Design Considerations for a Large-Scale Wireless Sensor Network for Substation Monitoring

Asis Nasipuri,
Robert Cox, and James Conrad
Electrical & Computer Engineering
University of NC at Charlotte
9201 University City Blvd.
Charlotte, NC 28223

Luke Van der Zel
and Bienvenido Rodriguez
Substations Group
EPRI-Transmissions & Substations
9625 Research Drive
Charlotte, NC 28262

Ralph McKosky
Technology Innovation,
Environment & Technology
Tennessee Valley Authority
1101 Market Street, SP-5D-C
Chattanooga, TN 37402

***Abstract*—This paper describes the design and deployment of a large scale wireless sensor network (WSN) for monitoring the health of power equipment in a substation. The sensor network consists of 122 low power nodes that that are spread over an area approximately 1000×400 feet in size and perform monitoring of equipment such as transformers, circuit breakers, and compressors. All nodes communicate over a multihop wireless mesh network that uses a dynamic link-quality based routing protocol. A primary objective of this project is to develop effective monitoring applications for the substation using low-cost wireless sensor nodes that can sustain long periods of battery life. We study the battery consumption in the network and present a transmission scheme that conserves communication cost by enabling the sensor nodes to transmit observation samples only when their values are significantly different from those transmitted previously. Experimental results that demonstrate the performance of the sensor network for several monitoring applications are presented.**

I. Introduction

Power transmission and distribution substations have a number of critical components such as circuit breakers and transformers that must be continuously monitored to reduce the possibility of expensive and disruptive power outages. This is becoming an increasing concern for today's substation managers and engineers due to the aging nature of substation equipment and infrastructure. Currently, such health monitoring is primarily performed using a combination of periodic physical inspections and real-time measurements taken by expensive wired sensors. Because of the growing popularity of low-power wireless sensor networks, utility companies have also begun to investigate the potential benefits of using large-scale wireless sensor networks for these applications. Wireless sensor networks are minimally invasive, easy to deploy, and can provide a cost-effective solution for the early detection of failure conditions.

This paper presents the results of an EPRI funded project on an experimental wireless sensor network for substation monitoring. The University of North Carolina (UNC) at Charlotte was a contractor for the EPRI project. There were multiple utility members in the EPRI project. This paper focusses on results gathered at one of those members, Tennessee Valley Authority (TVA), which involves the development of a wireless sensor network (WSN) at a substation located in Paradise, Kentucky. The experimental WSN, called *ParadiseNet*, was deployed over various phases, and currently consists of 122 wireless sensor nodes that are programmed to measure key physical quantities from several different subsystems in the substation. Data from these nodes is collected by a base station and transmitted via the Internet to a database at Charlotte, North Carolina. The primary objectives of this project are to experimentally verify the viability of using wireless sensors in a substation environment, to implement key applications required for substation monitoring using the low-power wireless sensor nodes, and to determine the design challenges for scaling up the network to cover the entire substation.

Early design issues for this network were presented in [1] and the design of some key components of the network were presented in [2], [3]. This paper focuses on design considerations for scaling up the network to 122 nodes with an ultimate goal of reaching 150 nodes. Emphasis is placed on energy and battery lifetime issues, as well as on new considerations that have been discovered using field data. In particular, we present a novel adaptive sampling scheme for increasing node lifetime. This approach, which is known as *level crossing sampling*, only transmits sensor data when the sensor values change by a predetermined amount. We present a summary of lessons learned from our field observations, with particular emphasis on energy consumption, routing performance, and the benefits of level crossing sampling. Results indicate that overhearing has a significant impact on energy performance, perhaps even more significant than the effect of data forwarding. Additionally, the results indicate that level crossing sampling is beneficial.

II. Related Work

Practical implementations of wireless sensor networks have attracted significant interest in recent years. Various applications have been addressed and reported in the literature, including industrial process monitoring [1], [4], natural-disaster forecasting [5], [6], habitat monitoring [7], [8], [9], structural monitoring [10], [11], and climate and soil monitoring for use in agriculture [12]. These examples demonstrate the viability and cost-effectiveness of wireless sensors networks in comparison to their wired counterparts.

978-1-4244-8389-1/10/$26.00

Fig. 1. View of the Paradise substation, showing the trailer that houses the current base station located at one end of the substation.

Several researchers have described practical experiments in which they considered issues relevant to the deployment of large-scale networks. Such issues include network architecture, coverage, and energy consumption. Reference [13], for instance, describes a network consisting of 557 solar-powered nodes covering some 50,000 square meters. This network featured seven gateways and one server. The primary purpose of this four-month experiment was to evaluate the use of multi-target tracking algorithms in wireless sensor networks. Other documented examples of large networks include the 50-node mobile sensor network *ZebraNet* [9], and the 150-node habitat-monitoring network described in [7].

In addition to network scalability, researchers have examined several other design challenges. Reference [4], for instance, describes the development of a general architecture for use in industrial applications, and it reports on the implementation of this architecture in two different target applications. The first was an oil platform in the North Sea; the other was a semiconductor manufacturing plant. In another industrial deployment, a wireless sensor network was used to monitor the condition of several motors located at a Boeing Company plant [14]. In addition to health monitoring, this work was also intended to estimate energy costs. Design objectives and initial results of our work on substation monitoring at Paradise when the WSN comprised of 45 sensor nodes was presented in [1]. Here, we present the design and performance of the WSN when scaled to 122 nodes.

III. Project Overview

The *ParadiseNet* project began in September 2006 and has been expanded in several phases over the past several years. This section describes the primary technical objectives of the project, as well as the key monitoring applications and the custom hardware platforms developed for each of these applications.

A. Project Objectives

The key technical objectives of *ParadiseNet* were developed by EPRI in collaboration with the utility members and the contractor (UNCC), and are as follows:

- *RF environment/connectivity:* A substation is comprised of many metallic structures scattered over a wide open area (see Fig. 1). The monitoring area extends to approximately 1000×400 feet with the base station located at one end. In such an environment, propagation of low-power RF signals, such as those transmitted from our wireless sensor nodes, is often unpredictable. Hence, one of the primary challenges of this project is to enable connectivity with all of the wireless nodes in the WSN deployed throughout the substation.
- *Application development:* Existing substation monitoring techniques use many sensors and sensing schemes that are not designed for wireless sensor networks. Examples include SF_6 (sulphur hexafluoride) gas density sensors, load monitoring systems, transformer bushing-monitoring systems, etc. Our research has shown that even in cases where the limited computational power of a wireless node would seem at first to be prohibitive, it often is not. Hence, a primary goal of this project is to determine a set of diagnostic and prognostic applications that are particularly beneficial when monitoring substation equipment.
- *Battery life:* While quick deployment and adaptive reconfigurable network formation are the key advantages of WSNs, the main challenge is to design the network to operate for a sufficiently long time without having to replace the batteries. This requirement is particularly important in substation monitoring applications due to the relative inaccessibility of the region due to safety and regulatory reasons. In this project we have explored energy-conservation issues as well as solar-energy harvesting for the wireless nodes deployed in the substation.

B. Monitoring Applications Developed

Since the initiation of the project in September 2006, the following monitoring applications have been developed and tested in *ParadiseNet*:

1) *Circuit breaker monitoring:* Substations and distribution

Fig. 2. Illustrations of wireless sensor nodes deployed in the Paradise substation: (a) surface temperature sensors for oil-filled circuit breakers, (b) temperature, vibration, and sound intensity sensing from oil-cooled transformers, (c) ambient temperature sensors, and (d) a solar-powered SF_6 gas density sensor node.

centers use circuit breakers to switch electric circuits or equipment either into or out of the broader system. These devices are typically filled with either oil or SF_6 gas. In oil-filled circuit breakers (see Fig. 2(a)), the oil provides cooling and prevents arcing when the switch is activated. A typical monitoring task would be to detect an impending fault before it can disable the breaker. We have developed a prognostic method that detects such failures by searching for relative changes in oil temperature. Our method compares the surface temperatures of the oil tanks to look for unexpected differences.

2) *Transformer monitoring:* Transformers in a transmission substation step-up the generator voltage to a much higher level (up to 765 KV) before transmission to utility customers. Such transformers may be dry, oil or fluid-filled. The transformers targeted for this project are of the oil-filled variety (see Fig. 2(b)). In these devices, the core and coil assembly are placed in a tank that is filled with a high-dielectric cooling oil. Although there are no moving parts, oil-filled transformers may fail as the result of the mechanical and thermal stresses induced by the high voltages involved. High-voltage experts believe that heating is a good early indicator of several potential transformer failures; hence, oil-tank temperature is one of the many physical quantities that we measure. In addition, our network also features nodes that monitor vibration and acoustic signals in order to track the health of fans, pumps, and other mechanical components associated with individual transformers[1].

3) *Ambient temperature:* As noted previously, many important substation diagnostic routines are temperature-based. For this reason, it is important to measure the ambient temperature at various relevant locations, as solar intensity and shading greatly affect surface temperatures. In addition, the temperature at the substation location is often below freezing in the winter and above $40°$ C during the summer. To account for this variation, many of the intermediate nodes in the WSN perform the additional task of monitoring ambient temperature.

4) *SF_6 gas density monitoring:* Modern High Voltage circuit breakers are filled with SF_6 gas, which must be checked for leakage. This is traditionally performed by physically sending personnel to the site who perform leakage tests at periodic intervals. A potential approach to automating this is to monitor and trend the gas density and look for small changes. The key challenge the team met in this task was to develop a solar-harvesting node to monitor and transmit the SF6 density signal at periodic intervals. This is a significant achievement as the density sensors draw significant current compared to what can be harvested with a small solar cell - so challenging solutions had to be engineered.

[1]Large transmission transformers often feature a number of ancillary components such as fans for cooling and other purposes.

C. System Description

ParadiseNet was designed using Crossbow's *MICAz* wireless sensor nodes (motes), which are equipped with the Atmel ATmega128L processor running at 8MHz, 2.4 GHz Chipcon CC2420 radio, 128KB program memory, 512KB measurement flash, and 4KB EEPROM [15]. This selection was motivated by a flexible open-source application development platform (TinyOS), availability of a range of supporting hardware such as sensor and data acquisition boards, and software support.

To explore solar power harvesting, we considered two types of solar energy harvesting modules: (a) in some of the surface temperature sensing nodes, we used the *Heliomote* solar harvesting units manufactured by Atla Labs [16], which are weather-resistant cases equipped with a $2.5'' \times 4''$ solar panel and a battery charger; (b) in addition, we developed a more powerful solar power harvesting unit that uses three $2.5'' \times 4''$ monocrystalline solar cells to power one of the three SF_6 gas density nodes.

Rather than invent a new routing protocol, we decided to apply Crossbow's *XMesh* mesh routing protocol [17] to evaluate its performance in such a large-scale deployment and to derive additional design considerations from the results. *XMesh* is a *link quality* based dynamic routing protocol that uses periodic *route_update* messages (RU) from each node for link quality estimation. Each node promiscuously listens to the radio traffic in the neighborhood and selects the parent that would be the least costly in terms of energy to reach the base. A parent must already be a part of the mesh and must have been a descendant node for the last three Route Update Intervals (RUI). Link quality estimation is performed by monitoring the multi-hop headers of received packets and running an exponentially weighted moving average (EWMA) algorithm to smooth out the estimate. Consequently, *XMesh* enables a set of interconnected wireless sensor nodes to form a mesh network rooted at the base, which is dynamically adapted based on link quality measurements.

Unlike the sensor nodes, the base is equipped with a 9.9dBi omnidirectional antenna (mounted on the side of the trailer) to enable better connectivity with the sensor nodes. The laptop computer running the base server is connected to the Internet via the cellular network and uses secure *ftp* to automatically transfer the data from the WSN to a database located at a laboratory in Charlotte. For all applications, we set the RUI as well as the data transmit interval to 15 minutes. In the following, we provide a detailed description of the different types of sensor nodes that were developed for *ParadiseNet*.

1) Surface Temperature Sensing Nodes: The wireless sensor nodes for detecting surface temperatures of circuit breakers and transformer oil tanks were developed using 1000 Ohm platinum resistor temperature detectors (RTDs) and a *MDA320* or *MDA300* data acquisition board. The *MDA* generates a 2.5V excitation voltage and the corresponding voltage drop across the RTD is sensed and converted to a temperature value by the *MDA/MICAz* assembly. This system provides temperature sensing accuracy of $\pm 1°$ in the laboratory; however ineffective physical contacts between the magnets and the surface of the tank is often a cause of error. Hence, we used three RTDs per temperature probe, whose measurements are averaged at the mote to reduce the scope of error. The RTDs are embedded into magnets that are either attached to the base of the node enclosure or attached to it by a cable (Fig. 3). In either case, magnets are used to attach the node enclosure to the surface of the circuit breakers and transformers.

Fig. 3. RTDs attached to magnets at the base of the node enclosure (left) and an external magnetic RTD probe (right).

2) Vibration and Sound Sensing Node: For vibration and sound sensing, we use the 2-axis accelerometer and the microphone on the *MTS310* integrated sensor board. The intensity of vibrations is obtained by measuring the standard deviation of 20 samples from the x-axis accelerometer taken at intervals of 20 ms. This operation is performed at 15-minute intervals, i.e. the data transmission interval of the nodes. Similarly, the sound intensity is obtained by the standard deviation of 20 samples of the microphone signal taken at intervals of 10 ms. For the case of the sound signals, the first 5 seconds of data samples had to be discarded to allow for stabilization of the microphone signal. The mote with the *MTS310* is mounted inside the enclosure with the magnetic base using metallic contacts to convey vibrations and sound effectively. Construction details and performance evaluations of this node can be found in [2].

3) Ambient Temperature Sensing Nodes: Ambient temperature sensing is performed by using the onboard temperature sensor (a surface mount thermistor) of the *MTS300* integrated sensor board. These sensor nodes require minimal engineering due to the manufacturer-provided 51-pin connection interface between the *MTS300* and the *MICAz* mote. The sensor node unit is attached to metallic structures using the same approach as used for the vibration sensing nodes.

4) SF_6 Gas Density Sensing Nodes: Gas density sensors such as the Trafag 8774 [18] apply quartz crystal oscillation measurements to generate highly accurate gas density estimates (within $\pm 1.8\%$ accuracy). The Trafag sensor requires a $10 - 30$ VDC power supply and produces an output current that is proportional to the measured gas density. We developed a *MICAz*-based wireless sensor node that obtains gas density measurements from one of these sensors. The solution, which is depicted in Fig. 4, includes step-up circuitry needed to meet the voltage requirements, a trans-impedance amplifier needed to convert the output current into a voltage, and actuation and sensing code needed to obtain measurements and account for sensor settling time. To conserve energy, the external electronic

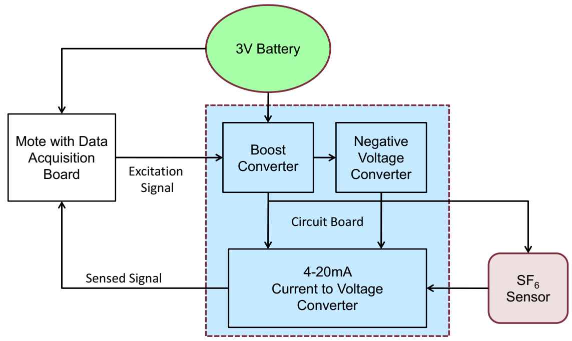
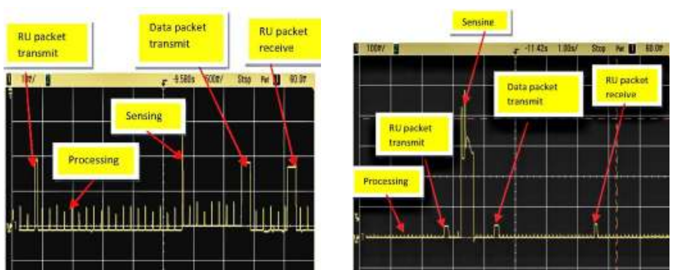


Fig. 4. SF_6 gas density sensor node using *MICAz*.



(a) (b)

Fig. 5. Observed current consumption from from (a) the surface temperature monitoring node, (b) the SF_6 gas density sensing node.

circuits and the sensor are energized for only 0.5s every hour, when samples are obtained.

IV. Energy Consumption and Lifetime Issues

Energy consumption is perhaps the most crucial aspect for designing a successful practical wireless sensor network. Each sensor node has finite electrical energy, which is determined by the capacity of the onboard battery. Solar energy harvesting modules also have limitations in the continuous power they can deliver, due to size and cost constraints, variations of solar irradiance, and constraints imposed by the rechargeable battery. Consequently, all design aspects of wireless sensor nodes must include considerations for energy conservation. In this project, we take advantage of the low power (LP) operation mode of the *XMesh* routing protocol, in which nodes sleep most of the time, waking up eight times a second for short durations to detect activity. If a signal is detected, it keeps its radio on to receive the signal. Since radio transmission and reception are the major energy consuming activities, the average energy consumption mostly depends on the number of packets transmitted and received by the node. An additional cause of energy usage is the sensing and actuation current, which are significant for applications such as vibration sensing and gas density sensing.

A. Energy Model

Due to the large number of parameters that affect the power consumption in the wireless sensor nodes in rather unpredictable ways, we used laboratory experiments to develop models for the average current consumption for all applications. Specifically, experiments were conducted for estimating the current consumption for various events occuring at the motes. Illustrations of the current consumption in a mote during various events of the circuit-breaker monitoring application (using the *MDA300*) and the SF_6 gas density monitoring application (using *MDA320*) are depicted in Fig. 5. For illustration purposes, these plots were obtained using specifically low data and route update intervals. A complete list of events performed by the motes for the different applications developed in this project is shown in Table I.

TABLE I
Measurements of current drawn by a *MICAz* mote under various events

Event	Current (mA)	Duration (ms)
RU transmit/receive (R_t/R_r)	20	140
Data transmit/receive (D_t/D_r)	20	140
Processing (P)	8	3
Sensing (S):		
−Amb. temp.	7.5	112
−Vibration/sound	9.5	7000
−Surface temp (MDA300)	16	25
−Surface temp (MDA320)	16	25
−SF_6 density (MDA3200	150	400

Using the above data, we can represent the average current consumption in a mote as

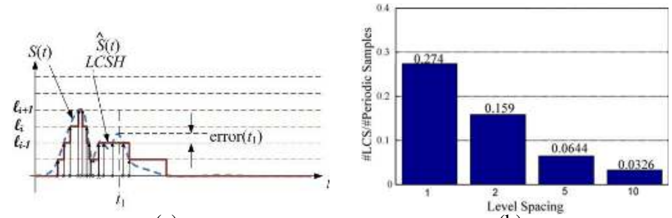
$$I = I_{R_t}T_{R_t}/T_{RUI} + I_{D_t}T_{D_t}/T_D + N(I_{R_r}T_{R_r}/T_{RUI} + I_{D_r}T_{D_r}/T_D) + I_ST_S/T_{D_t} + 8I_PT_P \quad (1)$$

where I_x and T_x represent the current drawn and the duration, respectively, of the event x; N is the number of neighbors of the mote; and T_{RUI} and T_D represent the RUI and data intervals, respectively. We validated this model by comparing the predicted values from Equation 1 with experimental results obtained in a 2-node network in the laboratory. These results are shown in Table II. The experimental results match our predictions closely. Also shown in Table II (last column) are the expected lifetimes of the nodes using a 5000 mAH battery, which is the battery used in the nodes in *ParadiseNet*.

TABLE II
Experimental validation of current drawn and lifetime estimates for various applications for $N = 2$.

Application	T_{RUI} (s)	T_D (s)	Calculated current (mA)	Observed current (mA)	Expected lifetime (months)
Ambient	60	60	0.486	0.495	14.2
temp	7200	900	0.203	0.211	34.1
Vibration/	60	60	1.58	1.59	4.39
sound	7200	900	0.276	0.288	25.2
Surface temp	60	60	0.478	0.481	14.5
(MDA300)	7200	900	0.205	0.219	34.21
Surface temp	60	60	0.97	1.079	7.09
(MDA320)	7200	900	0.70	0.821	9.87
SF_6	60	60	2.107	2.17	3.29
density	7200	900	0.854	0.87	8.13

Although the results in Table II are encouraging, it must be noted that the current consumption in a node increases with N, the number of neighbors. This is due to the overhearing problem, by which nodes waste energy in receiving all packets



(a) (b)

Fig. 6. (a) Illustration of level-crossing sampling, and (b) fraction of data samples transmitted using the LCS scheme in comparison to periodic 15 min sampling from an ambient temperature node in *ParadiseNet*.

that are transmitted in their neighborhood even if they are intended for others. The average current consumption due to overhearing depends on a number of uncontrollable factors such as node density, locations, and wireless transmission characteristics. With $T_{RUI} = 7200$ s (2 hours) and $T_D = 900$ s (15 minutes), the worst case current consumption in a node in a WSN of 150 nodes can be calculated by setting $N = 150$ in Equation 1, which gives a lifetime of 9 months for the vibration sensing nodes and a lifetime of 5 months for the SF_6 density sensing nodes. In the following, we present a mechanism to improve these lifetimes without losing the relevant data features.

B. Energy Conservation using Level-Crossing Sampling

Since *XMesh* requires approximately 8 times the route update interval for route reconfiguration, all nodes in *ParadiseNet* were programmed with $T_{RUI} = 7200s$ to keep the route reconfiguration period below 24 hours. Consequently, the only way to reduce current consumption is to reduce the frequency of data packet transmissions. In the absence of prior knowledge about the characteristics of the sensed signals (such as their bandwidths), it is hard to determine the minimum fixed sampling rates for different monitoring applications theoretically. The data sampling interval of $T_D = 900s$ was specified by the sponsors. Our observations, however, showed that the monitored signals do not typically vary much from one sample to the next. This finding motivated us to use a *level-crossing sampling (LCS)* scheme, where a data sample is only transmitted when it crosses one of a predefined set of levels. LCS is a non-uniform sampling scheme that is particularly efficient for transmitting bursty signals or those that are characterized by long periods of inactivity. It also eliminates the need for selecting a fixed uniform sampling rate, which can be difficult for unknown signals.

The concept of level-crossing sampling (LCS) is illustrated in Fig. 6(a), where a given signal $S(t)$ is sampled (transmitted) when it crosses a set of levels $\{\ell_i\}_{i=1}^{M}$. The error between $S(t)$ and the reconstructed signal using a sample-and-hold principle (termed here as LCSH), as well as the savings in the number of samples, depend on the choice of levels as well as the statistics of the signal. The savings in the number of data packets transmitted using uniform LCS over a periodic sampling scheme is illustrated in Fig. 6(b) for different level spacings. These results were obtained from data from an ambient temperature sensing node in *ParadiseNet*. It is observed that even a 1°C level-spacing provides nearly 75% savings in data transmissions for this application. A detailed discussion on the analysis of LCS may be found in [19].

V. Observations and Experiences from Deployment

The locations of the 122 sensor nodes in *ParadiseNet* are depicted in Fig. 7, where we consider four different zones in the approximately $1000' \times 400'$ deployment area for our performance evaluations. In the following, we provide a summary of our observations on various performance issues studied in this project.

Energy consumption: Of the 122 nodes deployed with their batteries most recently refreshed on 19 December 2009, 94 nodes are still under operation as of May 22, 2010. Table III describes the number of nodes from each application that were in operation on each month since the last time the batteries were replaced. Eight nodes did not operate from the start, which can be attributed to hardware malfunctions. It should be noted that batteries in some nodes were deployed much earlier than those in the rest of the network. Of the SF_6 gas density and surface temperature monitoring nodes, only one is still operational, which is powered by the custom solar power harvesting module.

To determine the actual energy consumption in *ParadiseNet*, we recorded the average drop in the battery voltage for each of the MTS300 and MTS310 nodes that are programmed for periodic transmissions. These nodes run applications that have very similar current consumption; hence their battery usage is a good indicator of their power consumption in the field. Fig. 8 shows the average drop in each zone between January and May 2010. It is observed that on average, nodes farthest from the base station (Zone-A) have experienced the lowest energy consumption while those in Zone-C have the highest. This is basically attributed to the fact that while the number of transmissions is approximately the same in all of these nodes, those closer to the center of the network (Zone-C) and near the base experience higher amount of overhearing traffic. The battery voltage drop of 0.2V in this zone is close to that expected over a period of five months, assuming the worst case calculated lifetime of 9 months.

Routing Performance: To evaluate the performance of the *XMesh* routing protocol, we calculate the average packet delivery ratio from all ambient temperature sensing nodes that use

TABLE III
Number of operational nodes after last battery replacement on December, 2009.

	Number of operational nodes on					
	Dec'09	Jan'10	Feb'10	Mar'10	Apr'10	May'10
Amb temp	29	28	28	28	28	28
Vib/sound	48	45	44	43	42	41
Surf temp	34	31	30	30	30	24
SF_6	3	3	3	3	3	1
Total	114	107	105	104	103	94

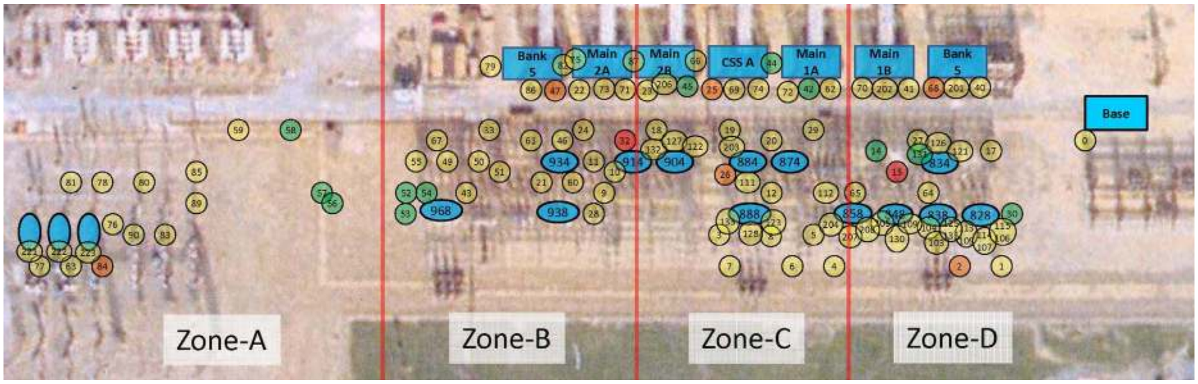


Fig. 7. Locations of nodes deployed in Paradise substation, the blue ovals represent banks of circuit breakers, and the light blue rectangle on the right is the trailer where the base station is located. The red vertical lines are used to depict four different zones in the network.

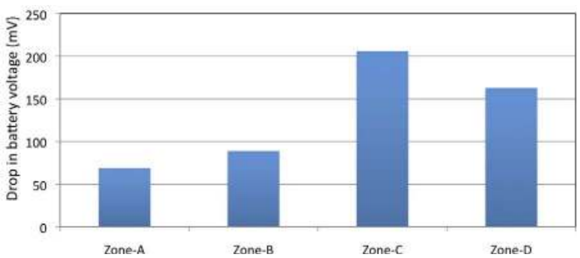


Fig. 8. Average drops of battery voltages across zones over January – May 2010.

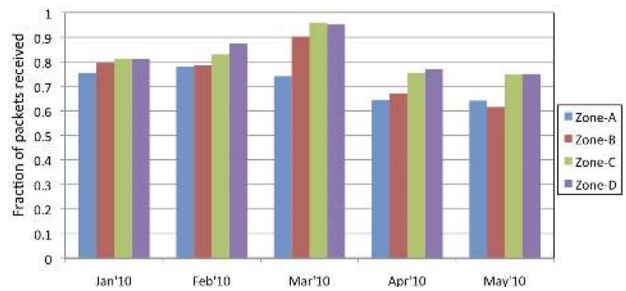


Fig. 9. Packet delivery ratio of periodic ambient temperature sensing nodes.

periodic transmissions. These results, shown in Fig. 9, depict that although the delivery ratio dropped slightly over time, on an average about 75% of the transmissions are successful in the network. As expected, the packet delivery ratio drops with distance from the base station. However, even nodes from the farthest end of the network (Zone-A) that require 4 or more hops to transmit data packets to the base, successfully delivered over 60% of their transmitted packets.

However, it was noted that *XMesh* created a high degree of load imbalance. Specifically, two nodes (15 and 32) carried a majority of the forwarded traffic, being included in the routes of > 20 nodes; six nodes were involved in forwarding the traffic of $10 - 20$ nodes; and a large majority of the nodes were included in the routes of only $0 - 5$ nodes. These nodes are marked in red, orange, and green, respectively, in Fig. 7. An interesting observation was that the load imbalance did not create a noticeable impact on energy drainage. For instance, the voltage drops in nodes 15 and 32 were not higher than in its neighbors. This is possibly due to the fact that the dominating cause for energy usage is overhearing and not data forwarding. Hence, in dense networks such as *ParadiseNet*, load imbalance is not a serious problem. In many cases, however, it may cause early death for the nodes that carry heavy forwarding traffic, leading to network partitioning and other undesired effects.

LCS performance: A fraction of the nodes for each application were programmed with the proposed LCS scheme. A comparison of sensor samples obtained from an LCS node (node 27) and a node with periodic sampling from the same location is depicted in Fig. 10(a). Both nodes sense ambient temperature, a quantity with temporal variations that tend to be gradual. The LCS samples show the effectiveness of capturing the temperature variations using the proposed non-

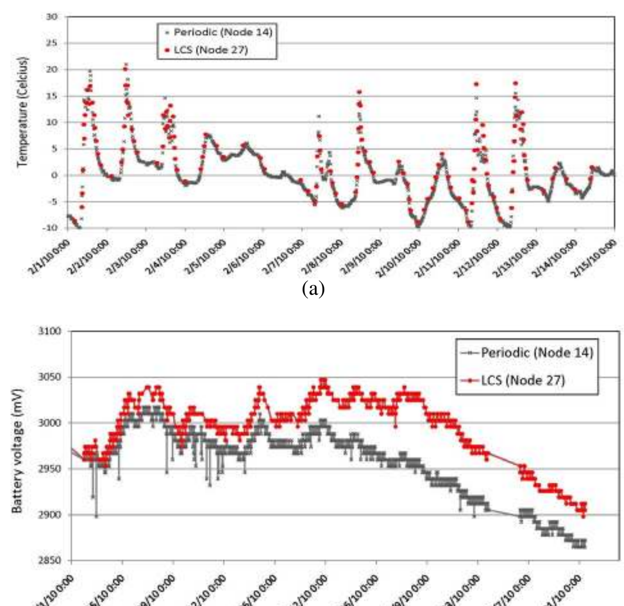


Fig. 10. (a) Ambient temperatures obtained from a periodic and an LCS node, and (b) the variation of the their battery voltage over time.

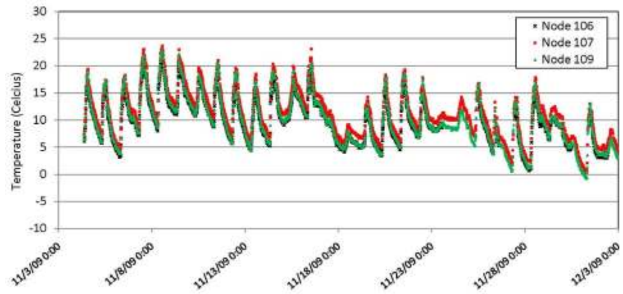


Fig. 11. Surface temperatures obtained from three oil-filled circuit breakers.

uniform strategy. The corresponding battery voltages shown in Fig. 10(b) demonstrate that that the LCS node uses less energy than a comparable periodic node performing the same task over the same period of operation. Furthermore, the average drop of the battery voltages of 30 LCS nodes performing ambient temperature sensing was found to be 31 mV over the past five months, compared to 117 mV for those nodes using periodic sampling. This proves the effectiveness of the proposed LCS scheme.

Monitoring performance: All applications worked as expected and no specific monitoring alarms were obtained during the operation period of *ParadiseNet*. An example of circuit breaker monitoring is depicted in Fig. 11, which shows the oil temperatures sensed from the surfaces of three oil-filled circuit breaker in Paradise. The figure indicates that one of the temperatures is higher than the other two and increasing over time. This is an indication of a possible problem, which raised an alarm. However, upon inspection the alarm was ruled out and attributed to a sensor malfunction.

VI. Conclusions and Future Work

Practical implementation reveals many realistic performance issues that are often not possible to realize from laboratory and theoretical analysis. This experimental study of a large-scale WSN provided important leads towards achieving energy efficiency in such networks. Several steps can be taken to further improve the battery life of the sensor nodes in such a large-scale deployment. Firstly, the energy consumed in overhearing must be reduced. Although much work has been done on this, practical implementations of mechanisms to reduce overhearing would be worthwhile. A power control mechanism can be largely useful. Other schemes such as automatic formation of subgroups with multiple orthogonal channels can also be used. Secondly, periodic route updates are wasteful in a static large-scale WSN. A mechanism that adaptively turns off route updates when transmissions are successful could be beneficial.

Acknowledgment

The following graduate students from UNC Charlotte worked on this project: Siddharth Kamath, Jason Anderson, Priya Puthran, Priyanka Lingayat, Rohit Kale, and Hadi Alasti. The authors like to thank Mark Goff from TVA Transmission Operation and Maintenance for substation field support. This work was sponsored by the Electric Power Research Institute (EPRI).

References

[1] A. Nasipuri, R. Cox, H. Alasti, L. Van der Zel, B. Rodriguez, R. McKosky, and J. A. Graziano, "Wireless sensor network for substation monitoring: Design and deployment," in *SenSys'08: 6th Intl. Conf. on Embedded Networked Sensor Systems*, Nov. 2008, pp. 365–366.

[2] A. Nasipuri, H. Alasti, P. Puthran, R. Cox, J. Conrad, L. V. der Zel, B. Rodriguez, R. McKosky, and J. Graziano, "Vibration sensing for equipments health monitoring in power substations using wireless sensors," in *Proc. IEEE Southeast Conference (SoutheastCon)*, March 2010, pp. 268–271.

[3] R. Kale, N. Singh, H. Alasti, A. Nasipuri, R. Cox, J. Conrad, L. V. der Zel, B. Rodriguez, R. McKosky, and J. Graziano, "Design and implementation of a wireless node for advanced sensor processing and network integration," in *Proc. IEEE Southeast Conference (SoutheastCon)*, March 2010, pp. 393–392.

[4] L. Krishnamurthy, R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, N. Kushalnagar, L. Nachman, and M. Yarvis, "Design and deployment of industrial sensor networks: experiences from a semiconductor plant and the north sea," in *SenSys'05: Proc. 3nd Intl. Conf. on Embedded Networked Sensor Systems*, Nov. 2005, pp. 64–75.

[5] G. Werner-Allen, P. Swieskowski, and M. Welsh, "Real-time volcanic earthquake localization," in *SenSys '06: Proc. 4nd Intl. Conf. on Embedded Networked Sensor Systems*, Oct. 2006, pp. 357–358.

[6] G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, and M. Welsh, "Fidelity and yield in a volcano monitoring sensor network," in *OSDI '06: Proc. 7th symposium on Operating systems design and implementation*, Nov. 2006, pp. 381–396.

[7] A. Cerpa, J. Elson, M. Hamilton, J. Zhao, D. Estrin, and L. Girod, "Habitat monitoring: Application driver for wireless communications technology," in *ACM SIGCOMM'01 workshop on data communication in Latin America and the Caribbean*, Sept. 2001, pp. 20–41.

[8] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, "An analysis of a large scale habitat monitoring application," in *SenSys'04: Proc. 2nd Intl. Conf. on Embedded Networked Sensor Systems*, December 2004, pp. 214–226.

[9] P. Zhang, C. M. Sadler, S. A. Lyon, and M. Martonosi, "Hardware design experiences in ZebraNet," in *SenSys'04: Proc. 2nd Intl. Conf. on Embedded Networked Sensor Systems*, Dec. 2004, pp. 227–238.

[10] K. Chintalapudi, J. Paek, O. Gnawali, T. S. Fu, K. Dantu, J. Caffrey, R. Govindan, E. Johnson, and S. Masri, "Structural damage detection and localization using netshm," in *IPSN '06: Proc. 5th Intl. Conf. on Information processing in sensor networks*, April 2006, pp. 475–482.

[11] S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, and M. Turon, "Wireless sensor networks for structural health monitoring," in *SenSys '06: Proc. 4th Intl. Conf. on Embedded networked sensor systems*, Oct. 2006, pp. 427–428.

[12] P. Sikka, P. Corke, P. Valencia, C. Crossman, D. Swain, and G. Bishop-Hurley, "Wireless adhoc sensor and actuator networks on the farm," in *IPSN '06: Proc. 5th Intl. Conf. on Information processing in sensor networks*, April 2006, pp. 492–499.

[13] P. Dutta, J. Hui, J. Jeong, S. Kim, C. Sharp, J. Taneja, G. Tolle, K. Whitehouse, and D. Culler, "Trio: enabling sustainable and scalable outdoor wireless sensor network deployments," in *IPSN '06: Proc. Intl. Conf. on Information processing in sensor networks*, April 2006, pp. 407–415.

[14] J. W. Fonda, M. J. Zawodniok, S. Jagannathan, A. Salour, and D. M. Jr., "Missouri S&T mote-based demonstration of energy monitoring solution for network enabled manufacturing using wireless sensor networks," in *IPSN '08: Proc.7th Intl. Conf. on Information processing in sensor networks*, April 2008, pp. 559–560.

[15] `http://www.xbow.com`.

[16] A. I. website, `http://www.atlalabs.com/`.

[17] C. Technology, "Xmesh user's manual," `http://www.xbow.com/Support/wUserManuals.aspx`, 2007.

[18] http://www.granzow.com/gasdensitycontrols/8774/.

[19] H. Alasti, "Applications of level crossing techniques for energy conservation in large scale wireless sensor networks," Ph.D. dissertation, ECE, The University of North Carolina at Charlotte, 2009.