Wireless Mesh Network Deployment

Results and Lessons Learned

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ABSTRACT

Wireless technology is fast becoming a widely accepted technology across many industries. Wireless has become a very popular technology on the premise that no wires are needed to transfer data between devices. This ability to not need wires makes deployment of wireless devices quick and cheap. Many industries are taking advantage of wireless technology to add sensors to systems long after the system has been in place and with minimal effort.

The power industry is also showing great interest in wireless technology as a quick, easy, and cheap way to add sensors to aging assets. While the physical implementation of a wireless network is much easier than that of a wired network, the selection of the proper wireless solution may prove difficult. There are many different wireless solutions on the market that contribute to the difficulty of selecting the right one for the need. EPRI has recognized the difficulty of making these selections and has begun investigate the role of wireless technology across the various sectors of the power industry. The work described in this report has been performed largely with a substation application in focus.

In 2005, EPRI developed the guideline, “Selection of Wireless Monitoring Systems for Application in Substations”, 1010591, to help utilities understand the differences between the various wireless solutions present on the market. Wireless solutions on the market use many terms such as the names of standards, bandwidth, modulation, nodes, frequency bands, and so on. The guide explains what all these terms mean and why they are relevant. The guide also presents a number of case studies of utilities that have implemented wireless sensors on their equipment. The case studies also address the drivers that led the utilities to make the decision they made.

In 2006, EPRI continued research with wireless technology with tests and the development of a wireless demonstration. The tests and demonstration are the first steps in evaluating the capabilities of wireless technology to perform in a substation environment. The first set of tests placed a Bluetooth radio in an environment with a significant amount of corona and other electrical activity. The demonstration was designed to show how flexible and easy to setup wireless mesh networks could be.

In 2007, EPRI will work on understanding the size limitations of a WMN size for practical substation applications. To date, WMNs are still young technology and the full potential has yet to be tapped. WMNs potentially can be very large, cover large areas, and be very reliable. WMNs are also designed to be low cost and require little power to operate. EPRI plans to evaluate these potentials and understand what the practical limits are with the existing technology.

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INTRODUCTION

Wireless technology is becoming a widely accepted technology across many industries. Wireless has become a very popular technology on the premise that no wires are needed to transfer data. This ability to not need wires to transfer data makes deployment of wireless devices quick and cheap. Many industries are taking advantage of wireless technology to add sensors to system long after the system has been in place and with minimal effort.

The power industry is also showing great interest in wireless technology as a quick, easy, and cheap way to add sensors to aging assets. While the physical implementation of a wireless network is much easier than that of a wired network, the selection of the proper wireless solution may prove difficult. There are many different wireless solutions on the market that contribute to the difficulty of selecting the right one for the need. EPRI has recognized the difficulty of making these selections and has begun investigate the role of wireless technology across the various sectors of the power industry. EPRI has taken on this effort in the Generation and Power Delivery sectors. The work described in this report has been performed largely with a substation application in focus in the Power Delivery sector.

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2
BLUETOOTH TESTS

First Evaluations

In 2005, EPRI had chosen Bluetooth as the first wireless protocol to be evaluated. This selection was made on part by National Grid. National Grid introduced to ERPI a Bluetooth solution developed by Expert Monitoring. National Grid had begun field trials at one of their substations with the Bluetooth solution and asked EPRI to further test Bluetooth's capabilities.

EPRI acquired a Bluetooth sensor module from Expert Monitoring called WiSNet to evaluate in EPRI's 230kV Accelerated Aging chamber. The WiSNet device shown in Figure 2-1 consists of a network controller shown in the left and a sensor module / transmitter on the right. The Bluetooth radio used is rated as Class 1. The power supply is two 1300 mAH D-cell batteries. In Figure 2-1, the sensor module is shown with a non-contact temperature sensor connected.

Figure 2-1
WiSNet Controller and Sensor Module

The EPRI 230kV Accelerated Aging chamber was designed to evaluate the aging mechanisms of transmission line components. In this chamber there are over 40 polymer insulators being aged at an accelerated rate of 10. During the aging, corona and arcing is present and throughout the chamber is a considerable amount of steel structure. Figure 2-2 shows one representation of the aging chamber.

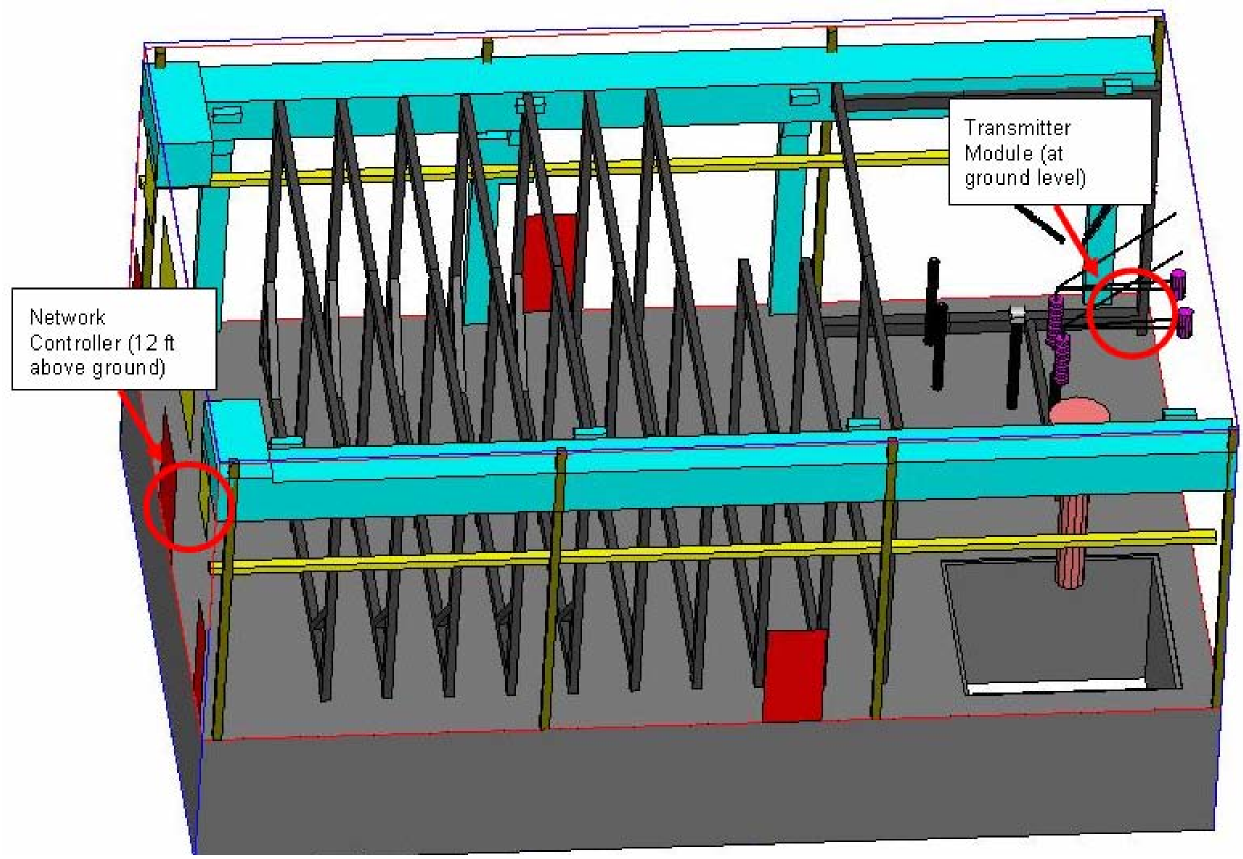

Figure 2-2
EPRI's 230kV Accelerated Aging Chamber

In the first evaluation performed in late 2005, the Bluetooth transmitter and receiver were placed across the chamber a distance of 76 feet (23 meters) from each other as shown in Figure 2-2. There were no sensors connected during this test. The data that was being monitored was the battery voltage level which was recorded with each successful transmission. The transmitter was set to transmit every second for a total of 86,400 data points per day. As a result, the radio remained active during the evaluation and therefore drained the battery in five days. During the five days, the data showed no transmission failures.

Second Test Run

A second evaluation was conducted in early 2006 to further test the Bluetooth reliability in a more practical setup. The location for transmitter and receiver was not changed. In the second test, three sensors were connected to the sensor module; a temperature sensor, a humidity sensor, and an UV sensor. The three sensors were powered using the same battery as the radio.

The evaluation ran for eleven days before the battery went dead. The transmitter for this test was set to sample the sensors every 25 seconds for the first four days. In the last seven days, the sampling period was extended to 50 seconds. At the 25 second sampling rate, 3,453 data points were collected per day and 1,726 data points per day with a 50 seconds sampling rate. The data was set to transmit every 10 minutes making 144 daily transmissions.

The data from the three sensors was used to track the timestamps and see if any data points were lost during operation. Of the three sensors, the UV sensor was not working correctly. In Figure 2-4 - Figure 2-6 is shown the data from humidity sensor, the temperature sensor, and the battery voltage. Figure 2-6 shows how the battery approached end of life in the last two days.

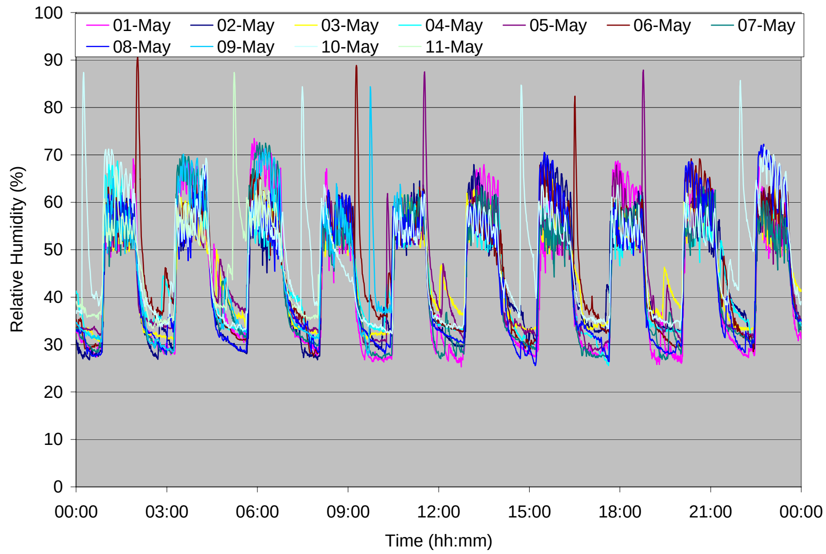

Figure 2-3
Humidity Data

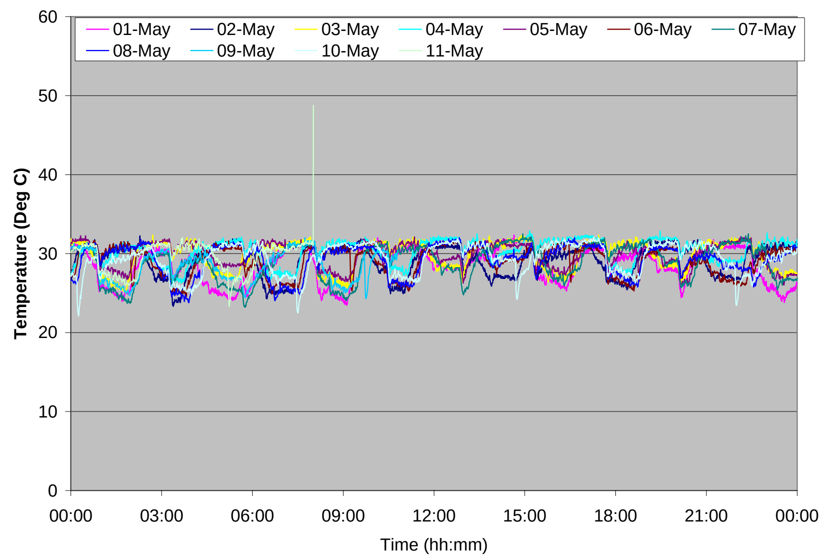

Figure 2-4
Temperature Data

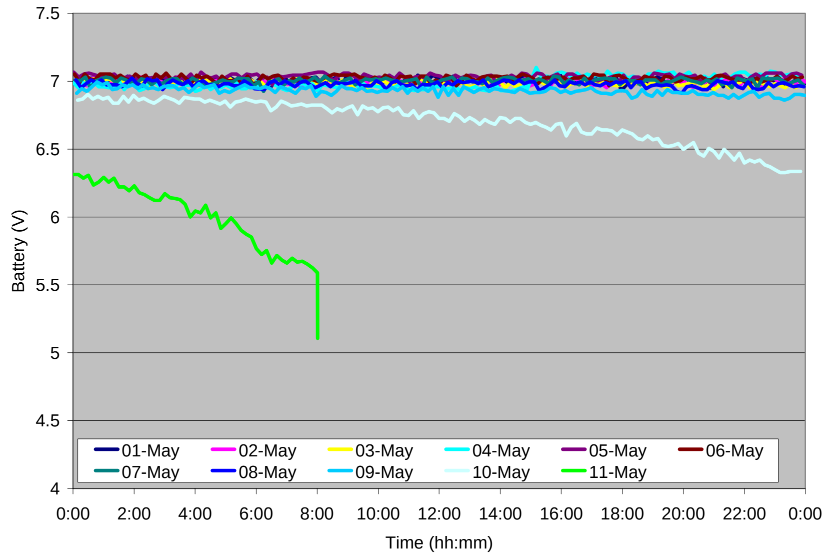

Figure 2-5
Battery Voltage

Of the 1,562 transmissions, only 17 were interrupted for a reliability rate of 98.9%. The sensor module has a built in buffer that helps prevent the loss of data during transmission interruptions. While the buffer is not full, sensor measurements will be stored until a successful transmission is made. When the buffer is full, the oldest measurements are lost as new measurements are added to the buffer. By using this buffer during the 17 transmission interruptions, no data was lost during the 11 day evaluation making the data reliability 100%.

This evaluation shows that the Bluetooth radio operating at 2.4 GHz with the IEEE 802.15.1 protocol would be resilient against electrical interference that may exist in a substation environment.

Calculation of Battery Life

After seeing the short battery life from the first two evaluations, the factors that drive battery life were looked into. By measuring the current draw of the WiSNet device, a simple load profile per cycle was developed as shown in Figure 2-6. A cycle is defined here as the time between data transmissions.

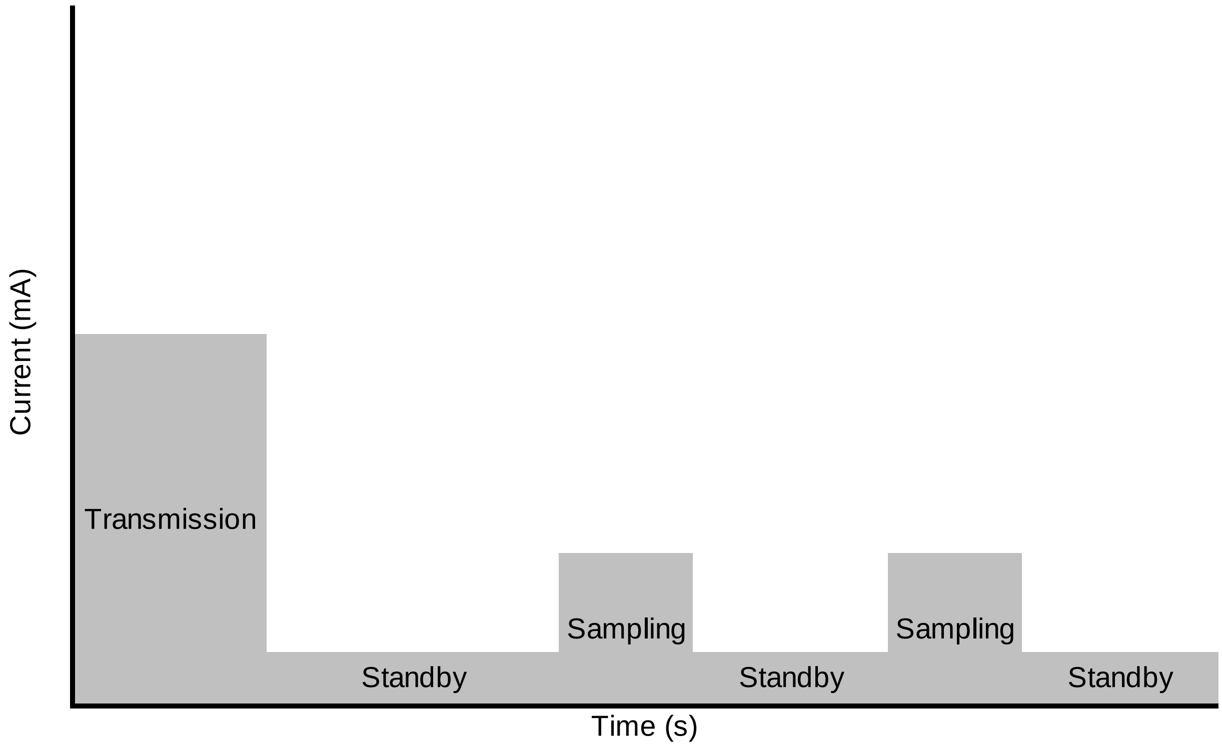

Figure 2-6
Sample Load Profile for a Wireless Device

This profile was developed over a short observation and therefore not all the operational modes of the Bluetooth device analyzed. There are a number of factors that were not considered during this evaluation. Many wireless devices have multiple operational modes as part of a power saving scheme. Another very important factor not taken into account is the discharge characteristics of the battery. The battery capacity is affected by how fast charge is drawn from the battery. The faster the charge is drawn, the lower the real battery capacity. This evaluation makes an attempt to make a rough estimate on battery life expectancy without taking the aforementioned factors into account.

The following calculations are based on one cycle.

Standby Current Load per Cycle:

Istdby * Tstdby * Nstdby = Qstdby / cycle **Eq. 2-1**

Sampling Current Load per Cycle:

Ispl * Tspl * Nspl = Qspl / cycle **Eq. 2-2**

Transmission Current Load per Cycle:

$$Itx * Ttx\ Ntx = Qtx / cycle \quad \textbf{Eq. 2-3}$$

Total Current Load per Cycle:

$$(Qstdby + Qspl + Qtx) / cycle = Qtotal / cycle \quad \textbf{Eq. 2-4}$$

Number of Cycles per Battery Charge:

$$Qbatt / Qtotal / cycle = Xcycles \quad \textbf{Eq. 2-5}$$

Battery Life Expectency:

$$Tcycle * Xcycles = Tbattlife \quad \textbf{Eq. 2-6}$$

Where:

I = Current (mA)

T = Time (s)

N = Times per cycle

Q = Charge (C) = Ampere – seconds (As)

In the above equations, battery capacity is equated to battery charge as:

$$1\ AH = 3600\ As = 3600\ C \quad \textbf{Eq. 2-7}$$

This evaluation of battery life is not exact; however, this calculation can help understand what parameters will affect the life of the battery the most.

3
WIRELESS MESH NETWORK DESIGN

In 2006, EPRI decided to demonstrate a wireless mesh network (WMN) to its funding members at the December task force meeting. Given the time constraints and the need to minimize one-of-a-kind expenses, this demonstration included the following:

- Sensors interfaced to wireless transceivers.
- Meshed wireless system.
- A wireless hub to receive sensor information from multiple sensors.

The objectives are to:

- Demonstrate the use of sensors in a meshed wireless system for monitoring the physical properties (e.g. temperature, vibration, pressure) of substation equipment
- Test the meshed wireless system for performance, availability, traffic levels, immunity to noise, and response to substation EMI.
- Show that a WMN can quickly and easily setup.
- Show that installation does not require expensive wiring.
- Show ability of WMNs to re-configure.
- Show that large distances can be achieved with additional relay points

In preparation of setting up a WMN demonstration, EPRI had to develop specifications as to how the network should operate and select the hardware that would best meet the specifications.

Development of Specifications

The development of operation specifications for a WMN requires an understanding of what issue the WMN will help resolve and what functionality the WMN should have to operate successfully. The following two sections describe why a WMN is being considered and what the WMN must be able to do.

Background to Requirements

EPRI initiated this project to demonstrate a WMN for condition monitoring of equipment in an electric power substation. The initial planned demonstration was to focus on acoustic and temperature monitoring of gas-insulated substations (GIS), in which the high voltage bus bars are encased in gas-filled pipes. The acoustic signals taken from outside the pipes can be used to detect arcing within the pipes. The temperature of the pipes can also indicate potential problems. Figure 3-1 shows the concept of the planned demonstration for a GIS.

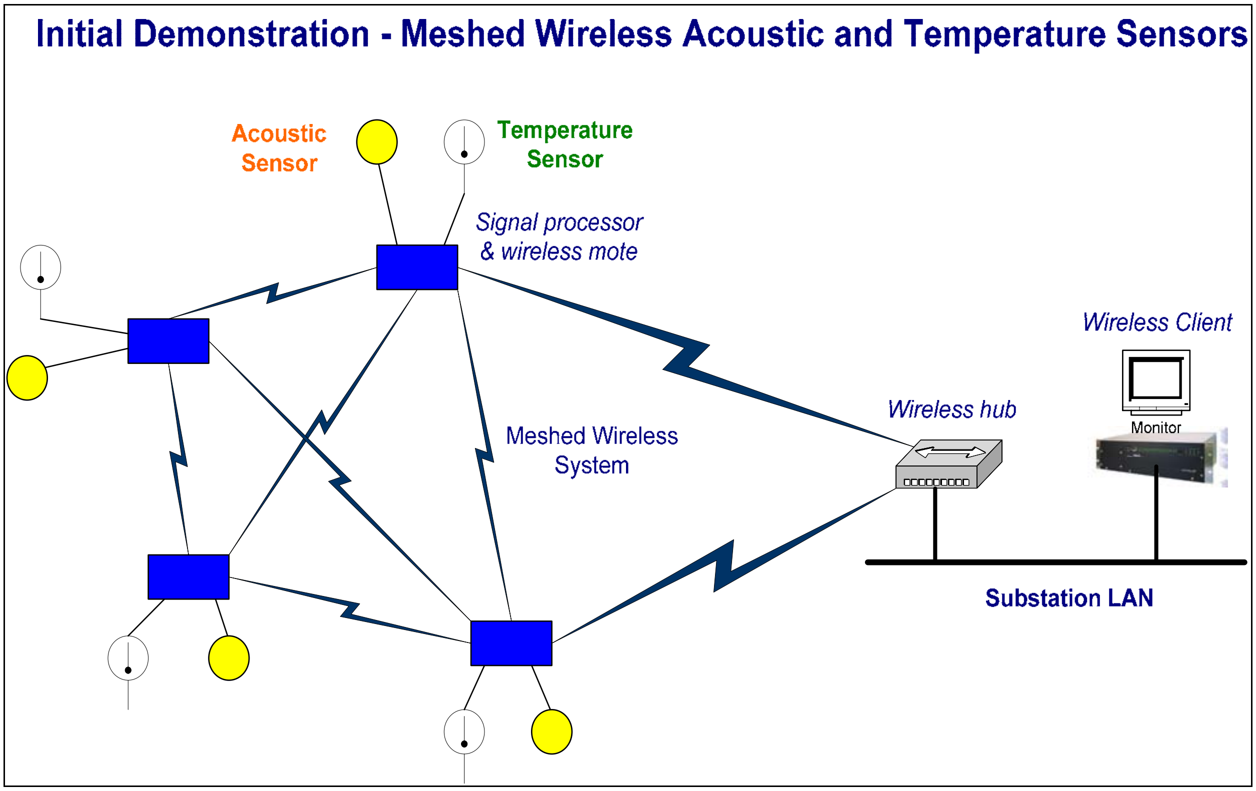

Figure 3-1
Diagram showing the conceptual wireless mesh network

WMN appear to be a feasible and economical solution to this condition monitoring. The reasons are:

- **Low cost**. Trenching, installing, and protecting wired communications in a substation are very costly efforts due to the electrically hazardous and very constrained environment.
- **Mobility**. Since arcing is expected to be very rare (but extremely important to detect), the condition monitoring system will be installed just long enough to determine no arcing events are taking place during power system operations (a month or so), and then moved every few months to monitor a new set of pipes or equipment. Wireless networks are easier to move than wired networks.
- **Non-critical time sensitivity of data**. Acoustic and temperature condition monitoring data do not require rapid responses to events. Minutes or even days are adequate for receiving the information.

On the other hand, a number of concerns about using WMN need to be assessed. These include:

- **Electrically noisy environment**. Electric power substations contain significant amounts of metal throughout the facility. One reason for specifying mesh networks is the expectation that the ability to re-route messages along different paths will increase the availability of the network.
- **Security**. Although confidentiality of power system data is not critical, integrity and availability of that data are very critical. Therefore any wireless network will need to include security measures to minimize security threats that could decrease integrity or availability.
- **Fading or radio interference**. In addition to the noisy substation environment, external sources of radio interference could impact performance, including other users inadvertently or deliberately hogging bandwidth in the selected radio frequency.
- **Scalability of the meshed wireless network**. Although the demonstration will not contain many sensors or nodes, substations could potentially require thousands of sensors. Multiple subnetworks with networked gateways could be a potential solution.
- **Range of wireless network**. Some substations are very large in addition to being filled with metal, so the range of wireless networks are of interest. Multiple subnetworks may be needed to address this concern.

It is expected that the project will involve at least two stages. The first stage of the project will be to test the feasibility and performance of a meshed wireless network used for this condition monitoring. This first stage system will be demonstrated at an EPRI facility in Charlotte, NC. The second stage will install the network in a gas-insulated substation, where the actual response and performance of the network to the harsh electrical environment will be assessed.

Requirements for the EPRI Wireless Mesh Sensor Network

The requirements of the wireless mesh network were developed to meet the needs specified in the section on Background to Requirements. The requirements are used as the baseline for which the WMN demonstrations were developed at both the EPRI facility and substation. Below are the general areas where requirements are specified. For a detailed list of the requirements, see Appendix A.

1. Physical configuration requirements:
2. Acoustic sensor interface requirements based on PAC R15I-AST
3. Acoustic signal processor requirements
4. Temperature sensor requirements
5. Temperature signal processor requirements
6. Wireless mesh requirements

The demonstration at the EPRI facility was designed to simply show off some of the capabilities of a WMN and therefore the requirements have been reduced to meet this purpose. The WMN being installed at the host utility site will meet all of the requirements.

Selection of a Wireless Solution

A solution consists of hardware being the radio and sensors and consists of a service being a integrator to build the WMN. There are providers of wireless solutions that provide all three parts or a solution can be a combination of different source. For this project, the parts are of different sources as described in the following sections.

Radio Selection

An initial list of eleven vendors was compiled that could provide wireless mesh solutions. Based on the requirements mentioned above, the radio must be ZigBee compliant. Two of the eleven vendors offered ZigBee compliant solutions:

- Crossbow Technologies
- Sensicast

Since sensors would be used in the demonstration, the selected solution would need to accommodate a variety of different sensors. Of the two vendors remaining, Crossbow Technologies provides radios with this type of flexibility.

The solution selected from Crossbow was the MICAz mote, a ZigBee compliant radio with an on-board processor. The motes / nodes have a 250 kbps data, can be enabled with an AES 128 bit level security, and approximate ideal range of 75-100 meters outdoors (20-30 meters indoors). Each mote is built in layers. The primary layer is a radio and subsequent layers are data acquisition modules that can connect to external sensors. Each mote can connect up to seven external sensors.

Sensor Selection

Two sensors are required as part of the demonstration, a temperature sensor and an acoustic sensor. The temperature sensor will need to be integrated into the packaging and have contact with the equipment that is monitored. The task of selecting an appropriate temperature is being handled by the integrator.

The acoustic sensor initially selected for the demonstration was the PAC R15I-AST. This sensor was selected based on EPRI's past experience. However, the PAC R15I-AST an active device that requires approximately 20 mA at 28 VDC. A task has been given to the integrator to evaluate using the PAC R15I-AST with the ZigBee solution.

Integrator Selection

The role of the integrator is to bring together the radio and the necessary sensors and to build the mesh network. The integrator also has the role of developing the enclosures that will protect the motes in a substation environment. Three integrators were considered for this project. The University of North Carolina at Charlotte (UNCC) was selected from the three as having the most experience working with Crossbow and the ZigBee protocol.

UNCC has the following tasks:

- Program the motes for appropriate excitation generation, calibration, conversion from analog to digital, and threshold detection. Appropriate summary statistics will be generated at the motes for transmission to the monitoring station.
- Design the attachment hardware for the thermocouples for detecting temperatures from the surface of gas-insulated pipes and circuit breakers. Simple magnetic attachments for quick deployment will be considered.
- Program the motes for reliable wireless communication across the WMN to the local hub using multi-hop wireless routing.
- Program the local hub for interfacing to the GSM network. Sporadically obtained data from the WMN would be transmitted using data/text messaging to a monitoring station using a GSM line.
- Designing an effective graphical user interface for displaying the measured temperature data at the monitoring station. The data needs to be displayed over the Internet in graphical form.

Testing Requirements

A series of tests have been developed to test the wireless mesh network to the specification described above. The tests and results are shown in Appendix B. The testing requirements were developed for the demonstration being held at the EPRI facility. They also form the foundation for which the test requirements for the substation demonstration.

4

WIRELESS MESH NETWORK TEST RUN AND DEMONSTRATION

Charlotte Demonstration

The demonstration was setup at the EPRI – Charlotte office in Building 1. A wireless mesh network (WMN) was set up along the halls of the building to relay temperature data the workshop area to the conference room where the meeting was held. The demonstration will transmit data along the path shown in Figure 4-1.

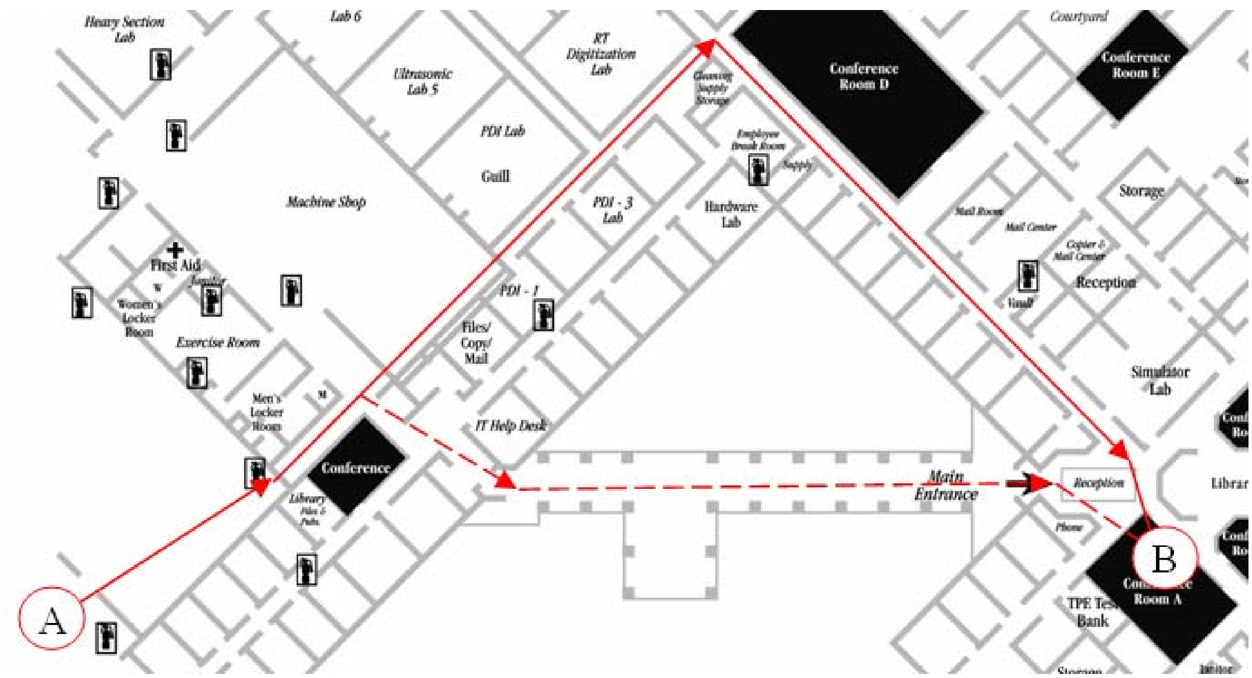

Figure 4-1
Planned Demonstration Path for the WMN

Two transmission paths have been selected for the demonstration. The primary path was along the solid line and the secondary path was along the dashed line. Figure 4-2 shows a node along the primary path and Figure 4-3 shows a node along the secondary path. Temperature will be measured at point "A" (see Figure 4-4) and transmitted along the primary path to point "B". During the demonstration, a node along the primary path will be disabled and therefore breaks the link between “A” and “B”. The WMN will then reconfigure so that the secondary path is used to re-establish the link.

Figure 4-2
A node on the wall along the primary path

Figure 4-3
A node on a pillar along the secondary path

Figure 4-4
Heater and temperature probes at point "A"

First Test Run

On November 1, 2006, UNCC made a site visit to perform a preliminary run of the WMN demonstration. The objective of this first test run was to find the optimal location for the nodes so that a complete signal path could be created. The primary path as described in Figure 4-1 by the solid line was complete in one hour. One of the issues that arose was the effect of signal reflections along the hallways.

The effect of signal reflections can benefit a wireless network or it can hinder. A benefit is the ability for a signal to bounce along the hallway much like waveguide. The bouncing of the signal can help get around objects when line of sight is not easy to obtain. A hindrance of signal reflection is that multiplication of signals may occur. These signals may arrive at the node with small time shifts and node may not properly decipher the data.

After having created a successful connection along the primary path, the next step was to create a link along the secondary path. The secondary path was routed through a covered walkway outdoors. The outdoor environment caused some difficulty in making the necessary links. After an hour the secondary path was connected to the network.

There were a number of features along the primary path that had to be overcome. There are two steel doors, one open door, and one right-angle turn. The open door and the right-angle turn did not pose a problem. The second steel door from point "A" was also not a problem, but the first set of double doors were heavy enough there the signal was attenuated significantly. At this point, a node each side of the door would be needed to relay the signal.

Along the secondary path, there are similar obstacles as the primary path plus five glass doors. The glass doors will reduce the transmission range along the path can be overcome with additional nodes as needed.

Demonstration

On November 30, 2006, UNCC performed the first full demonstration of the wireless mesh network. For the demonstration, there were 14 nodes to build the network and two temperature probes used as the data source. Each of the nodes was set to transmit data every 1 second. The first half of the network was in place in about 15 minutes. Each node had a startup time of 30-60 seconds.

As the second half of the network was assembled, the network had trouble maintaining the 1 second transmission rate. The buffers in each node were becoming overload and causing congestion along the network. Additional analysis will be taken to understand the relationship between network size and data throughput.

To improve the performance of the demonstration, two actions were taken:

- Reduce the size of the network
- Increase the time between transmission

By reducing the network size, the amount of data flowing through the nodes no longer created a buffer overflow. The network size was reduced by moving point “A”. Figure 4-5 shows the final demonstration network.

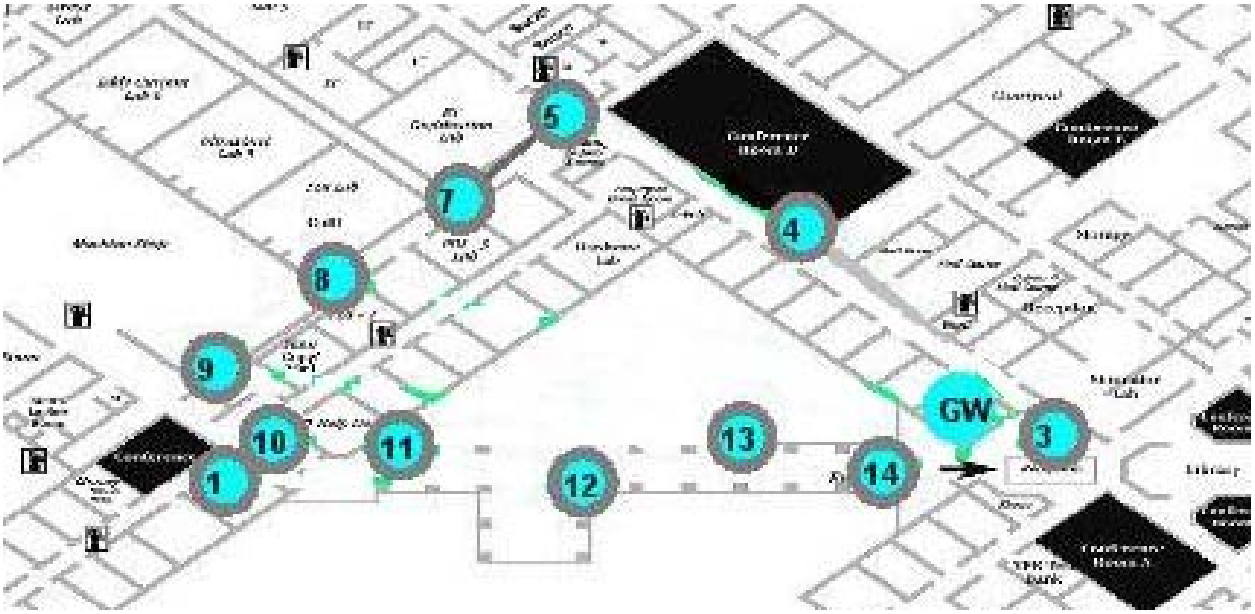

Figure 4-5
Final demonstration network

The increase in transmission time allowed each node to process the data through its buffer and therefore avoids congestion. Additional benefits of increasing the transmission time is the extension of battery life. For practical applications, the transmission rate may be extended to 10s of minutes.

After making the minor adjustments the network ran as expected.

Substation Demonstration

The demonstration described in Chapter 3 that was planned for a gas insulated substation (GIS) was changed to take place in an open air substation and will only monitor temperature. An acoustic sensor that would meet the needs of planned demonstration is still under evaluation. When an appropriate acoustic sensor is found, a demonstration at a GIS will be scheduled.

In 2007, a demonstration of a wireless mesh network will be setup at TVA's Paradise substation and last more than one year. The wireless mesh network will monitor temperature on circuit breakers and transformers. Each mote will be enclosed in a NEMA 4 box equipped with magnets to easily be attached to the steel enclosures of the substation equipment.

One cluster of motes will be located on equipment similar to that shown in Figure 4-6. The mote nearest the base station is about 30 feet (10 meters) away. The motes will communicate with each other to route the temperature data around the substation structure and equipment back to the base station. A second cluster of motes will be placed on equipment further away from and out of range of the base station. The proposed solution will be to place motes along the path to complete the connection.

Figure 4-6
Location of the sensors on the breakers at TVA

5
CONCLUSIONS

In 2005 and 2006 Bluetooth and ZigBee solutions were evaluated. The evaluations focused on their ability to operate in a substation environment. Both solutions had their pros and cons and both should be considered when developing a business case for implementing a wireless sensor network.

The tests performed on the Bluetooth solution show that it has the capability to withstand a significant amount to electrical interference from corona and arcing. The Bluetooth solution also has the ability to transmit large distances, is fairly simple to setup, and can handle multiple sensors and has a high data rate. However, the Bluetooth solution is limited in the size of network it can handle and maybe expensive if many nodes are required.

The ZigBee solution was evaluated with a wireless mesh network demonstration. The ZigBee solution can be small in size, require little power to operate, build large networks of sensors, can handle many sensors per node, is low cost, and easily adapts to changes in the network. Some of the drawbacks to the ZigBee solutions are that setting up the network requires some expertise, the transmission range is small, and the data rate is low.

Future research will continue to evaluate the capabilities ZigBee solutions in various substation environments. Of particular focus will be how large of a network can be built and maintain a low power demand and minimally affect the data rate. The ZigBee solution was not yet tested in the presence of electrical interference. While the results from the Bluetooth tests prove promising, the ZigBee solution still needs to be tested.

A
REQUIREMENTS FOR THE EPRI MESHED WIRELESS SENSOR NETWORK

The following are the basic requirements for the EPRI meshed wireless network and the condition monitoring sensors. The final set of requirements was modified slightly when issues arose about the capabilities of the acoustic sensors.

1. Physical configuration requirements:

   a. List of equipment:

      - Acoustic and temperature sensors:

        - acoustic sensor R15I-AST to be provided by Physical Acoustics Corporation

        - temperature sensor is open – no vendor selected

      - Signal processors with A/D converters and basic data processing capability

      - Wireless mesh motes based on IEEE 802.15.4 technology as a cluster

      - Gateway wireless processor to interface to each cluster

      - Human-Machine Interface (HMI) (PC for demo) interfaced to or part of gateway

   b. Number of acoustic sensors: 4

   c. Number of temperature sensors: 4

   d. Number of signal processors, each handling both one acoustic sensor and one temperature sensor: 4

   e. Number of wireless motes: 4

   f. Sensors hardwired to signal processor

   g. Maximum distance between sensor and signal processor: 2 feet

   h. Maximum distance between motes in a cluster: 30 feet

   i. Maximum distance between a cluster of motes and gateway to HMI: 100 feet

   j. Mote size: < 3” on a side is preferred

   k. NEMA 4 enclosures will not be needed for the demo, but may be required later

2. Acoustic sensor interface requirements based on PAC R15I-AST

   a. Acoustic emission sensor

   b. Operating frequency range: 50-200kHz

c. Resonant frequency: Ref V/μbar 150kHz
d. Integral preamplifier, 60dB
e. BNC connector
f. Analog signal output: 20 volts peak-to-peak maximum; however expected signal will be about one (1) volt of sub-second duration
g. Temperature range: -35°C to 75°C

3. Acoustic signal processor requirements
   a. BNC connector to receive analog input
   b. A/D must be able to handle 1volt acoustic signal of sub-second duration
   c. Acoustic signal processing provided by wireless module
   d. Signal processing converts A/D output to RMS digital data with adequate resolution to detect a digital amplitude signal derived from 1 volt sub-second analog amplitude signal
   e. Processors may handle 1 or more acoustic sensors, depending upon the configuration
4. Temperature sensor requirements
   a. Contact temperature thermocouple sensor
   b. Operating temperature range: -40°C to 100°C
   c. Accuracy: $\pm$ .5°C
   d. Output: 4-20mA or 0-5V
5. Temperature signal processor requirements
   a. May be built into sensor or separate processor, hardwired to temperature sensor
   b. Analog to digital conversion
   c. Temperature values in °C
6. Wireless mesh requirements
   a. Wireless mesh network of motes (not star network). Gateways may be star or point-to-point.
   b. Mesh routing protocol issues:
      - Throughput and delay per node: < 50 milliseconds
      - High reliability in finding new paths through meshed nodes due to interference or mobile configurations
      - Downshift (to lower rate) and upshift (back to higher rate) if applicable for optimizing availability and throughput
   c. Wireless radio frequency
      - Any frequency in the ISM bands (900 MHz, 2.4 GHz, and 5.8 GHz)
   d. Wireless protocols

- Based on IEEE 802.15.4 and/or Zigbee
- Direct Sequence Spread Spectrum (DSSS) or Frequency Hopping Spread Spectrum (FHSS)

e. Data protocols over wireless network:

- Standard (rather than proprietary) protocol preferred
- IEC 61850 preferred but not required for demo
- Modbus can be used

f. Security issues:

- IEEE 802.11i (AES encryption algorithm)
- Symmetric key for normal operations
- Public/private PKI for key updates and key management

g. Timing considerations

- Latency:
  - Time from sensor reading to reporting at gateway: < 1 second
  - Time from gateway to display on HMI: < 1 second
- Wakeup time of wireless radio < 20 ms

h. Availability of overall system

- 99.9% availability of overall system
- 99.5% availability of any one sensor and/or wireless node
- Scalability to handle large numbers of sensors: up to 1000 sensors
- Battery life:
  - 1 week: essential
  - 2 weeks: good

B

TESTING REQUIREMENTSTESTING REQUIREMENTS

A series of tests have been developed to test the wireless mesh network to the specification described above. The tests are shown in Table B-1.

Table B-1
Test Procedures for Meshed Wireless Sensor Network

No.	Test Description	Test Procedure	Expected Outcome	Actual Outcome[1]	Variances[2]	Severity of Variances[3]
1	Hardware equipment checklist	Verify that all hardware equipment is available and appropriately connected, using the equipment check list	All equipment on check list is available and appropriately connected. Ensure distances between equipment are within the requirements. Document the configuration being used.			
2	Specifications of temperature sensor equipment	Verify that the "nameplate" specifications for temperature range, accuracy, and output of the temperature sensors are within those required	All temperature sensor nameplate specifications meet the requirements. Document these specifications.			

[1] *Short answers can be included here. Longer answers may refer to external documentation or descriptions*
[2] *If needed, a separate document can track variances, including when and how they are going to be resolved*
[3] *Severity is defined as: High – testing must stop until variance is resolved; Medium – testing may continue but variance will need to be resolved before the test is signed off on; Low – variance is worth noting, but does not affect the test*

No.	Test Description	Test Procedure	Expected Outcome	Actual Outcome[1]	Variances[2]	Severity of Variances[3]
3	Specifications of wireless equipment	Verify that the “nameplate” specifications for wireless equipment are within those required	All wireless equipment nameplate specifications meet the requirements. Document the throughput and delay of the motes, reliability for the actual configuration, RF band used, wireless protocol used.			
4	Specifications of protocols	Document the wireless and data protocols being used over the wireless network	Since specific protocols were preferred, but not required, only documentation of the protocol is necessary			
5	Security specifications	Verify that IEEE 802.11i with AES is used	IEEE 802.11i is used. Document all security technologies and procedures			
6	Power up	Power up all equipment and check that basic operations have started correctly	All equipment has been powered up and is operating correctly in its basic mode			
7	Start applications	For any software applications that are not automatically started as part of the power up sequence, start them up. This includes any HMI functions and displays.	All software is executing correctly and the appropriate HMI displays are either being shown or available through navigation			
8	Measure node startup latency	Measure the startup latency of a node. (How should / can this be measured?)	Startup latency is less than 20 seconds			
9	Measure throughput of a node from receipt to transmission	Measure the average throughput of a node by sending 1000 (or other number) of data points through the node and timing the result	The node will show a throughput of less than 50 milliseconds per data point.			

No.	Test Description	Test Procedure	Expected Outcome	Actual Outcome[1]	Variances[2]	Severity of Variances[3]
10	Reliability with lost node	Determine if any messages are lost going through the network after removing a node from the mesh network.	All messages that were sent will be received			
11	Reliability with interference	Determine if any messages are lost going through the network after RF interference impacts one link	All messages that were sent will be received			
12	Downshift and upshift	Determine if the links downshift in data rates upon encountering RF interference. Determine if they shift back up when the RF interference ceases	Links in the network will downshift to a lower data rate upon encountering RF interference, and vice versa.			
13	Monitoring temperature data	View the temperature data on the HMI, comparing with a reference measurement at the same point.	Temperature measurements viewed on the HMI will reflect the actual temperature of the sensor within + .5°C			
14	Latency timing	Measure the time latency between when a temperature is sensed and when it is displayed on the HMI	The time latency will be documented maximum and minimum number of nodes in the chain.			
15	Battery life	Measure or calculate battery life of a node based on battery specifications and load of the node reporting temperature measurements every 1 minute	Document the projected life of the battery for measurement and transmission every 20 seconds 30 minutes			

No.	Test Description	Test Procedure	Expected Outcome	Actual Outcome[1]	Variances[2]	Severity of Variances[3]
16	Network availability	Measure the availability of the network over 100 hours (4+ days)	Availability of the overall system is at least 99.9% (unavailable for no more than 6 minutes) Availability of each node is at least 99.5% (unavailable for no more than 30 minutes)			
17	Text Message	Send one text message with data to a cell phone using the GSM modem from the laptop.	The text message will be successfully sent to and received by a cell phone.			
18	Restart	Power down and restart system	System will power down and restart without any “unexpected” steps			

_______________________________ _______________

Wireless Network Tester Date

_______________________________ _______________

EPRI Observer Date

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