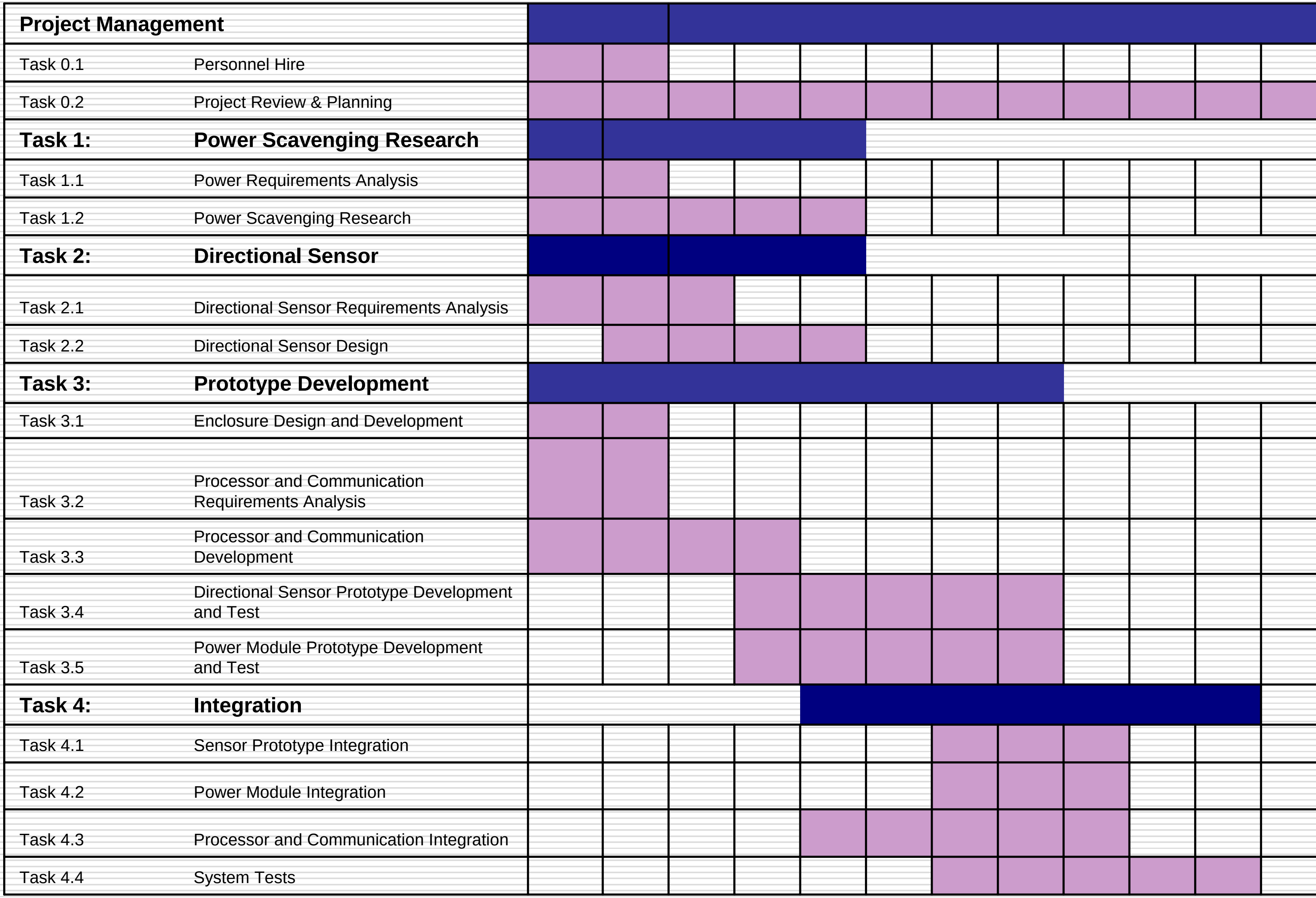
Mike Linahan – Logistics and Field Support

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)

Task 5:	**Embedded Application Development**	■	■	■	■	■	■	■	■	■	■		
Task 5.1	Firmware Requirements Analysis and Design	■	■	■	■								
Task 5.2	Firmware Development and Test		■	■	■	■	■	■	■	■	■		
Task 6:	**Field Test and Deployment**	■	■	■	■	■	■	■	■	■	■	■	■
Task 6.1	Identify/Prepare Field Test Sites	■	■	■									
Task 6.2	Field Testing			■	■	■	■	■	■	■	■		
Task 6.3	Identify/Prepare Grid Network Site									■	■		
Task 6.4	Network Deploy											■	■
Task 7:	**Server-Side Application Development**	■	■	■	■	■	■	■	■	■	■	■	■
Task 7.1	Data Center Requirements Analysis	■	■	■				■	■	■			
Task 7.2	Data Center Design / Implementation	■	■	■	■	■	■	■					
Task 7.3	Basic Data Center Applications Development (Message Handling, Data Processing)	■	■	■	■	■	■	■					
Task 7.4	Advanced Data Center Development (Interface, Alerting, Datafeeds)							■	■	■	■	■	■
Task 8:	**Data Integration**						■	■	■	■	■	■	■
Task 8.1	Grid Fault and SCADA Integration Design									■	■	■	
Task 8.2	Alert Protocol Design						■	■					
Task 8.3	Alert Protocol Development							■	■	■			
Task 8.4	Data Delivery Development and Test							■	■	■	■	■	■