*Design and Implementation of Power Line Sensornet for Overhead Transmission Lines**

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Outline

- Background
- Existing Sensors for Power Grid Monitoring
- Power Line Sensor Networks (PLSN)
- Laboratory Prototype PLSN
- Potential Applications

Background

- **Electric Power Industry Issues**
  - **The power grid represents perhaps the most complicated and largest network built by man, and is congested and under stress;**
  - **Utilities currently have very little information about the power grid beyond the substations;**
  - **For the Blackout 2003, lack of visibility and situational awareness were key contributors to the blackout;**
- **Critical Needs for Transmission**
  - **Improving utilization and reliability of power grid**
  - **Requiring a cost effective, massively deployed, widely distributed and intelligent monitoring scheme for power grid**

Background

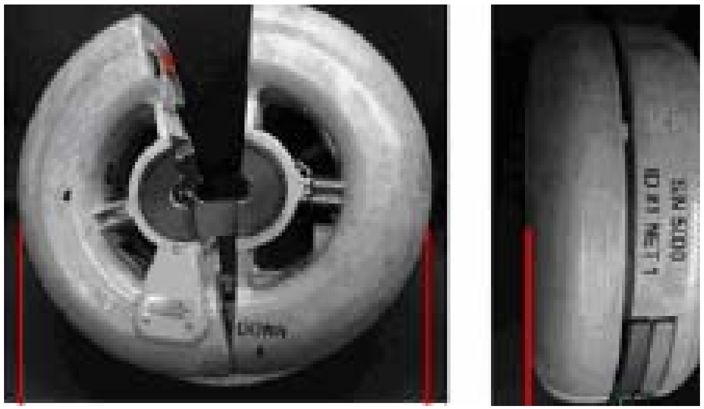
- **New Opportunities for Power Grid Monitoring**
  - **Communication technologies have already revolutionized many application areas, such as telecommunication, banking, and certain manufacturing industries. Networks that have been built or upgraded recently are smarter.**
  - **Reductions in sensors, μProcessors, computation and communications costs, coupled with enhanced performance, have raised the possibility of realizing widely and massively distributed sensor networks to monitor the grid.**

If Alexander Graham Bell were somehow transported to the 21st century, he would not begin to recognize the components of modern telephony – cell phones, texting, cell towers, PDAs, etc. – while Thomas Edison, one of the grid's key early architects, would be totally familiar with the grid*.

*** The Smart Grid: An Introduction. --- by DOE**

Existing Sensors for Power Grid Monitoring

- **Line Current and Conductor Temperature Measurement**

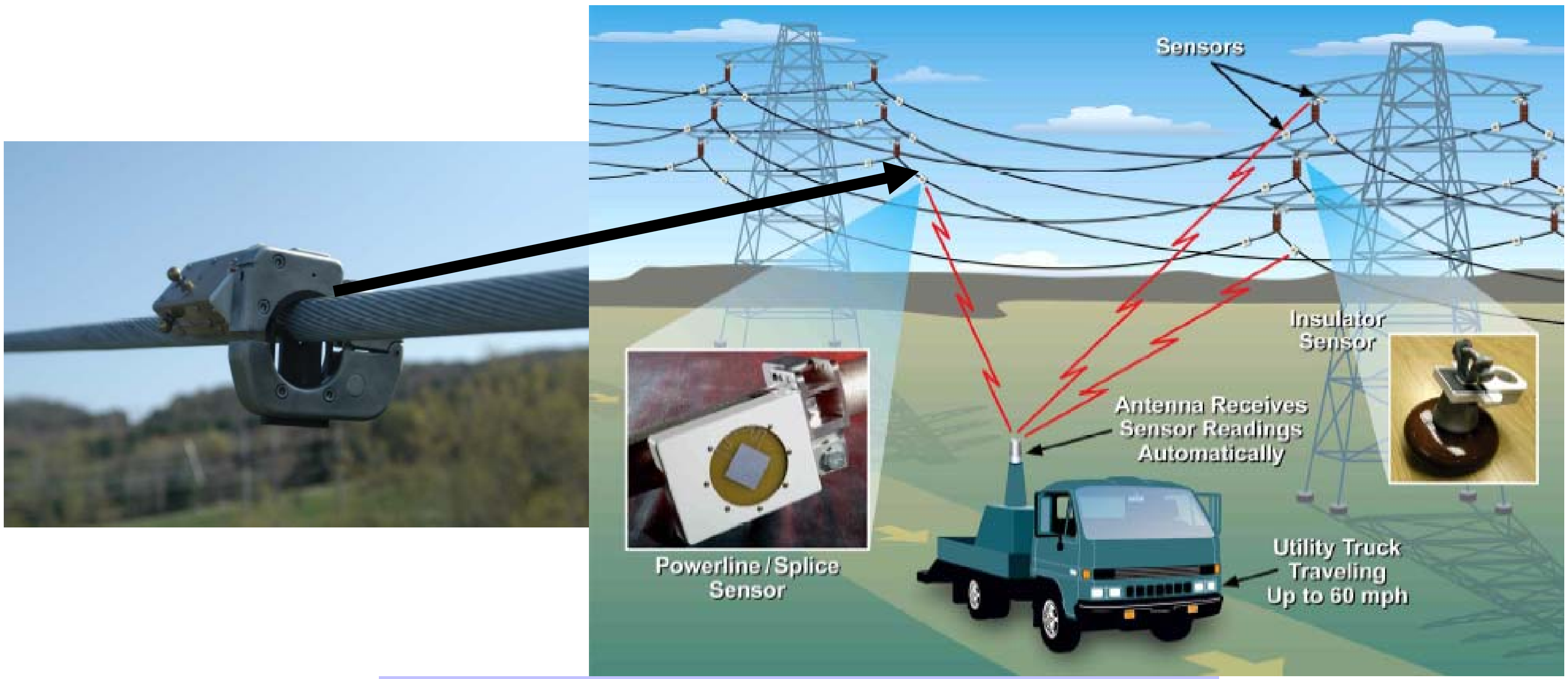


Power Donuts (USi)

Power Line Sensors (Protura)

Existing Sensors for Power Grid Monitoring

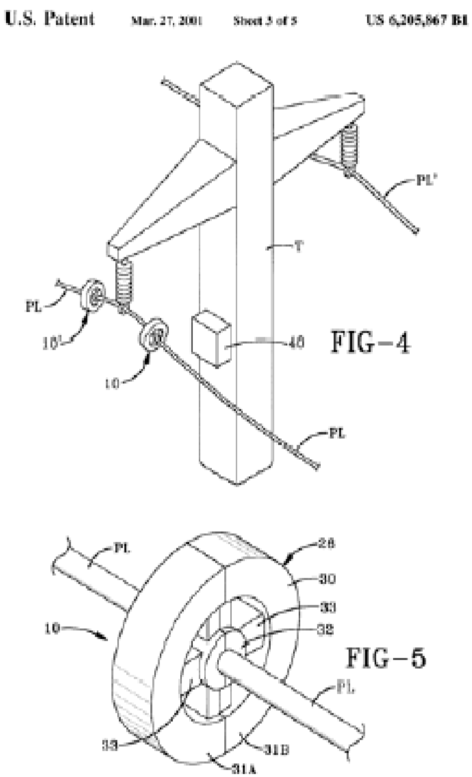
- **Line Current and Conductor Temperature Measurement**



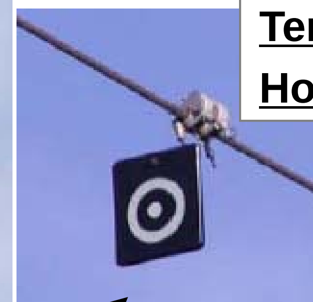
EPRI RF Backscatter Sensors

Existing Sensors for Power Grid Monitoring

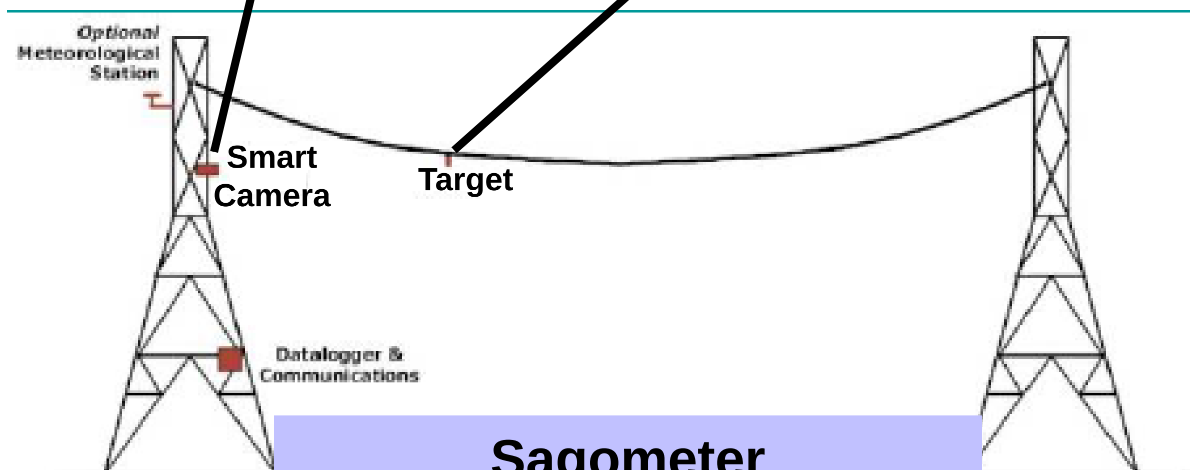
- **Sag Measurement**



Inclinometer



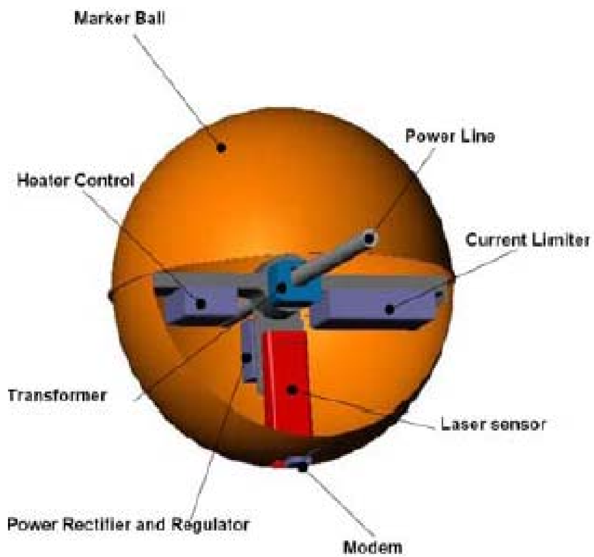
Vertical clearance;
Tension;
Horizontal movement



Sagometer (EPRI/EDM/SwRI)

Existing Sensors for Power Grid Monitoring

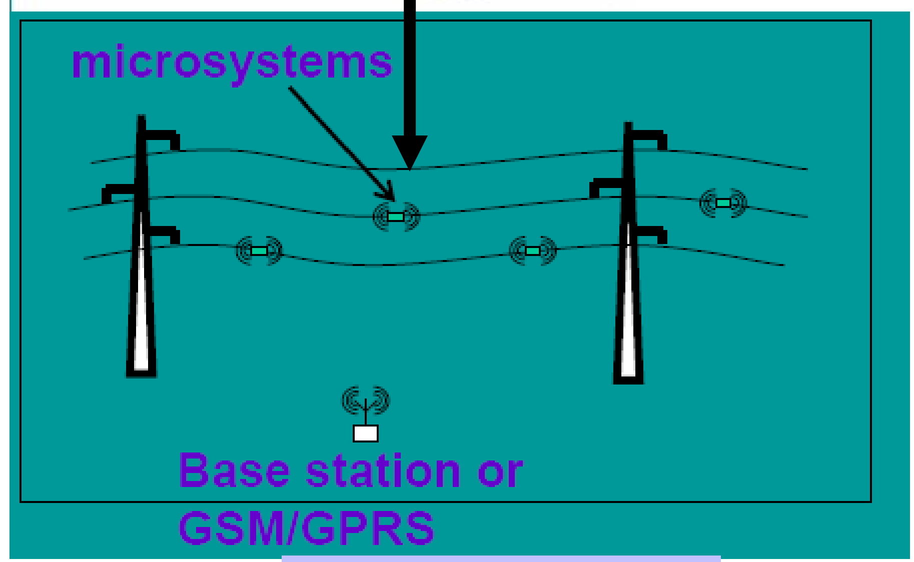
- **Sag Measurement**



Laser Distance Sensor (EPRI)

Accelerometer:

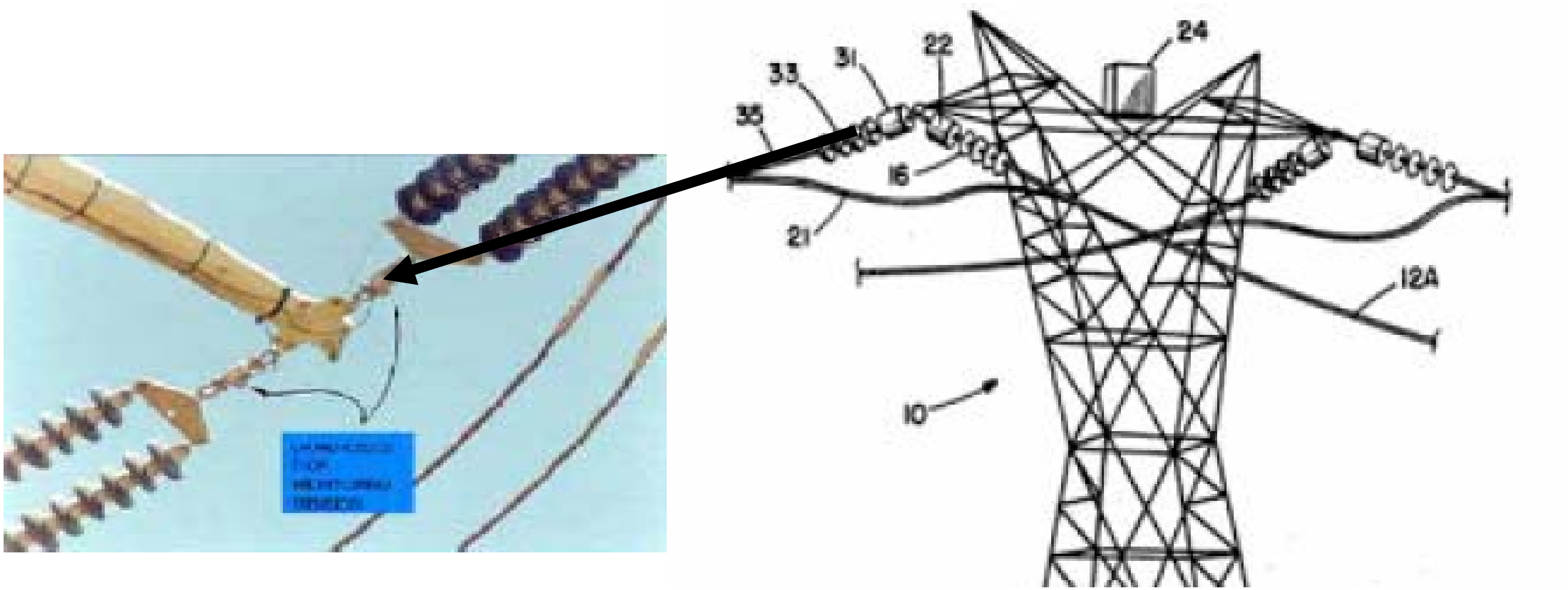
Aeolian vibration frequency → Sag measurement



AMPACIMON

Existing Sensors for Power Grid Monitoring

- **Tension Measurement**



Average conductor temperature can be indirectly measured by conductor tension within ruling span sections

Tension Monitoring

(T. Seppa,USA, 1993. Belongs to NEXANS from 2007)

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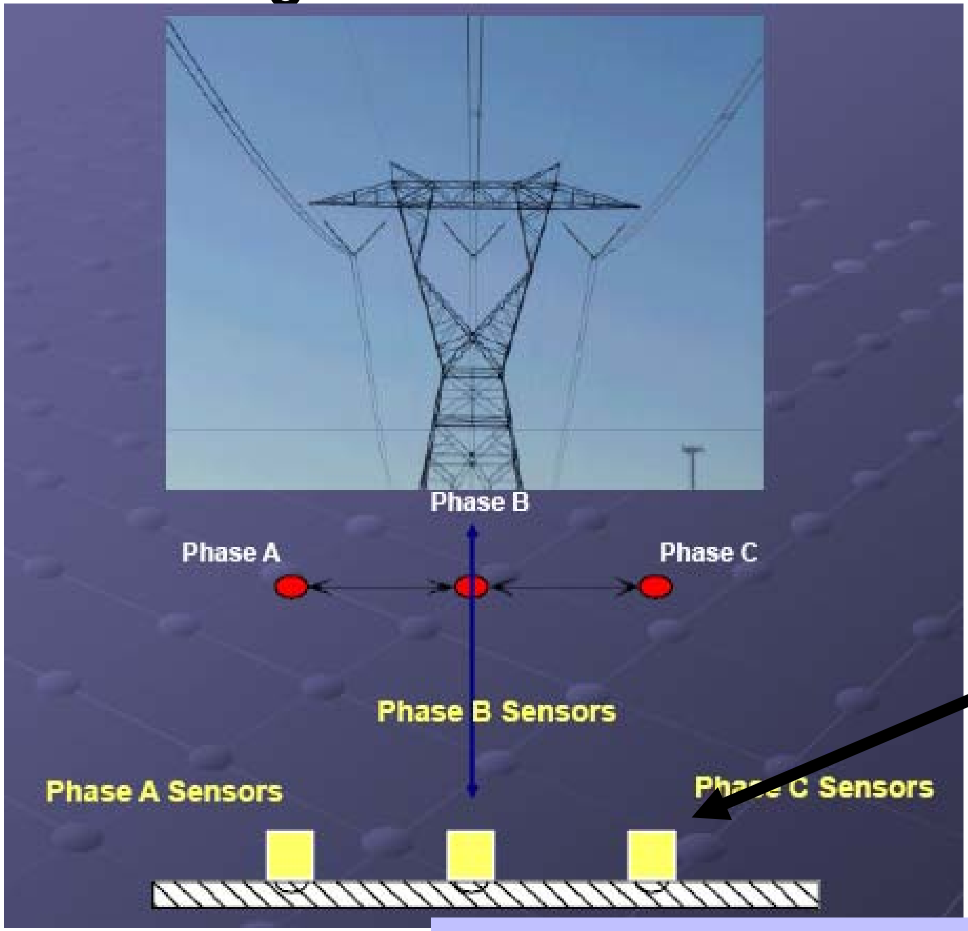
Existing Sensors for Power Grid Monitoring

- **Electromagnetic Field Measurement**



<u>Conductor Sag/Clearance;</u>
<u>Conductor current;</u>
<u>Conductor temperature</u>

Sensor consists of two orthogonal coils.

Promethean Devices

IEEE

Existing Sensors for Power Lines Monitoring

- **What are the challenges for power grid monitoring?**

Most of the sensors/monitoring devices deployed now a day are located within the scope of substations, or at predetermined critical sites.

Most of the sensors under development only deal with raw sensing data measured in real-time.

Most of the sensor development efforts are focused on the individual devices.

Very Low Cost!

"Smart/Intelligent" Sensor!

Self-organizing/self-healing Sensor Networks!

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Power Line Sensor Network (PLSN)

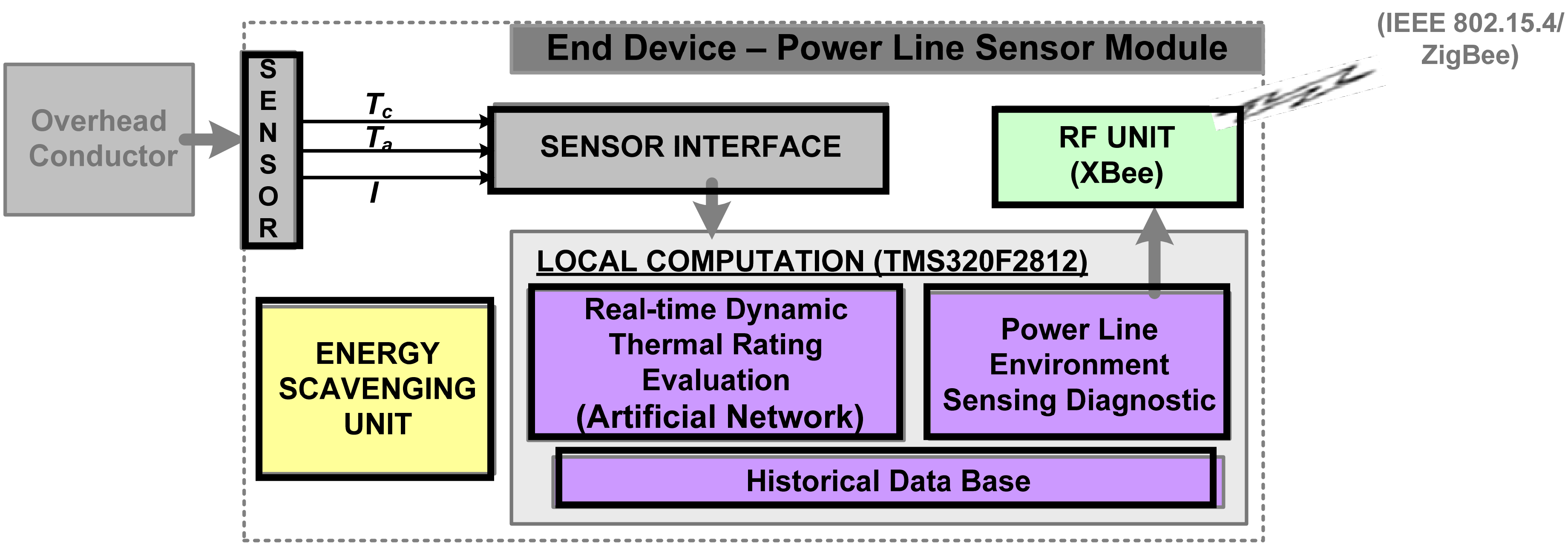
- **Project I: Power Line Sensornet (PLSN) (funded by NSF)**
  - With a large number of low-cost, unattended, smart and communication-enabled sensor modules clamped on power lines, the PLSN provides continuous on-line monitoring of power line status down to ‘per span’ level of granularity.
  - **Target Applications:**
    - Overhead Transmission Line thermal conditions and capacity under current weather conditions.
    - The presence of incipient insulator failure of the line, such as conductor clearance to ground or nearby vegetation.

Power Line Sensor Network (PLSN)

- **Project II: “Stick-on” Sensors (funded by NEETRAC)**
  - Low cost sensors under development can be **attached (‘stuck’)** to a utility asset;
  - A universal or semi-universal sensor mounting solution is proposed to maximize its applications;
  - Targeted cost < US$50.0.
  - **Target Applications:**
    - Live circuit detection, Non-revenue grade current monitoring, shunt capacitor status.
    - Substation - High voltage disconnect switch monitor – detect overheating contacts / connectors.
    - High voltage underground cable terminations – Detect overheating connector, live cable detection.
    - Padmounted switchgear / transformers - Detect overheating contacts / connectors / primary elbows.
    - Customer Side Equipment – Monitor any items normally covered now by periodic thermovision surveys for critical customers.

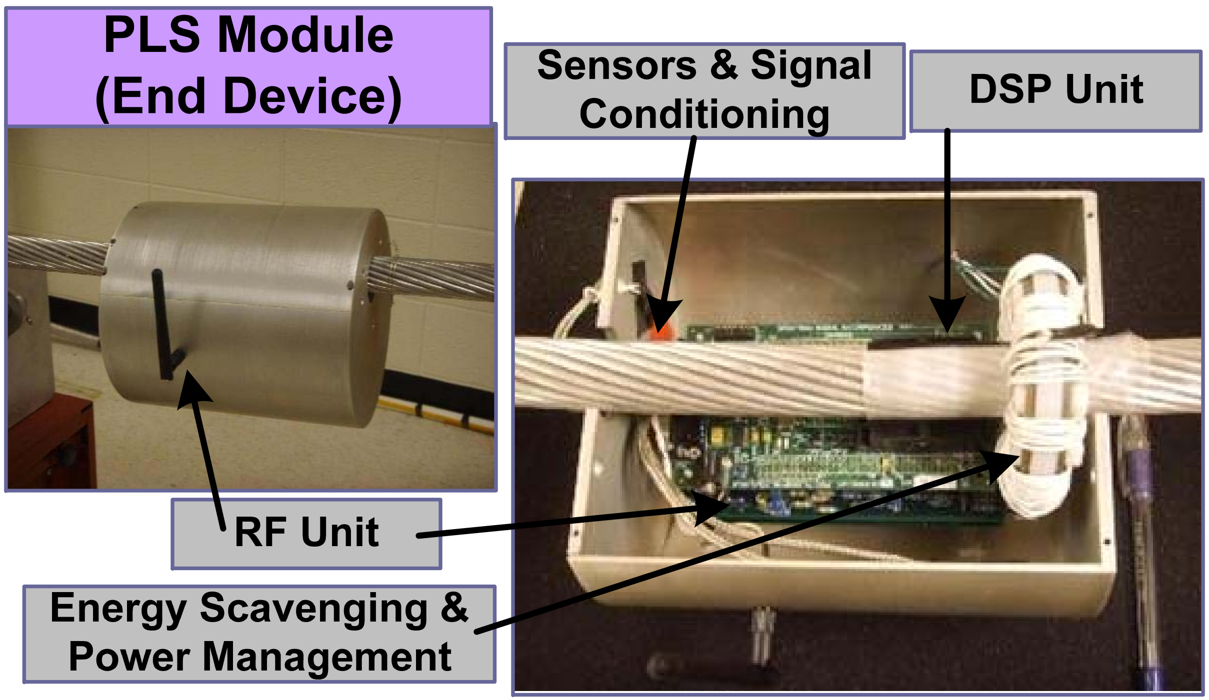
Power Line Sensor Network (PLSN)

- **Sensor Technical Features**



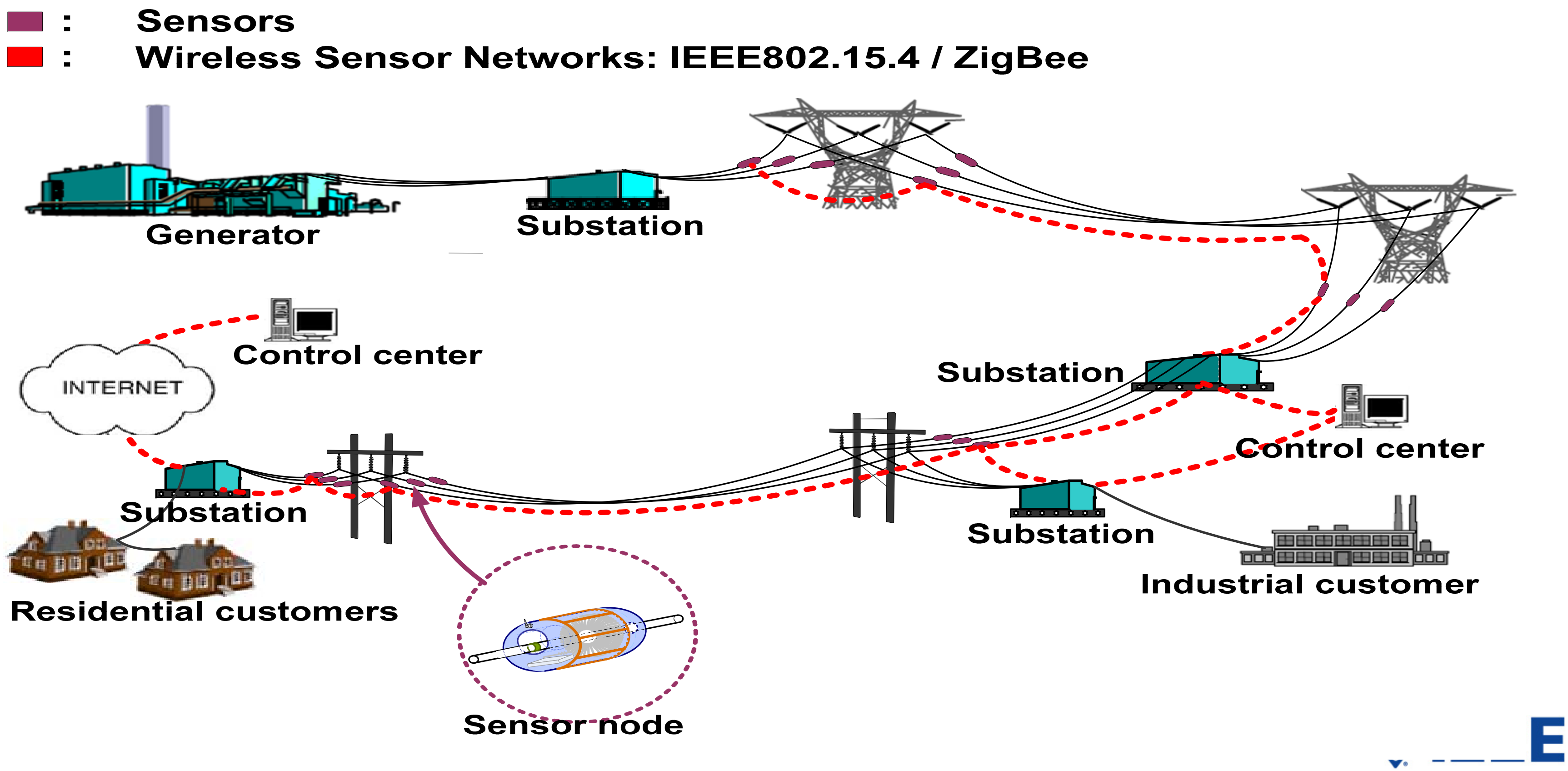
Laboratory Prototype PLS Module

- **PLS Module Characteristics**
  - **Low cost (Targeted Cost < US$300.0):**
    (Targeted cost < US$50.0 for "Stick-on" Sensor)
    - **No high voltage isolation; Low price sensors (temperature; current)**

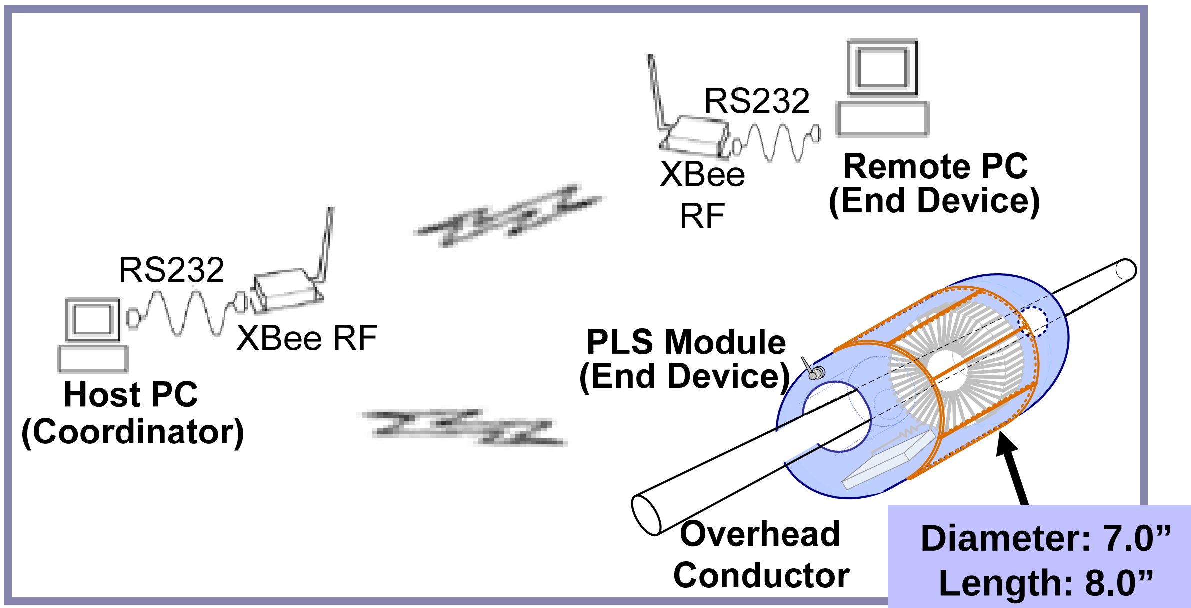


Power Line Sensor Network (PLSN)

Continuous on-line monitoring of the geographically dispersed power grid by using hundreds of thousands of *low cost, autonomous, smart, and communication-enabled* power line sensor (PLS) modules.



Laboratory Prototype PLSN



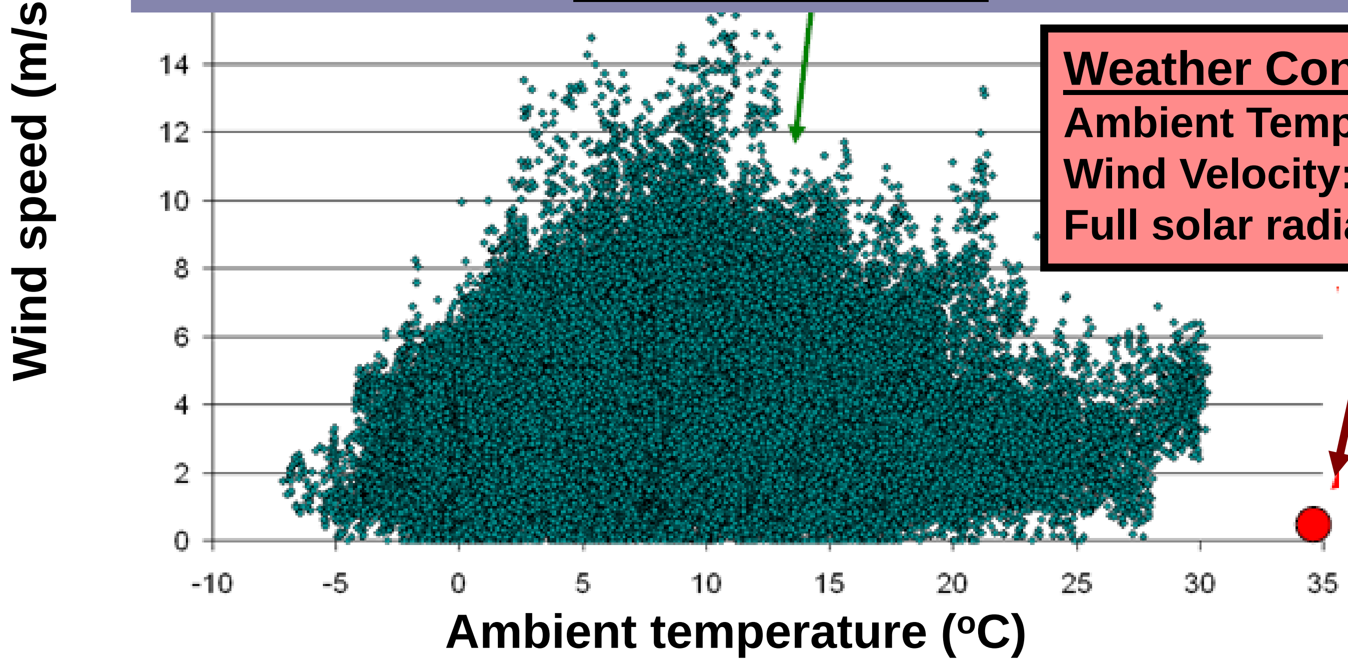
Maxstream XBee-PRO RF Module Field Test @GT Campus			
Range (m)	**RSSI (dBm)**	**PSR**	**Conditions**
100	~-92	~45%	Indoor @ I=1kA
500	-92	~35%	GT Campus Trees & Buildings

Potential Applications (1):
Real-time Thermal Rating of Overhead Lines

Traditional ‘Static’ Steady State Thermal Rating (SSTR) is determined based on “Worst” weather conditions.

Real-time ambient conditions are less constraining (98% of the time)

Real-Time Ambient Weather Conditions (One Year of Data)



Weather Conditions for SSTR:
Ambient Temp.: 35 °C
Wind Velocity: 0.6 m/s
Full solar radiation

*** J.L. Lilien, WISMIG Workshop, Arlington, USA**

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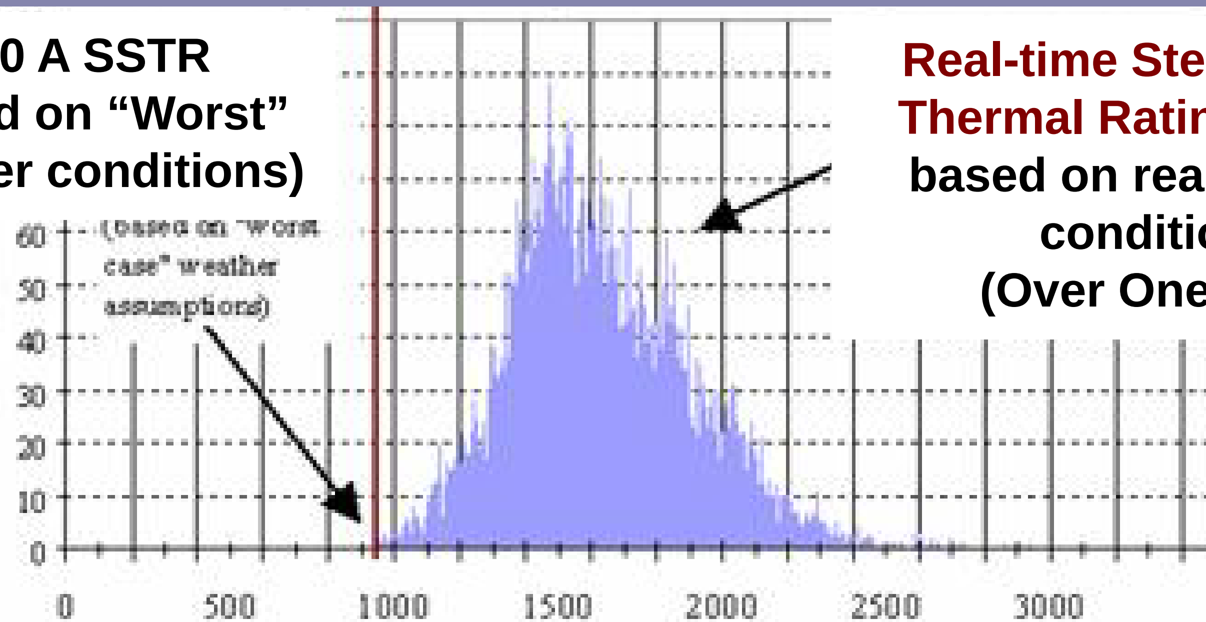
Potential Applications (1):
Real-time Thermal Rating of Overhead Lines

Line Real-time Thermal Capacity Distribution
(One Year of Data, Drake Conductor)

920 A SSTR
(based on "Worst" weather conditions)

Real-time Steady State Thermal Rating (RSTR)
based on real weather conditions
(Over One Year)



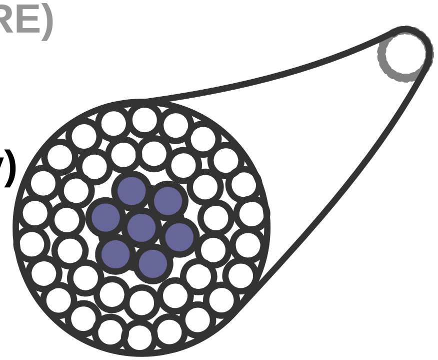
90-98% of the time OHPL can carry 10-30% higher load, if considering real-time weather conditions, than the conventional line capacity defined by SSTR.

*** J.L. Lilien, WISMIG Workshop, Arlington, USA**

Potential Applications (1):
Dynamic Thermal Rating of Overhead Lines

- **Overhead Conductor Thermal Behaviors**

<u>Heat Gain</u>:
- ~~Corona Heating: Q_f~~(IEEE&CIGRE)
- ~~Magnetic Heating Q_m~~(IEEE)
- **Joule Heating Q_j (line current)**
- **Solar Heating Q_s (sun intensity)**



<u>Heat Loss</u>:
- **Convection cooling Q_c (wind)**
- **Radiating cooling Q_r (radiation)**
- ***<u>Evaporative cooling Q_w</u>* (rain/snow/ice)**

<u>Heat Transfer Dynamics</u>:
- **mCp(dTc/dt)**

<u>Overhead Conductor Heat Balance Equation</u>

$$Q_j + Q_m + Q_s + Q_f = Q_c + Q_r + Q_w + mCp\frac{dT_c}{dt}$$

The temperature of the conductor changes gradually after a change in current. The delay is a result of the thermal capacitance, *mCp*, of the conductor.

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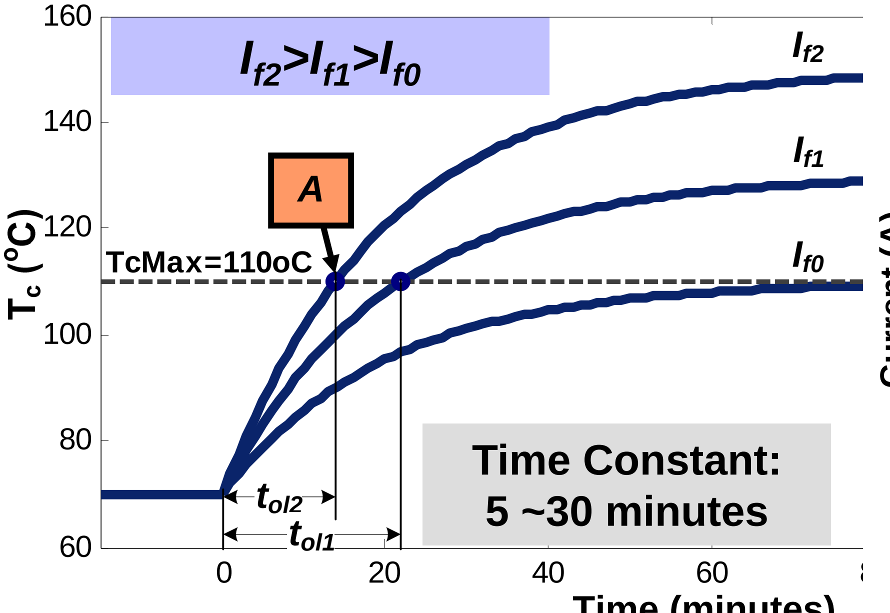
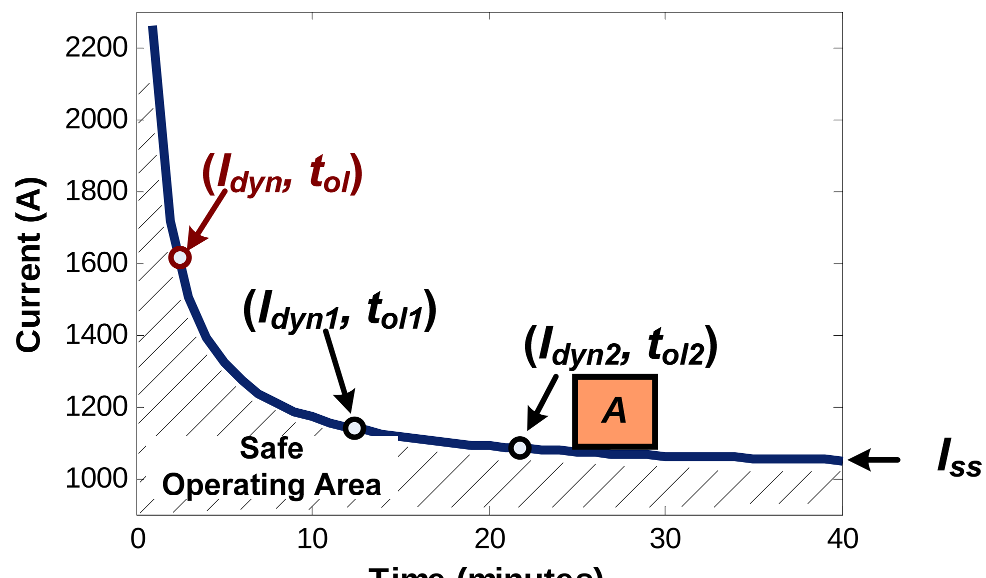
Potential Applications (1):
Dynamic Thermal Rating of Overhead Lines

- **What does Dynamic Thermal Rating really mean?**

Conductor Temperature T_c Response
Under Current Change from $I_i \rightarrow I_{f0}, I_{f1}, I_{f2}$.



I-T Thermal Limit Curve



This I-T Curve provides utilities a more realistic safe operating margin of a line under certain conductor ambient weather condition, and allows the operator to make efficient energy management decisions, especially under system emergencies.

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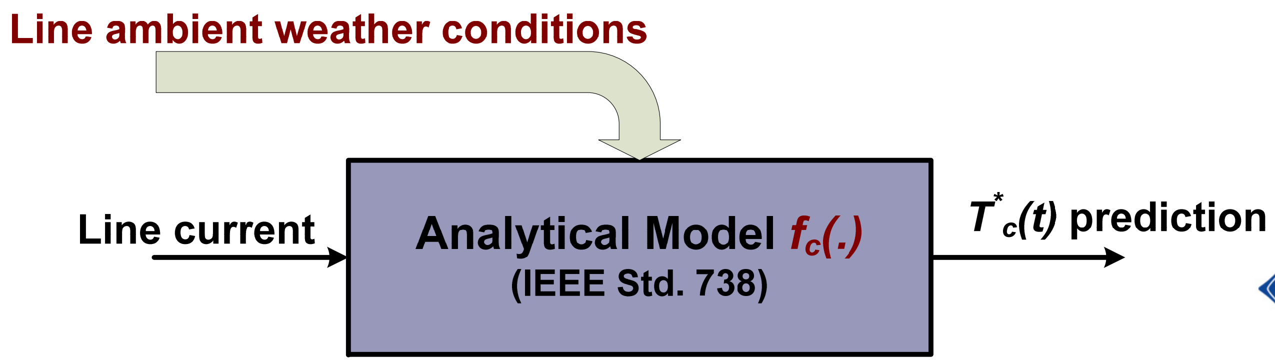
Potential Applications (1):
Dynamic Thermal Rating of Overhead Lines

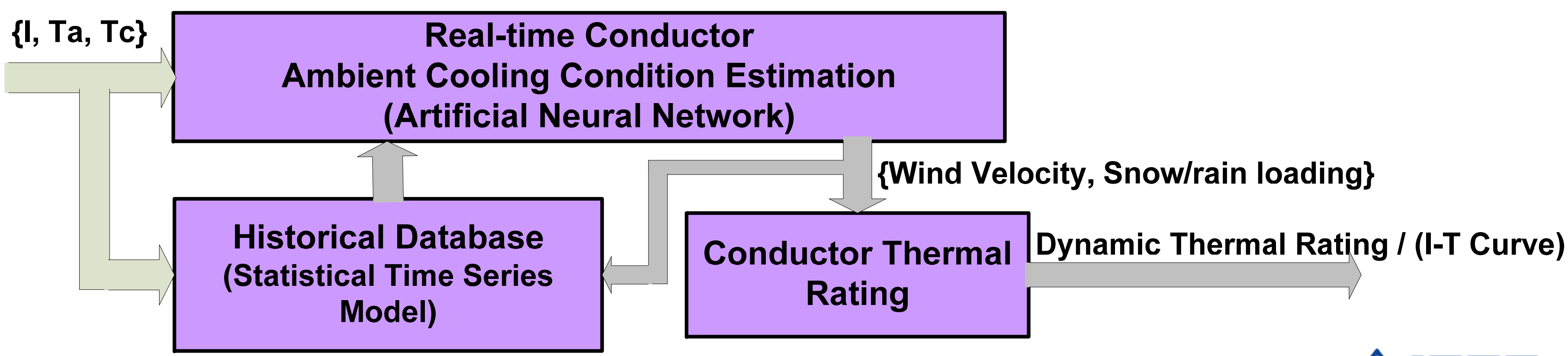
Static Steady State Thermal Rating (SSTR)
Real-Time Steady State Thermal Rating (RSTR)
Real-Time Dynamic Thermal Rating (RDTR)

- **Previous Works on Real Time Thermal Rating Evaluation**
  - **A 'weather station' at a pre-identified 'critical span' is normally used to provide the line weather condition. These methods are expensive and do not provide accurate information as micro-climate variations along the line are ignored;**
  - **Numerical complexity associated with computing conductor temperature analytically has discouraged utility engineers from attempting to use it in real-time.**



Potential Applications (1):
Dynamic Thermal Rating of Overhead Lines

- **Proposed Method**
  - **Only three real-time measurements are needed, i.e. conductor and ambient temperatures and conductor current;**
  - **Thermal heat removal capability of the conductor is estimated under present weather conditions by using artificial intelligence technologies;**
  - **Together with the knowledge of historical data, the true dynamic capacity of the line is estimated;**
  - **Each PLS module acts as a "micro-weather station" for the span/segment of the line where the sensor module is mounted, and the line RDTR evaluation is down to a 'per-span' level of granularity.**

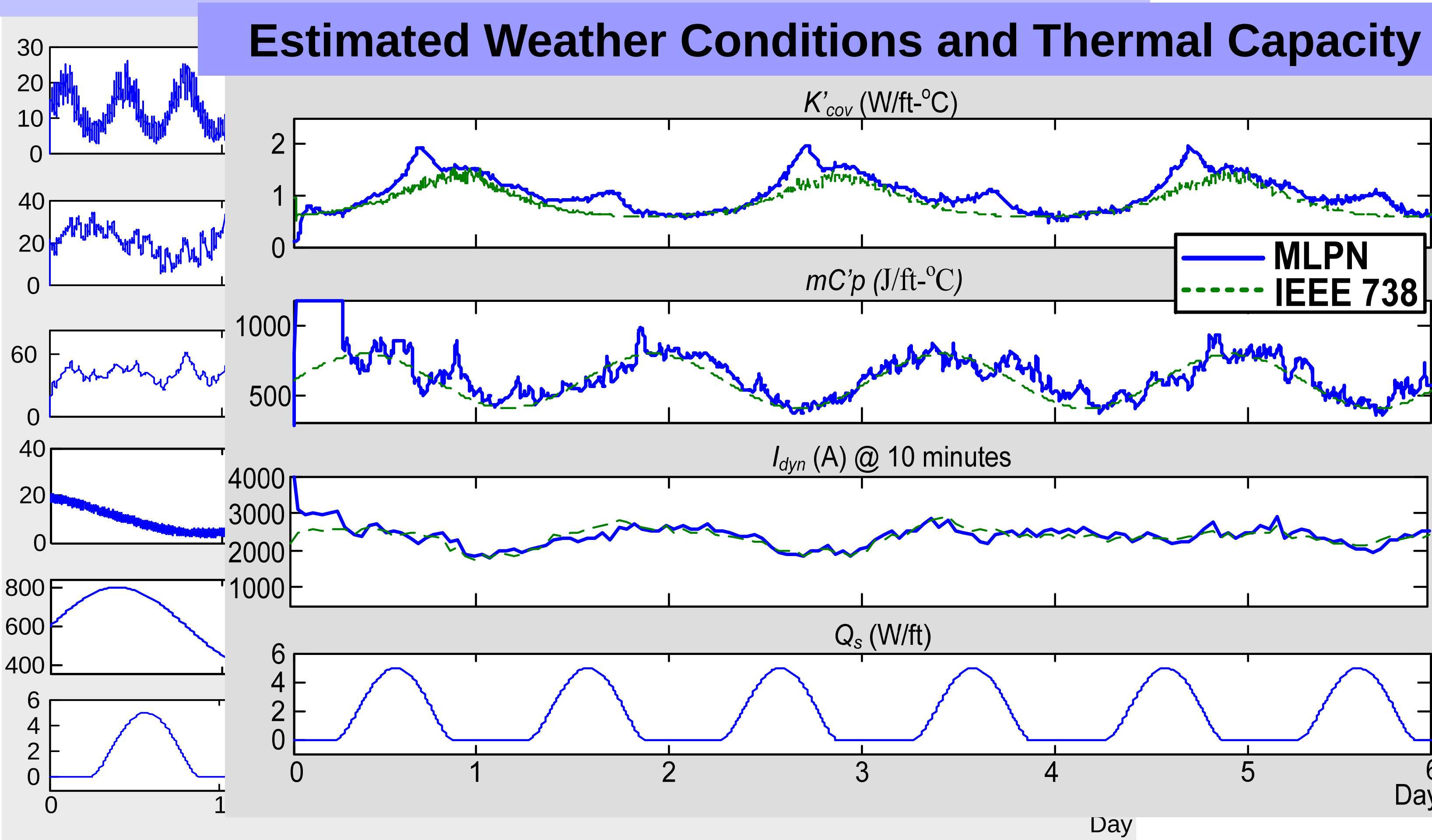


Potential Applications (1):
Dynamic Thermal Rating of Overhead Lines

- **Simulation Results (IEEE Standard 738)**

Overhead Conductor Thermal Conditions

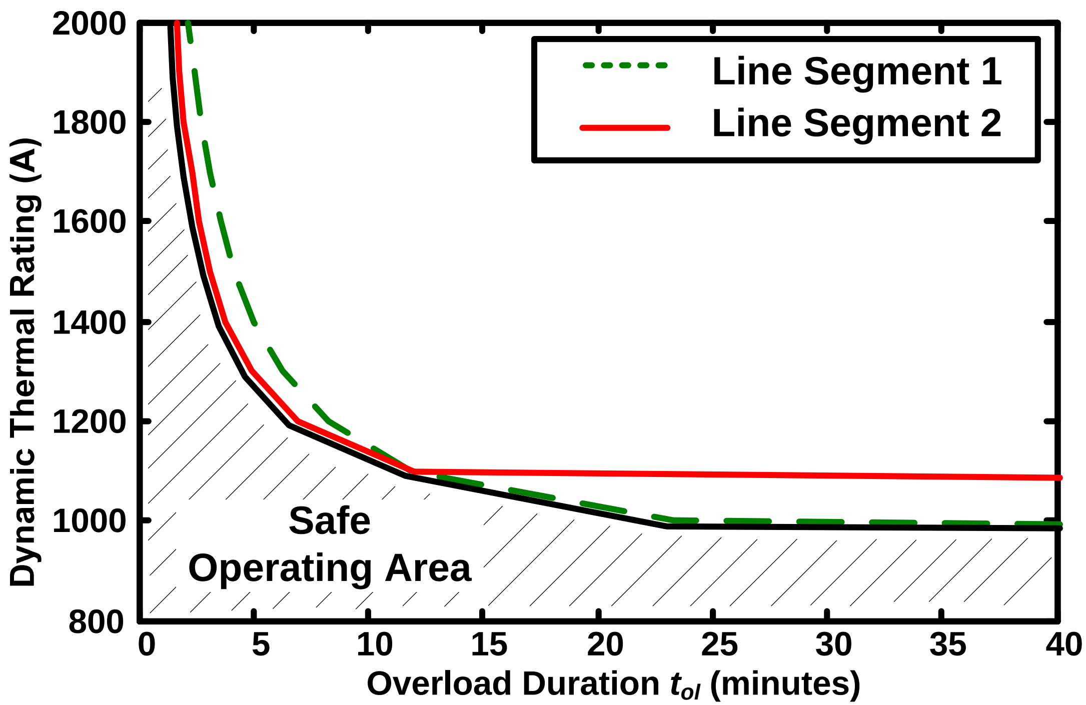
Estimated Weather Conditions and Thermal Capacity



Potential Applications (1):
Dynamic Thermal Rating of Overhead Power Lines

- **Simulation Results**

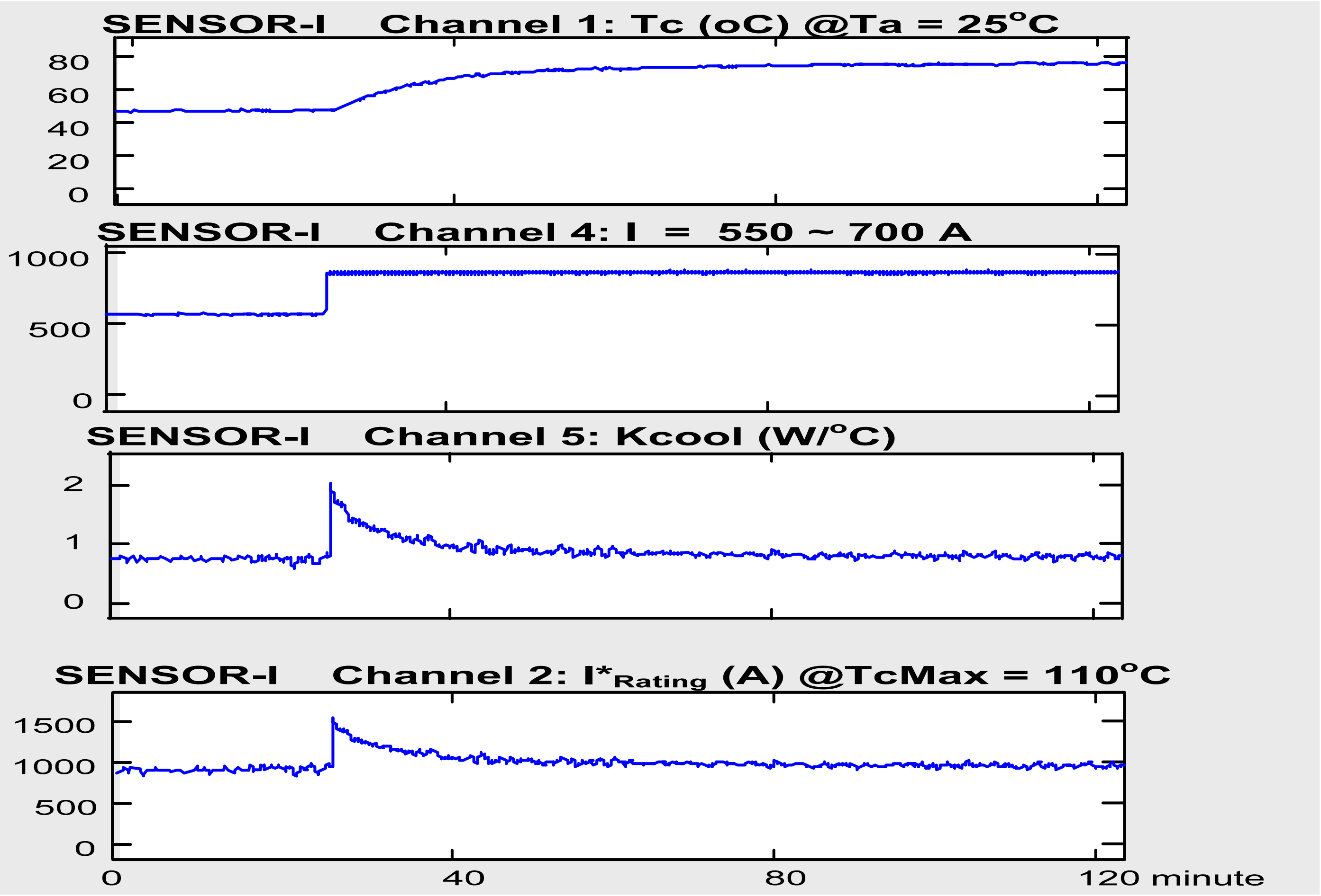
I-T Thermal Limit Curve for Multiple Line Segments



The I-T curves of all individual line segments can be sent to control center from the PLS modules, and superimposed to generate a composite 'worst case' I-T capacity (CWIT) curve for the entire line. Again, the CWIT is continuously updated every 15 minutes.

Potential Applications (1):
Dynamic Thermal Rating of Overhead Power Lines

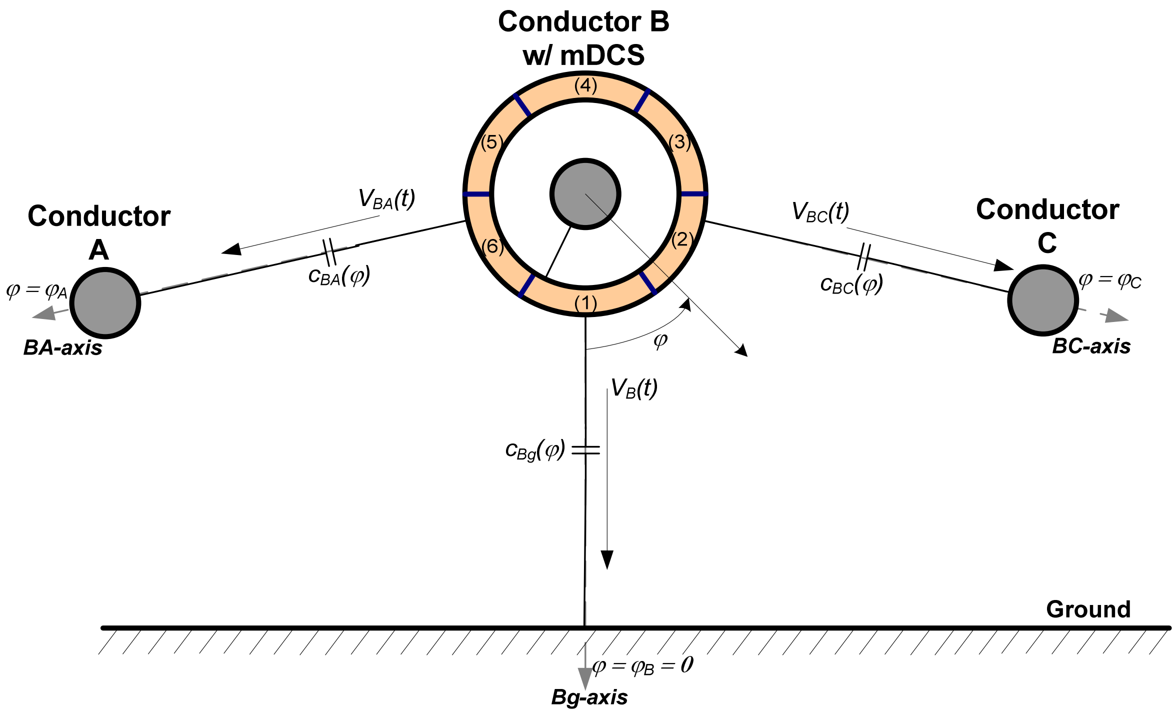
- **Experimental Results**



Potential Applications (2):
Displacement Current Measurement

- **Proposed Method**

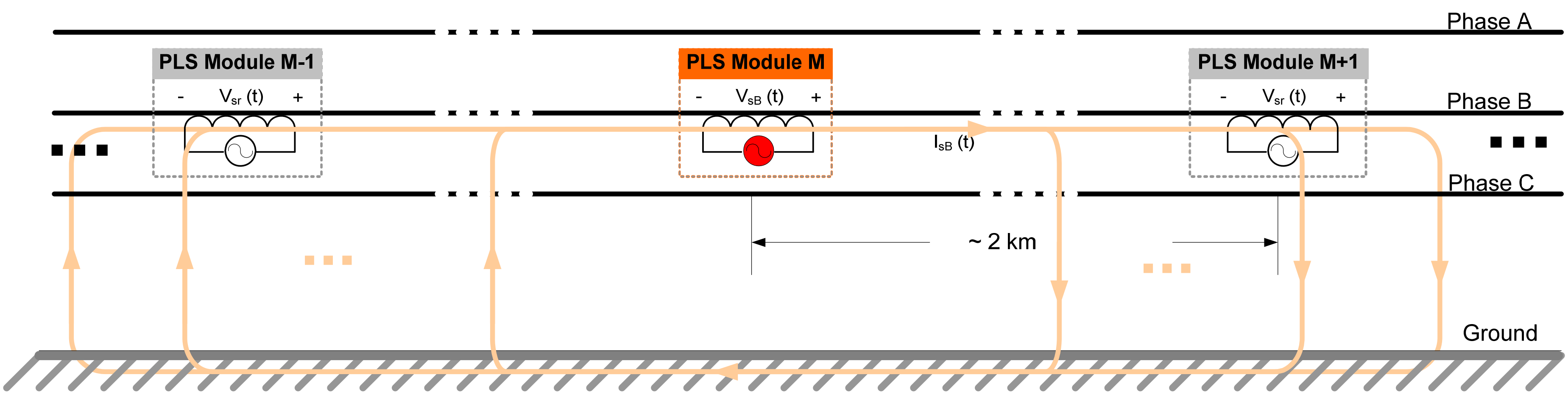
  A multiple displacement current sensor scheme is proposed to measure displacement current flowing from power conductor to its ambient, in order to monitor span clearance to ground or nearest grounded object, aeolian vibration, galloping conductors, etc., or to measure power line voltage.



Potential Applications (3):
Power Line Wave Propagation

- **Proposed Method**

  The PLS module is proposed to inject a wideband width signal into the power conductor. The electromagnetic (EM) wave propagation performance along the line is analyzed, in order to detect the present of incipient insulator failure between overhead power conductors and ground caused by, for instance, low conductor ground clearance, or vegetation proximity, etc.



Conclusions

- An extensive survey of literature in terms of sensing technologies followed by network and communications protocols were explored. System integration technologies were also presented.
- A prototype PLSN has been built up in IPIC lab. Its fundamental functions have been tested in laboratory environment.
- The PLS module and network using commercially available low power devices, offer the potential to dramatically reduce the cost of power grid monitoring.
- Experimental results demonstrate the potential impact of these devices in terms of better grid utilization and improvement in system reliability.

Questions