EPRI

Wireless Sensors and Communications for Application in Transmission Substations

Technical Report

Wireless Sensors and Communications for Transmission Substations

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REPORT SUMMARY

Recent developments in low-cost wireless sensors—together with elimination of the need for cabling when installing new monitoring systems—drive applications of wireless communications in high voltage transmission substations. Once installed, wireless technology either contributes to condition monitoring or communicates data used for asset management/maintenance decisions. An EPRI cost-benefit analysis shows that the technology may be at the point where widespread use of wireless sensors is now economically justifiable. This report summarizes the first evaluation of promising radio-frequency (RF) wireless sensors and communications for application within transmission substations. A tentative specification is given for a practical wireless system.

Results & Findings

The network architecture presented integrates a cluster of wireless sensor network (WSN) devices with a wireless Ethernet system. A PC connected to this Ethernet runs data management software that collects data from the sensors and saves it in an appropriate format for diagnostics. Initial field trials demonstrate the utility of both amplitude shift keying (ASK) and discrete sequence spread spectrum (DSSS) wireless sensor networks. Of the two sensor networks, however, the DSSS system has shown greater potential for reliable data transmission within substations. RF wireless sensors and networked smart sensors offer another clear benefit by eliminating or at least reducing the need for signal repeaters in a substation environment, where metal structures create obstacles for RF communications.

Challenges & Objectives

The most critical problem in using RF communications within substations is the presence of obstacles to direct line of sight (LOS). This study seeks to mitigate the LOS problem by using WSN devices for communications. The WSN technology of choice uses redundant, automatic message routing protocols implemented on low-cost hardware that includes data acquisition circuitry.

Applications, Values & Use

For wireless communications systems, a simple WSN with an Ethernet backbone is preferred. Initial experiments using both ASK and DSSS systems have shown that both systems work, but the DSSS seems to be less sensor-heavy and more reliable. An investigation of field applications of wireless sensor technology shows that each ground potential application can meet basic requirements. Further testing is planned to better evaluate communications performance in actual operating conditions over an extended period of time. Future work will include development and evaluation of wireless sensors for both ground and high voltage potential applications—

including, for example, wireless temperature sensors, pressure sensors, and acceleration and electromagnetic field sensors.

EPRI Perspective

Over the last few years, EPRI has been working with member utilities to improve the cost-benefit ratio for on-line monitoring and diagnostics in transmission substation applications. Wireless RF sensors and communications are on the list of candidate technologies offering the potential for cost savings by circumventing the need for traditional cabling. Avoided cable installation saves utilities the associated costs of meeting environmental requirements and conducting testing required prior to installation of new cables in existing substations.

Approach

Investigators first developed a specification for a wireless system. They next tested new RF sensors and communications devices with built-in networking capabilities in monitoring applications developed specifically for transmission substations. In this case, they selected a monitoring system for circuit breakers in a 345-kV transmission substation owned by Consolidated Edison Company of New York (ConEd) as a test application. They also developed a universal transmitter and made a general comparison of several wireless technologies.

Keywords

Wireless Sensors
Wireless Communications
Substations
Circuit Breakers

ABSTRACT

Recent developments in low-cost wireless sensors—together with elimination of the need for cabling when installing new monitoring systems—drive applications of wireless communications in high voltage transmission substations. Once installed, wireless technology either contributes to condition monitoring or communicates data used for asset management/maintenance decisions. An EPRI cost-benefit analysis shows that the technology may be at the point where widespread use of wireless sensors is now economically justifiable. This report summarizes the first evaluation of promising radio-frequency (RF) wireless sensors and communications for application within transmission substations. A tentative specification is given for a practical wireless system. The report will be complemented by field test results of a monitoring system for wireless communications circuit breakers, slated for 2003.

The most critical problem connected with installing cable communications in a substation is the presence of obstacles to direct line of sight (LOS). This study seeks to mitigate the LOS problem by developing wireless sensors and communications. The wireless sensor network (WSN) technology of choice uses redundant, automatic message routing protocols implemented on low-cost hardware that includes data acquisition circuitry.

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1 INTRODUCTION

This project, EPRI TC Project # P8132/C44097, relates to Wireless Communication in substations. This report is a deliverable for Task 1 of the project, giving a prioritized list of wireless monitoring applications, considering local constraints and recommending solutions.

Project Drivers

The drivers for this project are laid out in the Statement of Work Introduction/Background as follows:

"Recent developments in low cost sensors and low cost wireless communications together with the advantages of eliminating need for cabling when installing new monitoring systems are the main drivers for applications in high voltage transmission substations"

Project Objectives

The overall aim of the project is described in the Statement of Work Introduction/Background as follows:

"This project attempts to develop the specification for a wireless system (using ConEd as a Utility Case Study) and then test a product against this specification."

Individual project objectives are given in Appendix A, and details of Task 1 from the Statement of Work in Appendix B.

This report relates to wireless 'sensors and communication' rather than 'wireless sensors' and 'wireless communication' which is one reading of the content of subtask 1.1. The Statement of Work is a little more specific in the Introduction stating that the project should relate to monitoring.

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TASK 1: PRIORITIZATION AND PROJECT PLAN DEVELOPMENT

This section relates to Statement of Work, Subtask 1: *"Prioritization and Project Plan Development*."

This task has three subtasks, which are dealt with in the next three chapters.

3
TASK 1.1: REQUIREMENT AND PROJECT PLAN

This section relates to Statement of Work, Subtask 1.1:

"Prioritized list of potential application for wireless sensors and communication will be determined based on cost-benefit and feasibility analysis for applications in ConEd substations. Technical and business aspects for successful application will be addressed."

Assumptions

This report assumes that this project will not be investigating the development of novel sensor technologies, which would be infeasible within the timescales available. The investigation is into the benefits of wireless and customizing commercially available sensors and transmitters for applications in substations.

The Statement of Work, Subtask 2, gives a prioritized list of applications; these will be used in conjunction with constraints given by ConEd.

Application Philosophy

We need to know what data is needed in which location to support which decision. Then we can address issues such as where will data be stored, analyzed, what needs to be transmitted in what volume, at what frequency, and at what resolution.

Answering these questions depends on the decision-maker's data requirements. It will give a guide as to what are suitable technologies. In addition, we need to know what is the cost to the decision maker of having poor or missing data – this will impact on reliability choices, technologies and hardware.

Monitoring Background

Both CIGRE and IEEE have useful background information on monitoring of substation equipment, including cost benefit calculations [1,2]. This background information is, in general, common sense encapsulated, and is taken as read in subsequent discussions. The CIGRE guide on circuit breaker monitoring includes an extensive section on cost benefit calculations with examples. The IEEE draft report: "IEEE Guide for Application of Monitoring to Liquid-

Immersed Transformers and Components" includes a discussion of communication requirements, but does not directly refer to wireless communication technologies.

For example, when we look at cost benefits related to maintenance, the IEEE guide says:

"In performing the above analysis, it is important to calculate the true per-equipment-item cost of on-line condition monitoring. The cost can be minimized by:

- Using existing signals and equipment to the greatest degree possible;
- Sharing data acquisition and processing between similar equipment, and if possible, other equipment (e.g., use distributed or central intelligence) and other functions;
- Adopting industry communication standards;
- Using common monitoring installations in all applications "

Which may seem like common sense, but does note the need to refer to industry communication standards that are only just beginning to embrace wireless communications.

Both CIGRE and IEEE document the need to find a positive cost benefit analysis.

List of Applications from SOW – Discussion

General

Condition monitoring needs to be targeted to be cost effective. Where a known failure mode exists, appropriate monitoring for that failure mode is almost invariably the most cost effective.

This project, EPRI TC Project # P8132/C4097, is required to link in with EPRI TC project # P8131/C4096 relating to Circuit Breaker Monitoring System.

Data Collection and Availability – Project Constraints

Requirement of the monitoring systems developed within this project is that they must be able to supply data from a remote point without operator intervention or activity at the remote point. This constraint, which is at the behest of ConEd, precludes the use of, for example, thermochromic systems which show that a certain temperature has been reached in a given period of time, but requires an operator to view the thermochromic object.

A monitoring system must neither require operator presence on the substation for reading, or for resetting after a certain threshold has been reached. Again, this is a characteristic of certain thermochromic systems that are thus precluded.

Power Supplies

In any application of a sensor or system in substation monitoring, there needs to be a decision as to the power supply requirements. Is the device needed for continuous operation, as with a load monitor, or could there be a period of dormancy between readings where power consumption is somewhat reduced, as with transformer tank temperatures? This decision ties in to the parameter being monitored, the failure mode of the monitored plant and the frequency of data collection. In general, this report assumes either battery power for small sensor applications, especially those where intermittent operation is possible, or mains powered operation, supplied from a control cabinet. Solar panels coupled with small wind turbines may provide a means for trickle charging battery packs – the question will be one of cost and reliability.

Universal Transmitter

This approach takes generic data acquisition (DAQ) technologies capable of several sensor inputs of various forms and adds wireless technology for data transmission. A variation is to include the wireless transmitter as part of the DAQ hardware.

Power supplies to such generic systems may be via battery, or hard wired. Battery systems tend to have short life cycles.

The main advantage of universal systems is their flexibility, able to store data locally, with a variety of sensors acting as inputs. Examples include Doble's Insite (Appendix D), Alstom's M2000 product line and several CB monitors.

Previous commercial experiences have shown that field uptake of universal systems has been small. The main concerns have been the high cost and the limited benefit. Much of the cost is due to installation – both labor and infrastructure. Reducing the cost of installation through reduced labor for sensor installation, and reduced infrastructure will improve the cost benefit significantly.

It is possible that adding a wireless transmitter to a system such as a Hydran, a CB monitor or similar will make it more appealing – more cost beneficial. One of the drivers for this present project is availability of low cost sensors and low cost wireless communications. It is the combination which makes the monitoring viable.

Local storage and transmission of data reduces transmission requirements, but increases the need for local data storage and analysis. A trade off results, between the need for indication of anomalous operation and the need to analyze the data which has been processed to provide that information.

Wireless Temperature – Ground Potential

Temperatures may be needed from transformer tanks, tap changer tanks, bushings, breakers, or from ambient conditions, and from a range of other places. Multiple temperature sensors on one plant item may help identify anomalous operation in that item.

Costs of combined sensor/data-storage/data-transmission units have come down. They may not be cost effective alone as they do not provide sufficient indication of anomalous operation.

Sensors may be based on a number of technologies: thermocouple, Pt resistance, remote IR sensing.

The advantage of the patch approach is that there is no need to transduce the measurand into a transmittable signal for subsequent collection, storage and analysis. This meets the requirements for low cost sensors, and for cheap data transmission (in the optical). The effect of fog in an outdoor substation would limit the usefulness of such sensors.

Power supplies for these sensors would probably be via battery, unless some other local power source is available. Hard wiring such small devices into the mains may defeat the object of the exercise.

Wireless Temperature – Live Potential

One of the main problems of ‘live potential’ measurements is getting an adequate power supply. Then there is the problem of data transmission at what may be low power, in a potentially noisy background and presumed high electric field.

IR web camera applications also cover this possibility identifying hot spots through comparison with other sensed points. If no accurate temperature measure is required, and a number of points are to be monitored in one location, a comparison may be sufficient to show one temperature is somewhat different to the others.

Wireless Pressure Sensor

Pressure, generally speaking, is an SF6 application. Much of the discussion relating to temperature sensors, given above, is valid here. What is the measurement worth to ConEd? This is a utility decision, and may vary from substation to substation, and from equipment to equipment.

As per temperature sensor, the wireless device is relatively easy; it’s a case of picking a suitable sensor.

Wireless Combined Pressure/Temperature Sensor

There are no technological reasons why a combined sensor will not work on the measurement side. However, there is an increased complexity when dealing with two separate measurands in one data storage, analysis and communication system. A combined approach may improve the cost benefit analysis over that for two individual sensors. However, there is still the need to make this decision based on failure modes and plant criticality from decisions within ConEd.

One approach that may reduce installation costs is to use inexpensive video links focussed on CB control cabinet. This eliminates the need to break into gas lines, but does require dedicated video links for each control cabinet. The technology is unproven in the field and cannot be described as COTS.

Combined sensors may reduce sensor cost. Still need data network.

Wireless Circuit Breaker Monitor

Speed/Motion

This normally requires invasive sensing within the breaker mechanism. This usually means disaster for any cost benefit calculation related to monitoring due to the high cost of sensor monitoring, irrespective of communication options. There are a number of commercial systems for speed/motion available which are invasive. Non-invasive systems are, at present, limited to the research area. Consequently, this is not a COTS technology and removed from the scope of this project.

Estimated 'Operation' Time

In this case, a measure is taken of trip or close coil operation and used as an initiation time for operation. Measurements of current in the three phases are used to show when arc extinction has occurred on break operation or system current has stabilized on close operation. The resulting measurement is typically slightly different to actual operation time, but may be used as a good indicator of condition.

Making the measurements requires installation of simple clamp on CTs on relevant signals in the CB control cabinet. No breaking into wiring is required, but wireless communication will be of the 'universal transmitter' type as there will need to be monitoring of a number of signals and data storage/communication on operation.

Cost Benefit of Monitoring Systems

This subject has been covered extensively by the IEEE. The cost benefit analysis of any particular monitoring system is a strong function of the application, the utility where it is applied, and the value and criticality of the plant being monitored.

The costs may be identified, but the benefits depend on:

- **Deferring capital dollars** – on-line monitoring system enables deferral of capital dollars in equipment that has reached the end of its accounting life, which is normally 40 years for substation equipment. Utilizing existing equipment as long as possible been proven to be of economic sense [1,2]
- **Extending the life of equipment** – condition monitoring enables life-extension of equipment in a substation by identifying potential functional failures through performance trending of equipment in normal operating condition. Early identification of abnormal operation reduces unplanned downtime, cost of repairs and interruption of customer service.
- **Minimizing substation maintenance cost** – The most cost –effective means to perform maintenance is to us equipment condition assessment. Simple identification of abnormal behavior may be an indication of maintenance need.
- **Providing 'continuous' condition assessment of reliability** – In the case of breakers, continuous relates to 'on operation' and shows that a breaker is 'in spec'. Reliability calculations may then be used to indicate the likely ability of a breaker to operate on event or on demand subsequently.

Table 3-1 looks at aspects of monitoring system cost and prioritizes them based on cost and benefit. The resulting prioritized list is used as a basis for workflow within this project.

Table 3-1
Overview of Cost Benefit of Monitoring Systems

	System Cost Estimate	Installation Cost/$	Priority
Universal transmitter type (assumed to be covering all parameters possible)	800	50	1
Wireless temperature - ground	80	10	2
Wireless temperature - live	100	150	3
Combined temperature/pressure	90	150	4
Circuit Breaker Monitor	1000	100	1

Wireless serves to improve the cost benefit calculation of standard monitoring systems.

Where a known failure mode exists, specific breakers may be targeted to improve cost benefit calculations for that population. If failure mode of the breaker related to SF6 pressure loss, then that may be the most cost effective approach. Local knowledge is key in the final decision.

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TASK 1.2: TECHNICAL REQUIREMENTS

This section relates to Statement of Work, Subtask 1.2:

"Technical Requirements will be developed for selected applications identified in Subtask 1.1."

Review of Technical Goals

The overall goals of this project *paraphrased* from the Statement Of Work (SOW) are:

- to demonstrate how a wireless network can be installed in a substation to give access to measurements made by sensors attached to circuit breaker apparatus.
- identify a system architecture, devices, and operating conditions
- acquire, and/or develop system components, integrate and test the system
- test the system in Doble's environmental laboratories
- test the system in pilot installations and coordinate with "Circuit Breaker Monitor" project

The SOW refers to universal wireless transmitters - which are devices that acquire sensor data via ADCs (Analog-to-Digital Converters), 4-20mA loops, serial ports and/or other means. The measurement data is transmitted wirelessly to a receiver. Several universal wireless transmitters would be placed on apparatus around the substation and transmit data to a central receiver in a star network topology. Some preliminary attempts have been made to use off-the-shelf wireless devices to send data across a substation and have been shown to have major problems due to the severe constraints on Line Of Sight (LOS) that exist within the substation. The presence of obstructions to direct LOS is the biggest obstacle to installing wireless systems in a substation. For this reason any assumption that we can use a simple star topology will prevent us from arriving at a general solution.

Due to these LOS problems, several new technologies are investigated. These new technologies are referred to as Wireless Sensor Networks (WSN) and take the place of universal wireless transmitters. They provide a solution to the LOS problem by providing message relaying between devices, thereby allowing data to be routed via any near-by device and automatically find a route to its destination. By placing devices around the substation, the LOS problem is readily solved. Provided that the cost is acceptable, the WSN approach should play a prominent role in the final system architecture.

In this section, we discuss the issues leading up to our preliminary outline of the technical requirements.

Target Applications

From the Statement of Work (SOW) , Subtask 1.2: Technical requirements will be developed for selected application identified in Subtask 1.1.

Specifically the SOW presents the following (tentative) list of applications prioritized in order of interest:

(a) universal wireless transmitter/receiver with inputs suitable for applications with various commercially available sensors and/or monitoring systems/components

(b) Wireless temperature sensor for "ground potential" applications

(c) Wireless temperature sensor for applications at high voltage potential (high voltage and high current contacts temperature monitoring, for example)

(d) Wireless pressure sensor and combination of pressure and temperature sensor (for SF6 density)

(e) the use of above mentioned sensors/applications for Circuit Breaker Monitors

Project Constraints

This project, EPRI TC Project # P8132/C4097, is required to link in with EPRI TC project # P8131/C4096 relating to Circuit Breaker Monitoring System. The following *project constraints* have been identified:

(1) Low-cost – for wireless monitoring of Circuit Breakers the total system cost must be less than $1000 per breaker. This includes the cost of the sensors.

(2) It is highly desirable to avoid the need for an outage during installation – in other words, installation must be non-intrusive and simple.

(3) No novel sensor systems to be developed

(4) At the selected substation the operating temperature range is -30°C to 40°C. Any outdoor hardware will be capable of operating in an industrial temperature range of, say, -30°C to +65°C.

(5) No antenna will be allowed to project above a control cabinet. Antenna will have to be attached to the side of the cabinet. A hole may have to be drilled in the cabinet wall or door to attach the antenna.

(6) Simple timing measurements are required on breaker operation – for example, measuring time interval from the close control signal to zero AC signal. The detailed specification (accuracy, resolution) and method will be developed during tasks 2 and 3. Phase current measurements are also desired periodically.

(7) For data acquisition, we start with a tentative specification for 10 bits, at least 7 channels, and at least approximately 1 KHz sample rate. This specification will evolve during tasks 2 and 3.

(8) E13th St Substation will be used for field-testing (after preliminary Doble lab testing is completed)

(9) 4 Breakers have been selected to which we can attach the devices. The locations of these breakers have been chosen so that Line Of Sight (LOS) between apparatus is typical of a densely populated substation. Distance between these breakers is approximately from 50 feet to 200 feet.

(10) In situations where we do not have access to power, a battery powered maintenance free operation over a five-year period is desirable

(11) During this project, we will not be given access to the ConEd computer network. Therefore we will test connectivity using our own PC or laptop to illustrate the method for data collection; when ConEd is satisfied with the results, we can then discuss the process of moving the data collection software and network interface to their network (but this is not within the scope of this project)

(12) ConEd's operations within the substation call for special measures to be taken if hazardous systems are used. Lasers are considered hazardous above Class II - corresponding to anything more powerful than low level semiconductor lasers. ConEd have stated that they prefer avoiding anything that forces them to review safety measures for this project.

Analysis of Approach

The first step in this analysis is to identify the types of problems that must be solved in five well defined areas. The second step is to inspect several *types* of readily available technologies to determine if they can solve these problems. Finally one or more potential solutions are suggested that will be studied in detail in the remaining project tasks.

The technical requirements for this project can be split into five areas:

1. Measurement type and sensor device – for example, using clamp-on CTs in the control cabinet

2. Data acquisition – investigate several devices including modified Doble hardware (IDD or F6050), TinyOS/WSN.

3. Communication – investigate the use of wireless sensor networks (for example, TinyOS/WSN), wireless Ethernet (IEEE802.11b at 2.4GHz), Bluetooth and other wireless data acquisition systems.

4. Storage and Analysis – Intranet PC and software

5. System Architecture – define a system architecture that integrates multiple sensor and/or networking technologies.

In the following sections, each of these areas will be discussed and a list of requirements will be developed. Some off-the-shelf products will be rated in terms of their ability to meet these requirements. In this way we will identify and prioritize some approaches that meet our goals.

Measurement Type and Sensor Devices

The specific details of the sensors are developed in the sister EPRI-sponsored project, “Field and Laboratory Testing of Intranet Enabled Circuit Breaker Monitoring System", EP-P8131/C4096. For the purpose of this report, we need to determine the general types of sensors and sensor interfaces that may be required. This report has indicated that a simple measure of circuit breaker timing may be the most cost effective way to monitor breakers, given the constraints and requirements at ConEd.

For circuit breaker timing measurements we need to make timing measurements on a waveform at least at approximately 1 kHz sample rate. The specific waveforms are likely to be the open and close command signals, the CBs’ open and close reporting signals, and the 3 phase currents. This is a total of 7 signals. For the command signals we may need to record the times of transitions. For phase currents we need to record up to 3 seconds of samples in order to determine in a reliable manner when the current has fallen to zero using a potentially very noisy signal.

We may also be required at a later to record gas pressure and temperature, and ambient temperature. These may affect the breaker timing. Again, the details will be developed in a separate project.

The device will acquire as a minimum the following 7 signals (specific details will be determined in subsequent tasks):

(1) Trip command signal - time of start of command (1 signal)
(2) Close command signal - time of start of command (1 signal)
(3) 3 separate phase currents (current sensors) - time to zero (3 signals)
(4) Breaker status - times of reported close and open (2 signals)

Timing measurements will be made to a resolution of 1 millisecond. Current measurements will be made with an accuracy of +/- 10% of full scale. In addition, the system will be able to accept standard signal inputs such as 0-1V and 4-20mA from any sensing device. Additional details will be presented in Task 1 report on EPRI project EP-P8131/C4096.

Data Acquisition Devices

The specific interface to the sensor device is to be determined in the other EPRI-sponsored project (EP-P8131/C4096 mentioned above). However in the majority of cases the data will be converted to digital via Analog-Digital-Converter (ADC). Some sensors may have built-in ADC and convert the data for access over some other interface – such as a serial port or standard SPI. In addition some sensors provide a 4-20mA current loop interface – which we can acquire digitally.

Based on an examination of Doble's TDR9000 data, it appears that 10-bit resolution on the ADCs is adequate resolution to make these timings. The input range will depend on the selection of current sensors. An input range of +/-5V can be adapted to most current sensors. A sample rate of 1 KHZ has been selected for initial consideration. These parameters may be updated in subsequent tasks.

To summarize the preliminary minimum specifications for data acquisition:

Sampling rate: greater than or equal to 1 KHZ
Time measurement resolution: 1 Millisecond
Number of bits: at least 10
Input range: +/- 5V

Communication Devices

The major problems facing wireless communications systems in a substation are:

(1) Line Of Sight (LOS) obstructions
(2) interference
(3) security

The positioning of many large metallic objects throughout the substation is the reason why LOS obstruction is the major problem. Some substations will have many apparatus located in a small area – severely restricting our choices in solving the LOS problem. Placement of wireless devices at the apparatus in most cases makes it impossible to get LOS to a central receiving wireless device. Given that the substation managers do not want antennae extending above certain levels for safety reasons, this problem is made especially hard to solve. The allowable locations of antenna at the apparatus are therefore constrained to the sides of the cabinets attached to the apparatus.

What this suggests is that we will require additional wireless devices that act entirely as messaging relays. Some (possibly all) of these extra wireless relays may not connect directly to any sensors. These devices will be placed at strategic locations in the substation to re-broadcast data along any available LOS paths. During subsequent project tasks we will determine where the optimal set of LOS paths occur in the substation.

Network protocols should ideally support ad-hoc operation. Ad-hoc operation is a methodology for autonomously establishing the operational parameters of a communication protocol. In other words, you don't need to configure devices to operate in these types of network because when they sense the presence of the network they automatically configure themselves to operate with the network. These types of networks are good at operating in situations where there are LOS constraints because they simplify the installation of nodes that relay messages around obstructions. Addition of new devices to this type of network is also simplified because no network-specific configuration is required.

Security is not a deciding factor in this research project although in a full scale implementation we would expect to implement reasonable security. Without getting involved in software encryption methods we can add some security using either a sector or directional antenna and taking advantage of the short range. As the project progresses we will take advantage of any opportunities that arise that can be used to demonstrate this.

An additional issue is measurement of interference. In a wireless network interference will affect the signal to noise ratio measured at the receiver - which affects the data error rate. When errors are detected the device will request a retransmit (this is handled by the protocol). Consequently by monitoring the retransmit rate we can get an indirect indication of the levels of interference. Ideally the devices would be able to measure the signal to noise ratio directly - some RF silicon devices give a measure of signal power. In either case the device could be programmed to monitor the effects of interference continuously. The results will be useful in analyzing the RF conditions of the substation - particularly giving us visibility of transient interference that might be missed by a short-term RF survey. If the opportunity arises Doble will configure devices to continuously monitor the RF signal and report any detectable interference.

Communications Strategies

To minimize the costs we need to reduce the required bandwidth. As we progress during this analysis we will see how a wide range of bandwidths are supported by the various technologies. The higher bandwidth devices are always the most expensive.

Network message traffic will be highest when a major event (e.g. a fault) occurs. Consider a scenario in which a large number of devices are installed in the network. When a system event/fault occurs it is possible to flood a low-capacity network because the event tends to propagate through the substation within time scales as short as a few milliseconds. Each device will broadcast its data immediately, thereby increasing network traffic.

It is desirable (from cost, interference perspectives) to target as much as possible a low bandwidth network. To achieve these goals:

- minimize size of unsolicited data transfers - limit to status indicators or small measurement packets – i.e., no large data sets
- allow local storage of larger data sets (e.g. waveforms)

The reason for providing local storage is to make any larger data sets available to provide information to an engineer that enables better decision making and analysis of system events/failures. Again, the reason for storing this data locally - rather than transmitting it whenever its generated - is to minimize bandwidth requirements. Local storage is very cheap these days. It may add only $30-$50 to store waveforms or other large data sets for later interrogation. The waveform data would normally be requested when there is less traffic on the network, some time (i.e., the time it takes for an operator to decide to request data) after a system event/fault has occurred.

Storage and Analysis

The measurement data must be made available on the customers' network in a format that customers can readily use. MMW is used at ConEd and can use simple formats such as CSV (Comma Separated Variable) and XML. These formats are standard throughout the IT industry and compatible with many other types of data base interfaces. CIM compliance will be incorporated into any software. Where CIM does not cover particular entities, recommendations will be made to EPRI for future expansion and inclusion into the CIM standard.

For this project we will collect data on a PC and store it in CSV format. The PC will have some hardware that connects to the wireless network. We will develop some simple software to show that we can receive data from the sensors over this network. If we use TCP/IP based networking, then the likely interface API will be sockets.

Data will be automatically transmitted when system sensors are triggered by a system event. The PC software will be capable of collecting this data from all sensors without loss of data (provided that the wireless network remains operational). The PC software will also allow the operator to interrogate each sensor individually and download potentially large waveform data sets and store them in the supported file formats.

Due to the constraints placed on us during this project, we will not make an actual connection to the ConEd network. We will demonstrate this functionality on a PC or laptop.

Use of GSM

Cell or mobile phones provide a wireless communication solution. Depending on data transfer requirements, they may be expensive. Local conditions may mean they are unusable due to substation location underground, lack of signal coverage or high communications noise if the frequency bands where the phones operate.

It is sensible to look further at a GSM solution as an option in particular situations, but it is unlikely to be a general solution to monitoring requirements at ConEd.

Use of Power Line Carriers

Power line carriers use mains cables at 110v as a means of networking between devices. Several commercial systems are available . Though not strictly wireless in operation, they do mitigate against laying of cables in substations. Whether the dc supply within a substation could be used as a carrier is to be investigated. As with GSM, this may be an option at some locations.

System Architecture

The wireless sensor network will be distributed around substations that could vary in size from about 100 feet up to approximately half a mile. Some of the wireless technologies have short ranges (30-50 feet) and others have longer ranges (up to several miles). A general architecture is proposed which can be used to either:

(a) makes use of multiple technologies - optimized in performance and/or cost in both short and long range devices

(b) utilizes a single technology - cost per node may be slightly higher, but overall cost and performance is acceptable.

In locations containing a cluster of apparatus (for example within 30-60 feet of each other) we can choose to use short-range devices. Refer to the diagram below. A network access point will be located within each cluster to connect the short-range wireless sensor clusters over a longer range wireless network – which we will refer to as the backbone. A large number of sensor clusters could be connected to the backbone. The PC performing data collection will also be connected to the backbone. Appropriate devices will be purchased or developed to bridge between the short-range clusters and the backbone.

Backbone devices will generally require unobstructed Line Of Sight (LOS). The wireless sensor cluster needs to be capable of operating around obstacles using message routing via the wireless sensing devices or additional wireless relay devices.

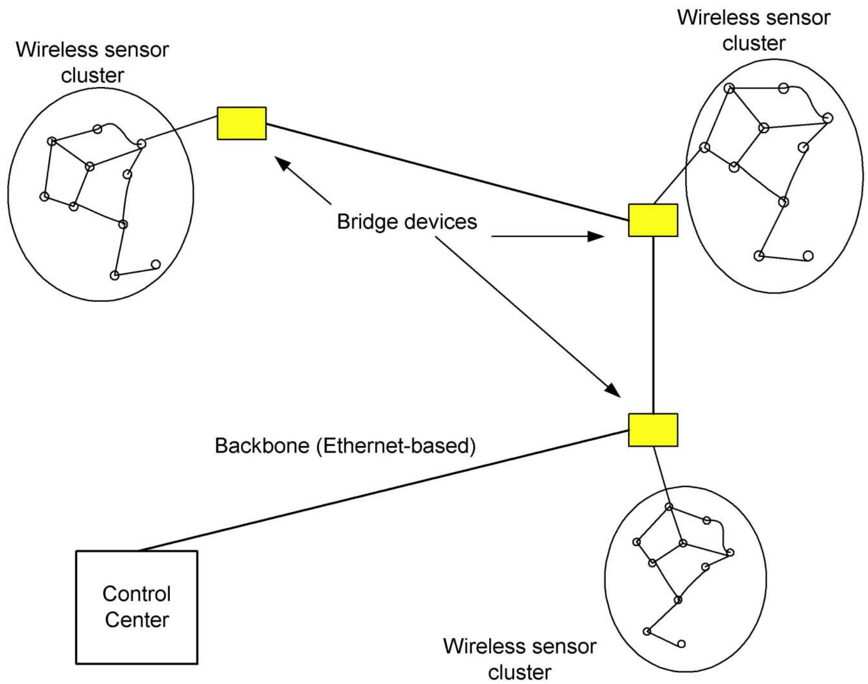

Figure 4-1
A General Network Organization

To summarize, here are the basic ingredients of this architecture:

- Clusters – short range wireless links (10-60 feet)
- Backbone – longer range wireless links (100-1500+ feet)
- Bridges – links between the clusters and backbone.

Technology and Device Comparisons

In the following sections some basic information is presented for several types of wireless network devices suitable for outdoor industrial use. For our purposes our initial selection is wireless Ethernet (IEEE802.11b), Bluetooth,Wireless Sensor Networks and Laser.

The approach is to identify the key characteristics of these technologies with respect to the project constraints listed earlier. Then each technology is rated in terms of its applicability to the general architecture described in the previous section - cluster, backbone and bridges. Note that this approach could lead us to select either a single technology (e.g., we could end up using wireless Ethernet for both clusters and backbone) or multiple technologies; there is no bias towards using multiple or single technologies.

Wireless Device Technologies

Ethernet IEEE802.11b

The IEEE802.11b wireless networking standard defines the operation of the physical (PHY) layer and the Medium Access Control (MAC) sublayer. The PHY layer is the lowest of 7 layers in the Ethernet OSI model. The MAC is based on Ethernet IEEE802.3 standards. IEEE802.11b is used in most of the wireless LANs (WLANs) today.

The standard uses digital spread spectrum (DSS) technology which improves the range and bandwidth available at a given power level compared to more traditional FM and AM approaches. DSS allows grater versatility while operating in unlicensed RF frequency bands, because legally there are restrictions to the power levels transmitted in these bands.

Several companies have been shipping wireless Ethernet PCMCIA, PCI cards and bridges to wired Ethernet. Their cost is often below $100. However, external devices that operate in the industrial temperature range are less easy to find and are more expensive - up to approximately $1500.

Range - varies from 300 feet to 1500 feet.

LOS - ad-hoc network, network access points can be used to work around direct LOS obstacles.

Maximum number of nodes: 128

Data rate: 2MBS to 11 MBS

Cost - for outdoor use, industrial temperature range, up to approximately $1500 for a single access point. For indoor use, cost is between $50 to $400.

Security - provisions for security using standard encryption algorithms.

Health/hazard issues - none.

Development tools - software can be developed using standard networking protocols - TCP/UDP/IP, sockets API.

Hardware development - if hardware development is required, Doble can modify either the IDD or F6050 hardware to act as a bridge between sensors and a wireless Ethernet/wired Ethernet bridge.

Availability and usage - wireless Ethernet is widely used in indoor commercial temperature applications. Availability is less for outdoor industrial temperature range.

Examples of suppliers:

ALX Technology: Spectra NT-2400 ($1195) and Spectra NT-910 ($1095) - rugged outdoor device

Netgear (for indoor use - connected to test PC): 802.11b Wireless Access Point (ME102NA) ($140 - $210)

Bluetooth

Bluetooth is an RF wireless technology developed for short-range communications up to about 30 feet. It is aimed at portable, low power devices (such as hand-held computers, laptops, multimedia devices, cameras, hand held data acquisition systems) that need to communicate with other devices (such as PCs, printers). Bluetooth is a wireless competitor to USB. Bluetooth supports up to 8 nodes per piconet, does not support message routing/passing.

In a substation a Bluetooth device would be ideal for a system that requires personnel to carry a wireless data collection tool around the substation, automatically collecting data from wireless data acquisition systems connected to apparatus, then dumping the data to a PC after the walk-around. As the user walks around the substation there is no effort required by the user (other than turning the device on) to collect the data.

For our type of application we would consider Bluetooth a good candidate were it not for the LOS problem. Bluetooth is widely recognized as not being able to handle situations requiring multiple nodes with automatic message routing. However it is interesting to note that at least one of the wireless sensor network protocols (that do support message routing) evolved from the Bluetooth standard.

If we were to use Bluetooth in this application, we would require unobstructed LOS between each Bluetooth data acquisition data and a local communication station. It is likely that several communication stations would be required, and connected via some other means (for example wireless Ethernet). For a given substation, the number of clusters is likely to be more than a wireless sensor network - but this depends heavily on the LOS restrictions found within a given substation. In other words, we may face more problems configuring a Bluetooth system in some substations than a more flexible wireless network system - such as WSN or IEE802.11b.

Range: 30 feet

LOS: restricted ability to work around LOS. Integration with other ad-hoc networking tools may be required.

Maximum number of nodes: 8 devices

Data rate: approximately 700 KBPS

Cost: approximately $10 to $50 for a chipset. Cost per node would be about $300 using modified Doble F6050 hardware.

Security: short range provides some security

Health/Hazard Issues: none

Development tools: development kits for Bluetooth cost approximately $1000-$3000. Costs of a Bluetooth stack are as high as $5000. Open source Bluetooth stacks may be available.

Hardware development: chipsets with reference designs are available.

Availability and usage: Bluetooth has not yet become widely available in the commercial or industrial markets. Concerns were raised about 1-2 years ago about incompatibility with IEE802.11b. Several chip manufacturers are expecting Bluetooth usage to increase rapidly during the next 5 years.

Examples of suppliers:

Cypress: silicon devices: $20

Motorola: modular component: $60

Ceeyes Systems: software library $4995

Stonestreet Bluetooth: software library $4000

IAR Systems: software library $3000

Estimated cost per Bluetooth wireless node: approximately $300 + data acquisition costs + sensor cost + packaging.

Wireless Sensor Network (WSN) - TinyOS/Crossbow

Crossbow's MICA/MOTE devices and University California Berkely's (UCB) TinyOS have been chosen to represent the Wireless Sensor Network. This is a new and exciting technology that is being developed at several universities and businesses. During Task 2 we reserve the option to stay with TinyOS/WSN or to select another WSN, or to try more than one WSN. An example of alternative WSNs is Ember - which provide a higher data rate but fewer nodes.

The main features that distinguish WSNs from other wireless/data acquisition systems are:

(a) built-in data acquisition

(b) small size

(c) lower cost

(d) automatic message routing

(e) ad-hoc network

(f) large number of nodes

Crossbow originally based their Wireless Sensor Network devices on Bluetooth but have recently developed hardware used as a proving ground for the TinyOS ad-hoc wireless sensor network software developed at UCB. This is an ultra-efficient protocol that operates on a microcontroller using a small amount of internal memory. The hardware consists of a small circuit board with a microcontroller, memory and RF transceiver. The microcontroller has built in data acquisition, specifically 8 channels of 10-bit ADCs. The memory device is a serial FLASH that could be used to store waveforms.

Range: up to 200 feet. Current practical ranges attained are approximately 50 feet.

LOS: use of additional nodes to work around LOS obstacles. Supports message hopping.

Maximum number of nodes: a 64-bit ID is used, so the theoretical limit is 2^64 (i.e., extremely large). A network of 800 devices has been tested.

Data rate: approximately 50 KBPS max.

Cost: from Crossbow Technologies the cost is approximately $300. Doble manufacturing cost would be approximately $60 (Atmel microcontroller, RF Monolithics TR1000 transceiver chip and 4 MBit serial storage device, PC board and assembly).

Security: a simple security protocol is used. Short range provides some security.

Health/Hazard Issues: none

Development tools: open source software.

Hardware development: Doble can develop the hardware at low cost.

Availability and usage: this product has been available in its current form since fall 2001. They are widely used for R&D programs in DoD. There is also a great deal of interest from the commercial sector.

Examples of other suppliers of WSN:

Ember (http://www.ember.com)

Laser

Initially we looked at optical systems as a possible use for the backbone. Optical systems require lasers. They are design for the "last-mile" problem facing broadband network operators. To solve this problem using wired or fiber optic cables is extremely expensive in built-up areas, so they resort to laser technology in these areas. Since a beam of light is easily interrupted, these systems are made of several beams of light to provide some redundancy. They also consist of tracking systems that keep the beam on target while being subjected to motion from building sway and wind.

Several companies make these types of devices that are packaged for plug-and-play with an existing Ethernet network.

Range: up to a mile.

LOS: requires at least one direct LOS.

Cost: $10000-$15000 (AirFiber)

Security: highly secure.

Health/Hazard Issues: can not use high-powered lasers. There is a bias against use of any technology that may require special handling as per health and safety regulations.

Development tools: if the device supports Ethernet then software can be developed using standard network APIs, such as sockets.

Hardware development: none.

Availability and usage: used mostly in the communications industry.

Examples of suppliers:

LightPointe: make several types of laser communicator heads

AirFiber: make the AirFiber 5800

Plaintree Systems Inc: FiRLAN ET300

Other Combined Sensor Interface and Wireless Devices

Several devices are available that combine sensor interfaces and wireless devices. In the statement of work these are referred to as the universal wireless transmitter. They operate with a 4-20mA interface, some digital inputs and transmit the data wirelessly.

Range - varies from 300 feet to 1 mile.

LOS - point-to-point

Maximum number of nodes: varies depending on manufacturer

Data rate: 19.2KBPS - 900KBPS

Cost - for outdoor use, industrial temperature range, from $500 up to approximately $2500 for a single access point.

Security - some use spread spectrum which provides some security.

Health/hazard issues - none.

Development tools - PC-based software. Usually connected to serial port.

Hardware development - if we pursue this type of technology we may have to develop hardware to relay the RF signal around LOS obstructions.

Availability and usage - these types of systems are often used to collect data from systems placed in remote locations. In the case of utility substations, they are generally used to transmit data to a distant receiver. The data is collected from within the substation via cables by an RTU. Clearly this is a very different application compared to ours - which requires wireless, cable-free communications within the substation.

Examples of suppliers -

Metric Systems Corporation: RAMM 210 2.4GHZ RF RS232 modem ($795 with antenna)

Cirronet: make various types of OEM modules for applications with unobstructed LOS.

Rockwell: produce an expensive type of wireless sensor network, Hidra.

Bentek Systems: ScadaLink 900 - an RTU/RF modem device.

Industrial Control Links Inc: RF modems for use with RTUs

Comparison Charts

As described above, the approach is to identify the key characteristics of these technologies with respect to the project constraints listed earlier. Then each technology is rated in terms of its applicability to the general architecture described in a previous section - cluster, backbone and bridges.

Table 4-1
Comparison of Wireless Technologies

Technology	Estimated cost per node	LOS solution[1]	Message routing	Number of nodes	Range	Data rate
Wireless Ethernet	>$1500 + DAC[2] + sensor costs (TBD)	Yes - additional nodes	Yes	128	300 - 1500 feet	2MBPS - 11MBPS
WSN	>$300 + sensor cost	Yes - additional nodes	Yes	250-800+	50 - 200 feet	50 KBPS+
Bluetooth	>$300+DAC +sensor costs (TBD)	No	No	8	30 feet	700 KBPS
Other RF wireless	>$500 + sensor cost	No	No	Mostly point -to- point[3]	Up to 1 mile	Up to 900 KBPS
Laser	>$10000 + DAC + sensor cost	No	No	Point - to- point	1 mile	> 1 GBPS

Notes:

1. *If LOS solution is "No" this means that the devices MUST have an unobstructed line of sight.*
2. *DAC : data acquisition component*
3. *Some RF SCADA/modems are point-to-point but support multiple channels so that several devices can transmit simultaneously to a single receiver in a star topology (requires unobstructed LOS).*

Clusters

Clusters are required to work in small areas with many obstructions to direct LOS. For this reason alone the choice is restricted to either wireless Ethernet or WSN. The cost issue affects the choice as follows:

(a) Where several nodes are required WSN should be used to keep down costs.

(b) Where longer distances from 300 to 1500 feet are required then wireless Ethernet should be used.

Backbone

There are more choices in the backbone. Our basic premise is that the backbone will have unobstructed LOS. The basic criteria for selecting the devices for the backbone are range and ease of integration.

If the range is short then the backbone can be implemented with WSN - i.e., an all-WSN solution could be implemented. Several WSN devices would have to be chained together if the distance is greater than approximately 50 feet.

For longer ranges up to about 1500 feet and for convenience in terms of integrating with existing networks, a wireless Ethernet would be selected.

For even longer ranges connecting large numbers of clusters, we could consider using free space optics (Laser).

Summary

Derived on the above information and giving most weight to LOS issues, several configurations (with the most attractive approach listed first) follows:

- WSN Clusters with Wireless Ethernet Backbone
- WSN Clusters with Backbone WSN Clusters
- Wireless Ethernet Clusters and Wireless Ethernet Backbone
- Bluetooth Clusters with Ethernet Backbone
- Other RF (e.g., modem) Clusters and Backbone
- Any Clusters with Laser Backbone

WSN Clusters and Wireless Ethernet Backbone

Because of its low-cost and strong solution to the LOS problem we will pursue this option.

Doble has made a preliminary study of the TinyOS/WSN system and has begun investigating other WSN products.

In task 2 we will broaden the search for alternative sources of wireless sensor network hardware and software. For example, Ember is beginning to offer wireless sensor hardware that includes a bridge to an Ethernet network.

If necessary we can implement a bridge between WSN and IEEE802.11b with either a Z180/WSN/IEEE802.11b bridge or modified IDD (depends on availability).

The IEEE802.11b can be used to connect the data-collection PC to the network. An indoor wireless access point (compatible with a PC) costs about $210 or less. Software will be written to communicate to the sensors, collect the data and save it in CSV format.

5
TASK 2: SELECTION OF PRODUCTS AND APPLICATIONS

This section relates to Statement of Work, Subtask 2:

"This task is subject to modification based on the results of Task 1."

where the aim is to select products and applications. The application has been chosen based on the statement of work and discussions with ConEd and EPRI. In this report we look at the application, then products to achieve success in those applications.

Applications

The focus of the project has been determined, in conjunction with ConEd and EPRI, to be the monitoring of circuit breakers and disconnect switches.

Circuit Breaker Application

The aim with this application is to produce a 'rough' timing measurement for breaker operation which can be used to indicate anomalous operation. This indication would then be used to initiate maintenance activity, including a full off line timing test for the breaker.

Disconnect Application

The disconnect application requires measurement of temperatures of live conductors. This, as has been noted may be achieved either by direct application of sensor/wireless systems to the conductor, or via a remote sensing, or by a combination of the two.

Products

The main goal of this project is to demonstrate a wireless sensor network operating in a substation, with a focus on collecting measurements of the most significant performance indicators of a circuit breaker.

The most relevant performance indicators for a circuit breaker have been identified (timing) and methods for making and reporting the measurements are being identified in a separate project.

Background

Previous experiments performed by ConEd at E 13th St. substation had showed some success with simple radio systems. These required direct line of sight that meant the systems failed when line of sight was lost. Two networking systems have been chosen which use two or more networked nodes to provide seamless communication – message passing system using ASK and DSSS.

Wireless Sensor Networks

Wireless Sensor Networks (WSNs) utilize a message passing protocol. In its simplest form this protocol allows each device to rebroadcast any message it receives, provided it has not done so before. In this way a message is propagated through the network in such a way that direct line-of-sight is not required between the sender and designated receiver. All that is required is a chain of these devices within listening range of each other. Effectively the devices act as transceivers, sensor data collectors and repeaters in a single low-cost package.

These devices can be connected directly to PCs via an RS232 - or alternatively via a bridge device to other types of networks, such as Ethernet, wireless Ethernet, satellite pagers/cell phones, modem, and so forth. The bridge device could be designed to provide substantial processing power. In this case the bridge could perform analysis on several hundred devices within the substation and send the results via SCADA or other network system. These are options for future development.

The following diagrams illustrate several types of WSN architectures. The simplest architecture (all-WSN) is the type that will be used in this investigation.

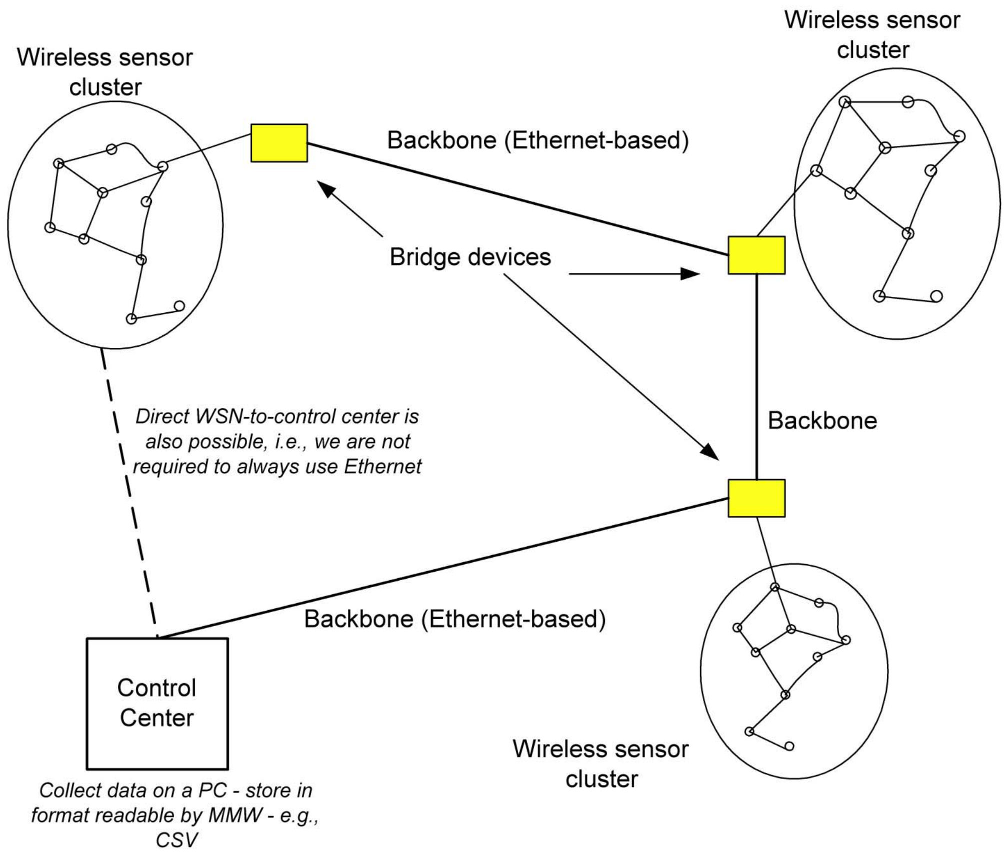

Figure 5-1
A General Network Organization

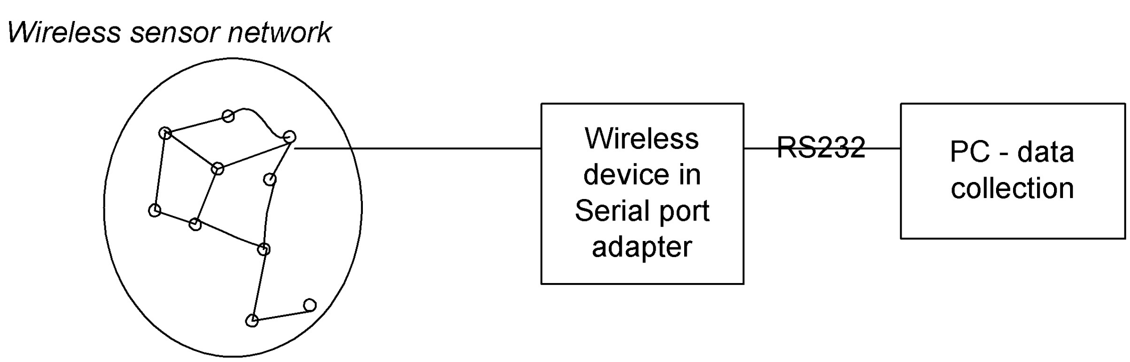

Figure 5-2
Wireless Sensor Network and PC - no other networking components

Wireless Sensor Devices

The Wireless Sensor Devices (WSD) consist of the following components:

- wireless communications
- data acquisition
- sensors

Two types of WSD have been evaluated. They share the following features:

- they use a microcontroller (ATMEL Atmega103 or equivalent)
- they have local storage for data (up to 4 MBITs)
- they have an RS232 interface
- they have low-precision ADCs build into the microcontroller
- they use low-cost components

The devices differ in their use of the available radio spectrum. The first uses Amplitude Shift Keying (ASK), and the second uses Direct Sequence Spread Spectrum (DSSS).

The ASK WSDs have the following distinctive features:

- they use a simple RF chip (RF Monolithics TR1000)
- operates at a single frequency (916 MHZ) in the ISM band
- they use amplitude modulation, specifically *ASK (Amplitude Shift Key)*
- the hardware design/schematics are in the public domain
- the software and protocols are open source, developed at University of California, Berkeley - referred to as TinyOS

The DSSS WSDs have the following distinctive features:

- Direct Sequence Spread Spectrum (DSSS) baseband processing (FPGA/ASIC)
- operates at several frequencies in the ISM band
- professional technical support

DSSS extends the range of communication for a given transmission power level compared to ASK modulation. Consequently DSSS gives these devices a major advantage over the ASK devices.

However, we will continue to use both technologies until we have completed our evaluation, as these are new and immature technologies that will require monitoring before gaining widespread use. There are also concerns that emerging standards (IEEE) relating to ultra-low cost wireless sensor networks may appear in the same time frame, and that these devices may not incorporate these standards.

For the prototype, Doble has selected a Rabbit processor and data acquisition module for the purpose of acquiring raw data from sensors attached to the circuit breaker. The WSDs will also have a low-cost temperature sensor attached to the ones used in the high voltage experiment.

In order to use both the ASK and the DSSS WSDs an interface is developed which will be applied to both. The interface uses an RS232 connection. Messages consist of a header, including destination and source address, the data payload and checksums. The ZWORLD Rabbit module will be programmed to communicate with either device using this common interface. The ZWORLD Rabbit board will acquire data as needed, process the data and store results, transmit both status and a measurement summary.

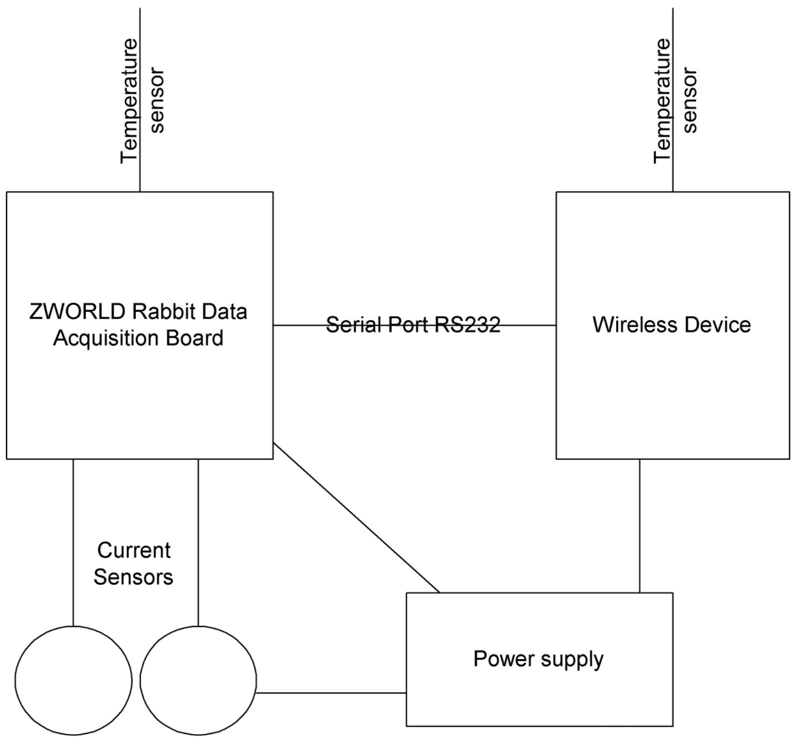

Figure 5-3
Wireless Data Acquisition and Wireless System

6
TASK 2.1: UNIVERSAL TRANSMITTER

This section relates to Statement of Work, Subtask 2.1:

The original concept for the universal transmitter was a wireless transmitter with a standard data acquisition interface such as a 4-20 current loop, RS232, or similar. This concept has been superceded by a cheaper and more flexible technological development: self-organizing, low-powered, wireless mesh networking (WMN) devices - also referred to as Wireless Sensor Networks (WSNs). Several implementations of this technology have appeared on the market, and new implementations are appearing about once every 6 months.

The wireless mesh networking (WMN) technology was selected because it provides an ideal solution to the problems that arise from the positioning constraints that limit the "line of sight" between any two points in a substation. This is achieved because each node on the wireless network is effectively a repeater and will re-broadcast any received message packet to its neighbors, thus ensuring that the message gets to any destination even when there is no direct view.

Several companies have made different implementations. One implementation uses several channels in the ISM band in combination with a short sequence DSSS code to provide security and some degree of immunity to interference. The device will use multiple channels to optimize the re-broadcasting strategy - this is accomplished by proprietary algorithms.

Another implementation (by a different company) is much simpler, but results in less total bandwidth. It uses ASK modulation techniques and a simple public domain algorithm. Several variations of the hardware are available, some in the public domain.

In all cases, each node can be connected to a small general-purpose data acquisition unit - with analog and digital inputs. For a prototype/proof-of-concept we are using an off-the-shelf board. The board contains multiple ADC inputs as described below. Some simple software is written to perform the following functions:

- send data to the WMN device
- acquire data and generate measurements
- store waveform data
- process requests for waveform data from the WMN device
- process requests for status, parameter changes, local settings via the WMN device

The connection between the data acquisition board and the WMN device is via an RS232 or SPI using the message protocol defined by the WMN's manufacturer.

Two types of wireless devices have been selected - the DSSS and the ASK. The DSSS device is actively being used. The ASK device is available as a backup.

Details of the Data Acquisition Board

Zworld BL2120

Features

- 22.1 MHZ Rabbit processor
- 4 serial ports
- 128K SRAM
- 256K FLASH EPROM
- Operating temperature -40C to 70C
- Input voltage 9V to 36V DC
- Power: 1.5W
- Real-Time Clock

Interface

- Analog inputs:
  - 11 channels, +/- 10 Volts, 1 M input impedance, 12-bit
- Digital inputs:
  - 40 digital I/O:
  - 24 inputs:
    - *hardware configurable pull-up, pull-down*
    - *+/- 36 V DC, switching threshold 2.4V*
  - 16 outputs:
    - *software controlled sinking/sourcing*
    - *+36V DC, 200 mA max per channel*

7
TASK 2.2: WIRELESS TEMPERATURE SENSORS

This section relates to Statement of Work, Subtask 2.2:

The curent wireless scheme - the wireless mesh network - provides the infrastructure for all other sensors. The temperature sensor must be integrated into this infrastructure. This can be done via the data acquisition board.

Contact Methods

Examples:

Contact thermistor

Contact thermocouple

Platinum resistance thermistor (PRT)

These techniques all use a sensor which reacts to the physical quantity by direct contact with it. For normal ambient conditions, it's a straightforward solution. However, the ambient conditions at the disconnector are not normal. The reaction if these devices, and their associated data acquisition boards, to the 138kv field is unknown. It might very well be that these devices cannot survive in the environment. Also, providing power to the devices is problematic.

Tests will need to be executed to determine if this line of investigation should continue. At present the benefits of a contact sensor do not outweigh the costs of producing such a sensor. One company which was known to offer these combined devices has withdrawn from the market.

In theory the application is simple, in practice there are many obstacles to overcome: insulation issues when insulating from the bus voltage or e.m.c. issues when referencing the bus voltage. These are compounded by the need for an outage to fit sensors, which may add to costs and complexity in the field. Alternative, remote, methods for temperature sensing seem more feasible.

Infrared

Examples:

Remote IR with laser sighting for setup

Single high quality IR camera

Insulated or non-insulated close-in IR

These methods all rely on infrared sensing to determine temperature. They suffer from a common problem, which is not insurmountable, that the surface to be measured may need some preparation to obtain a useful reading.

Remote IR allows us to put the sensor in a convenient, electrically quiet location. A laser sight would allow continuous or regular verification that the sensor was on target. Field-of-view limitations of available devices may rule out this solution. Costs are also expected to be higher than the project cost target. Discussions with vendors are continuing.

Deploying a single (or few) high-quality IR camera would allow the high cost of such a device to be amortized over many disconnectors. The camera(s) would be positioned to get all the switches in the view of at least one camera. Software would examine the pictures and determine the switch temperature.

Close-in IR would place an inexpensive IR sensor within a few inches of the switch. The data acquisition board and wireless unit would also be located there. There is no contact between the sensor and the switch. The device may be insulated from the switch, or may be at the same potential as the switch. This solution exhibits some of the same risks as contact solutions.

Thermochromic

Examples:

Thermochromic label - reversible or non-reversible

Thermochromic paint

Thermochromic crayon

Thermoluminous materials

Thermochromic materials are available in a wide variety of forms and sensitivities. They can be obtained in many colors, and in the form of labels, paints, crayons, or a solid mass. Use of a thermochromic material may simplify the solution, but it is not the entire solution. The change in color must be reported somehow.

The most cost-effective solution may be to put a non-reversible thermochromic label on the switch. When the switch overheats, the label records the event. Some time later, during a routine survey, the label can be inspected. This scenario depends on the timeframe in which the overheating occurs, and the frequency of inspections.

An automated solution must rely on detection of the changes in the label. This might be done by inexpensive webcam, or with strip light sensitive diodes. These solution share some of the problems of the solution above: difficulty sensing at a distance, or survival and powering in the 138kv close-in environment.

Thermoluminous materials occur naturally. These emit a characteristic light when heated. Presumably a material could be tailored to this application. We have found no commercially available devices using thermoluminous materials.

Other Techniques

Autonomous inspection vehicle (AIV)

An autonomous inspection vehicle can reduce the cost of a total system solution by placing the most expensive system components on a substation "rover" and having it make routine inspections, for example, to check for any changed thermochromic labels.

Heat-catalyzed chemical reactions

Heat sensitive materials, in which a chemical reaction takes places at a predetermined temperature, could be used to provide a secondary signal, such as sound or visible light, which is more easily detectable than the switch temperature.

Phase change materials

Materials that change phase from solid to liquid at precise temperatures could also be used to stimulate a secondary signal. For example, a pressurized container of air, plugged with a material that changes phase at the alarm temperature, could operate a loud and distinctive sound generation device, which could be sensed by a data acquisition unit some distance away.

Depending on the temperature range, a phase change from liquid to vapor might also be employed to stimulate a secondary signal. For example, if the alarm temperature is 100 C, a "tea kettle" might be placed in good thermal contact with the switch. The kettle could be designed so as to be replenished naturally by rainwater. On reaching the alarm temperature, the expanded vapors would pass through a constriction, generating a loud and distinctive sound.

A combination of phase change materials might form the optimal solution. Imagine a non-pressurized container filled with liquid, which liquid changes phase to vapor at temperature X. A solid material is used to seal the container, which solid material changes phase to liquid at

X+dt. The container is fixed in good thermal contact which the disconnector switch. Once X is reached, the liquid begins to vaporized, raising the pressure in the vessel, effectively raising the boiling point. When X+dt is reached, the vessel is unsealed, and the liquid rapidly boils, providing a large supply of vapor for operating a sound generating device.

Summary

In spite of its minor problems with spot size and lenses, the IR temperature sensor is the preferred device for use in HV applications. This is because it does not require contact with the high voltage apparatus. Any problems arising from big target spot size can be overcome by either a cheap lens (e.g, approx $2 - $50 per lens) or by compensation of the temperature measurement in software.

8 TASK 2.3: WIRELESS PRESSURE/DENSITY SENSORS

This section relates to Statement of Work, Subtask 2.3:

The system described in section 6 “Universal Transmitter” is capable of adding wireless WMN capabilities to any analog measurement device, or RS232 device. Pressure and density silicon sensors typically have a serial interface (SPI or RS232), or an analog output. Using the WMN combined with the data acquisition board, we can provide wireless pressure/density sensors. This will broadcast measurements from all points in the sub-station using the wireless mesh network.

9
TASK 2.4: WIRELESS CIRCUIT BREAKER MONITOR

This section relates to Statement of Work, Subtask 2.4:

The circuit breaker monitor is required to record and report the times of the following events: time of start of trip current, time of zeroing of 3 phase currents. The system we have reviewed so far consists of the wireless mesh networking (WMN) device and a general purpose data acquisition board (low-cost) with on board processor. This system will be adequate for the purpose of a wireless circuit breaker monitor. All that is required is a current transformer connected to the ADC inputs of the data acquisition board. A resistor and tranzorb is added across each input.

10
TASK 3: LABORATORY AND FIELD TESTS

This section relates to Statement of Work, Subtask 3: which is split into Laboratory and Field tests:

"a. Laboratory Tests
Doble's HV and Environmental Laboratories will be used to test transmitters, sensors and components in simulated conditions, preferable before field tests. Electromagnetic interferences, ambient and HV tests will be used for functional tests, including antenna and shielding design tests for application at HV potential.

b. Field Test
Pilot installation in selected ConEd substation will be used for field test. Combination of individual sensors and wireless circuit breaker monitors will be installed for simultaneous field test."

Introduction

Laboratory and field trials have pursued the suggested route of lab then field. Initial work on communication systems has been done in advance of combined communication and sensor combinations.

Wireless Communication - Lab Trial

Wireless Communication - Initial Field Trials

A visit to ConEd's East 13th St substation allowed test of two types of products for wireless communication. The goal was to demonstrate that we could communicate from any location in the yard, back to a designated location in the control room. The first product tested was a UCB-derived product using Amplitude Shift Keying (ASK) radio technology. The second was uses Direct Sequence Spread Spectrum (DSSS).

In parallel with the test of these wireless devices, an RF survey was conducted on the site.

Both wireless products performed adequately, although the DSSS units were clearly superior, with longer range and less sensitivity to loss of Line of Sight (LOS). About twice as many ASK units were required to cover the same distance in the substation, as compared to the DSSS units.

Given the expected coverage when fully deployed, this may not be an issue. However, it's predicted that the protocol implemented on the ASK units will cause performance degradation as the population density increases.

Details

It was first decided to plot the route from the LAN connection inside the substation house, out to the yard. The house consists of 3 long east-west corridors, roughly 40 feet long. The first corridor, about 15 feet wide north-south, is the control room. The middle corridor, about 10 feet wide, contains the LAN connection about half way down the length. The rear corridor is the break area; is backs onto the oil storage, is below the relay house, and is just in front of the yard.

The substation covers approximately 100 yards east-west by 75 north-south. The house is in the center of the southern wall. About two thirds of the yard is covered with breakers, the other third by steam apparatus associated with the generating plant across the street. About 3 stories above the steam apparatus is the "flight deck", also supporting breakers.

House to Yard - ASK

The ASK units were identical to each other in hardware, but programmed with 3 different personalities: a sender, repeaters, and a receiver. The sender sent the message "Hi from Doble" about every half-second; the receiver printed any messages it received out an rs232 port on an attached adapter card. The repeaters simply rebroadcast any messages received.

The sender was placed in the corridor near the LAN connection. The receiver was connected to a laptop and carried out of the house. Communication ended about halfway up the stairs to the yard. We tried going all the way up and around the corner, in alignment with the LAN connection, but communication did not resume. By using some or all of the repeaters, we could have gotten closer to the yard. It was felt that this test summarized the ASK capability in a broad sense.

House to Yard - DSSS

The DSSS units were also identical in hardware, but programmed either as an endpoint or repeater. The endpoints were programmed with a "chat" application. Anything appearing on their rs232 port would be broadcast, anything received would be sent out the rs232 port. This required a person typing at least at one end.

Again, one endpoint was left at the LAN connection point. The other endpoint, connected to a laptop, was carried out of the house and up the stairs. There is a clear area in the yard at the top of the stairs. Communication was good all the way up and into the clearing.

Subsequent Experiments

The next set of experiments was to try to send the signal from the remote northwest cornet of the yard, at breaker F8, back to the clearing.

Breaker F8 to House - ASK

The sender was left at F8, and the receiver moved away until communication dropped. A repeater was left a few meters inside the range of the sender. Then the receiver was moved away again, towards the clearing. Each time when communication dropped, another repeater was placed inside the range of the previous one. We had a total of 4 repeaters, all of which we used. Once all the repeaters were used, we were still short of the clearing by about 15 yards. If we had more repeaters, or had time to place them more optimally, it's likely we could have reached the clearing.

Breaker F8 to House - DSSS

We could move away from F8 a much longer distance with DSSS than with ASK before we needed a repeater. It seemed to be the intervening apparatus rather than the distance that limited us. We used 2 repeaters, and got to the clearing right outside the house. It's possible we could have gotten inside the house without another repeater, and almost certain that if we used out 3rd (and last) repeater that we would have completed the link, all the way from F8 to the LAN connection.

After demonstrating communications with the DSSS units back to the clearing, Mike and I walked inside the control room and back to the LAN connection area. We were able to communicate from there back to F8. So, the entire end-to-end communication chain was established with the DSSS units.

Wireless Communication – Initial Trial Conclusions

With both types of units, communications problems were noticed before the connection was terminated completely. This took the form of either garbled messages (ASK), or missing messages (DSSS). This could be used as an indication of communications problems.

Either technology could be made to work. ASK requires a more dense population of nodes, which may exist anyway in this substation due to the dense population of apparatus. We have also been warned by the supplier that a dense population of ASK nodes may cause performance problems. This potential problem needs further investigation.

Continuing with both solutions will alleviate some risk that one might fail, either for technical or business reasons.

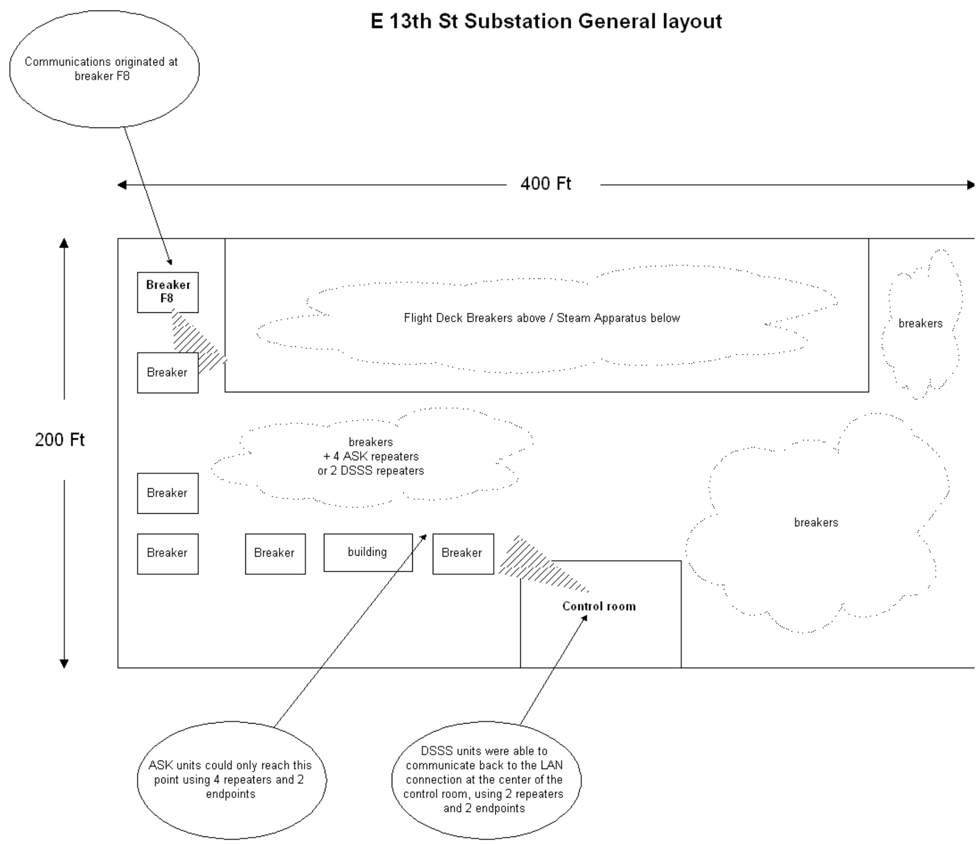

Figure 10-1
System Substation Layout

11
TASK 3.1: PROJECT PLAN AND MILESTONES

This report is based on the work done within project with broader scope of the work as presented in the following table.

ID	Activity	Date for Completion
1	Site rf survey at taget substation	July 2002
2	Development of basic universal transmitter	August 2002
3	Sensor identification for CB monitoring	August 2002
4	Laboratory trials of universal transmitter modules	October 2002
5	Operating Condition Specification Milestone Final Report	October 2002
6	Identification of temperature/pressure sensors for lower priority monitoring systems	November 2002
7	Laboratory trial of sensors in activity ID 5	December 2002
8	Field deployment of universal transmitter and CB sensors	December 2002
9	Field deployment of ID 5 sensors	February 2003
10	Final report	March 2003
11		

12 CONCLUSIONS

For wireless communication systems, a simple wireless sensor network, with Ethernet backbone, is preferred. Initial experiments at E 13th St. using both ASK and DSSS systems have shown that both work, but the DSSS seems to be less sensor-heavy and more reliable.

Alternative solutions, including GSM and power line carriers, have been identified as not being within scope of the project.

A tentative specification for the data acquisition and wireless elements of the system has been given.

Sensor systems have been investigated for the applications described in the Statement of Work. These appear to be addressable through application of the Universal Transmitter that is being developed as part of this project. The HV contact sensors are possible, but would require research and developments which are not feasible within the constraints of this project.

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A
PROJECT OBJECTIVES

A “Identify and prioritize applications for low cost wireless sensors and wireless communications in substations.”

B “Determine operating conditions for selected applications in ConEd substations”

C “Develop Requirements Specification for selected applications in ConEd substations

D “ Identify Doble’s Wireless Technologies and products for Testing”

E “Test wireless sensors and communications in Doble’s environmental laboratories”

F “Test wireless sensors and communications in pilot installations at one of ConEd substations’”

G “Co-ordinate testing with testing of “Circuit Breaker Monitor” (ConEd TC project)

B
STATEMENT OF WORK DETAILS

Task 1 Details from the statement of work:

Task 1: Prioritization and Project Plan Development

Subtask 1.1: Requirements and Project Plan Development

"Prioritized list of potential application for wireless sensors and communications will be determined based on cost-benefit and feasibility analysis for applications in ConEd substations. Technical and business aspects for successful applications will be addressed."

Subtask 1.2: Technical Requirements

Technical requirements will be developed for selected applications identified in subtask 1.1.

Subtask 1.3: Project Plan and Milestones

Detailed project plan with milestones for laboratory and field tests will be developed based on specific requirements for selected applications.

Pilot installations for field test will be determined in co-ordination with Circuit Breaker Monitor testing program (testing of Circuit Breaker Monitoring system is a separate TC project).

C
TENTATIVE SPECIFICATION

Signals Measured with Current Sensors

The following signals will be measured using current sensors:

1. Trip current
2. Close current
3. 3 individual phase currents
4. 52A - trip command
5. 52B - close command

Other Sensors

A temperature sensor will be attached to a wireless device. Determine the ability of the resulting system to record and wirelessly report measurements while attached to a high voltage component.

Measurements

1. The timing measurement will start with the on-set of the trip current and stop when the corresponding (or all - depending on configuration) phase current falls below a threshold.
2. The maximum time reported will be 3 seconds.
3. If there are multiple trips/closes then the time of each trip and close event will be recorded.
4. In some cases (for example, high voltage application) we will record and report temperature.

Measurement Accuracy

Timing measurements will be made to an accuracy of 2 milliseconds.
Temperature measurements will be made to an accuracy of +/- 3C.

Expected Ranges of Current Measurements

Trip current	- 6 to 12A typical, 50A maximum
Close current	- 10A maximum
52A, 52B	- TBD
3 phase currents	- from 5 to 25A

Preliminary - Current Sensor Spec

Nominal input current - 50A
Nominal output current - 50mA into 200 ohms (variable)

Data Acquisition Board

Zworld BL2120
Features
- 22.1 MHZ Rabbit processor
- 4 serial ports
- 128K SRAM
- 256K FLASH EPROM
- Operating temperature -40C to 70C
- Input voltage 9V to 36V DC
- Power: 1.5W
- Real-Time Clock

Interface
- Analog inputs:
  - 11 channels, +/- 10 Volts, 1 M input impedance, 12-bit
- Digital inputs:
  - 40 digital I/O:
  - 24 inputs:
    - *hardware configurable pull-up, pull-down*
    - *+/- 36 V DC, switching threshold 2.4V*
  - 16 outputs:
    - *software controlled sinking/sourcing*
    - *+36V DC, 200 mA max per channel*

Wireless Devices

Power output is limited to 500 milliwatts (ISM band regulatory limitation)
Range is dependent on type of modulation technique and environment - expect from 30 feet to 100 feet for ASK, up to 2000 feet for DSSS.
Interface - RS232 UART. Custom messaging protocol (for prototype).

Power Supply and Enclosure

Low-cost plastic small NEMA4 enclosure.
IDD power supply - 110V AC input.

D
CIRCUIT BREAKER MONITORING

Introduction

The life span of newly installed circuit breaker is expected to be from 20 to 30 years or more. During its' life, a breaker will be expected to operate in normal rated condition for less than 10 minutes and in abnormal transient condition for less than 60 seconds.

After a long 'idle' time, we wish to know whether a circuit breaker is in a state where it will be able to perform its' circuit breaking function.

One procedure is to perform regular maintenance at pre-determined time intervals. This may return a breaker to some specified original condition, but takes no account of actual wear and tear that the breaker has seen.

Circuit Breaker Monitoring

This project is based on monitoring certain characteristics of circuit breaker that will allow early detection of possible problems – i.e. detection of anomalies, which require investigation and/or explanation. As mentioned above breaker is mechanical device and all measurement will give a condition of mechanical functionality.

Monitorable Parameters

The following parameters are among those monitored in commercially available systems:

- Time and current of charging motor
- Motion and Speed
- Trip and Close coils integrity and currents
- Supply voltage
- Auxiliary switches
- Main contact current
- Vibration
- Acoustic Emission

- SF6 Temperature and pressure
- Travel
- Phase Currents

The question at this point is: what failure mode are we hoping to detect and what are the parameters that could give us information about the likelihood of that failure mode? If loss of SF6 leads to the inability of a breaker to perform its function, then SF6 pressure and temperature may be the key monitoring parameters.

Possible Sensor Solutions

There are four stages – generate data, store data, transmit data to decision-maker, analyze data. After generation of data, the other three steps may be performed in any order, with raw or processed data being transmitted.

Data generation

First step is to use sensors to transduct one measured physical value to electrical signals. Choice of sensor will directly influence design and performance of monitoring system.

Standard sensors – simple, relatively cheap and robust. Use of such sensors require additional processing and communication systems

Smart sensors – more complex in design, higher price than standard sensors with advantage of processing at sensing level. Such sensors may not have communication systems embedded in them.

The remaining steps – store, analyze and transmit - need to be designed into a system based on the requirements of the project. For circuit breaker timing, it may make more sense to analyze the data on capture to determine the timing, and send a timestamped result for comparison with other values at a central point. If a ‘good’ time is known, the sensor system may only be required to send an alarm. This approach reduces data transmission requirements, but increases the need for local data storage for reference at a future time.

For this type of monitoring standard sensors will be used.

Circuit breaker timing monitoring

Trip operation

Pre conditions:

- Circuit breaker is in close position and current is present.

- Maximum breaking time is known for that particular breaker
- Main current is measured and zero current detected - time

Monitoring

Auxiliary switch position change can be used as beginning of trip operation t1

Pre determined time is stored t expected

Current zero is detected t2

Delta time t2-t1 is compared with expected time

Delta t2-t1 < t expected no action

Delta t2-t1 > t expected alarm " circuit breaker anomaly – investigation required"

If there is a 'graceful' failure mode where timing degrades over an extended period, then time to failure may be calculated based on current rate of increase in timing and likely number of operations in the future.

E
DOBLE INSITE AND CIRCUIT BREAKER MONITORING

The following Insite analyses are done for circuit breakers: -

- AC1PHMotor_Press
- ACMotor
- CBContact
- CBControlCurrent
- CBTimingAB
- LowPressureAir
- Motion
- Motor_Spring
- PhaseCurrentClose
- PhaseCurrentTrip
- SF6SinglePressure
- SF6TwoPressure
- TripDCAB

The input to an analysis is one or more sensor signals. The signals could either be multi-point, such as current or motion, or could be a single value, such as temperature or pressure. An analysis calculates parameter values, called features, from the signals. Rules are then applied to the features to determine if an alert should be sent. The two analyses, CBContact and CBControlCurrent, are called base analyses because they do not have rules of their own but their features are used by other analyses, such as CBTimingAB.

Each analysis has a detailed specification document that describes the input, features, and rules.

For CB timing, we are only interested in monitoring the three phase currents and trip and close coil currents. That narrows down the Insite analyses that we would be interested in to: PhaseCurrentClose, PhaseCurrentTrip, and CBTimingAB. CBTimingAB requires CBContact and CBControlCurrent. A brief description of these analyses is given below.

CBContact - Processes digital signals to determine transitions times.

CBControlCurrent -- Analyzes trip and close control current waveforms.

CBTimingAC -- Analyzes circuit breaker timing to determine if breaker is working satisfactorily. Input signals are trip or close control currents and 52A, 52B digital signals.

PhaseCurrentClose, PhaseCurrentTrip -- Analyzes the three phase currents to provide information about the condition of a circuit breaker.

Clearly, Doble Insite is able to provide the monitoring required for this project, but it is probably a too general solution and outside of ConEd project constraints.

F
WIRELESS NETWORK ARCHITECTURE

This section briefly outlines the thought process behind selecting the network architecture.

Wireless communication on substations is inherently difficult due to a number of problems and constraints:

- line-of-sight - work-around is to add more devices (wireless network nodes) - creative analysis of the site layout will often lead to cheaper solutions
- interference - work-around is to have error detection/re-transmit, and reduce bandwidth requirements
- total system cost - cheaper means cheapest devices and shorter range wherever possible
- technology availability and environmental specifications - prefer off-the-shelf solutions to bring down total cost
- complexity of installation and configuration - prefer not to require expensive RF surveys for normal installs

Design Considerations

There are two significant but competing architectures available for wireless communication: a single technology wireless network versus a hybrid wireless network (integrating several types of wireless systems).

Consider the first approach: big sensor networks over the whole system with a single wireless technology.

Advantage: purchasing logistics is a little more simple

Disadvantages:

- planning requires some understanding of the wireless issues
- unlikely to be feasible in several situations (e.g., rural, remote sites) if short range devices are selected
- Not cost-effective if cellular is selected for each device

Using this approach we would experience greater difficulty in keeping the cost down due to the larger number of more expensive RF devices needed to mitigate line-of-sight problems.

The point raised above is that a single wireless technology is unlikely to provide the right kinds of solutions to our problem.

Consider the second approach: partition the problem into an interconnected hierarchy of networks as follows:

- for substation areas we use a low-cost add-hoc wireless sensor network
- for communications between nearby substations or between sections - use a longer range wireless network
- for communications between remote substations and control center

The attraction of this approach is that we have lower cost components in the substation that allows us to mitigate the line-of-sight problems while staying within budget. The number of longer-range devices is kept small.

One possible solution: local sensor networks (short range) with a backbone network (for longer ranges) and cellular connections at key point(s) in the backbone if required.

Advantages:

- to reduce need for more higher cost wireless communications equipment,
- improved chance of meeting line-of-sight needs within budget
- improved versatility

Disadvantage:

- purchasing logistics is a little more complex
- planning requires some understanding of the wireless issues

Target:

Substation Operation and Maintenance

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