OPPORTUNITIES AND CHALLENGES OF WIRELESS SENSOR NETWORKS IN SMART GRID

[1*] **Mr. Sarada Prasad sahoo**, [2] **Mr.NARESH KANUNGO**
[1*] *Asst. Professor, Dept. Of Electrical Engineering, NIT BBSR,*
Asst. Professor DEPT. of Electrical Engineering, NIT BBSR,
[1*], sarada@thenalanda.com, , nareshkanungo@thenalanda.com

Abstract— **Wireless sensor networks (WSNs), which are cooperative and less expensive than traditional communication methods employed in today's electric power systems, provide a number of advantages. WSNs are now widely acknowledged as a promising technology that can improve a number of current electric power systems, including generation, delivery, and usage. As a result, they are now an essential part of the smart grid, the next-generation electric power system. Unfortunately, the reliability of WSN communications in smart-grid applications is severely hampered by the harsh and complicated surroundings of electric power systems. This study begins by providing an overview of the use of WSNs for electric power systems, along with opportunities and obstacles, and it then paves the way for future work in a number of understudied research topics in numerous smart-grid applications. A thorough experimental research on the statistical characterization of the wireless channel in several electric-power-system contexts, such as a 500-kV substation, an industrial power control room, and an underground network transformer vault, is then presented. The background noise, channel characteristics, and attenuation in the 2.4-GHz frequency band have been measured in real-world power delivery and distribution systems using field experiments on IEEE 802.15.4-compliant wireless sensor nodes. Overall, the empirical measurements and experimental findings help to inform design choices and trade-offs for WSN-based smart-grid applications and offer useful insights on IEEE 802.15.4-compliant sensor network platforms.**

Index Terms—**CC2420, diagnostics, IEEE 802.15.4, link-quality indicator (LQI), monitoring, received signal strength indicator (RSSI), smart grid, wireless sensor networks (WSNs).**

I. INTRODUCTION

THE global climate change and rapidly growing popula-tions over the past decades have generated increasing demands for abundant, sustainable, and clean electric energy on a global basis. However, in most countries today, the increasing energy demand means an even heavier burden on the already overstressed, overaged, and fragile electricity infrastructure. In the U.S., for example, the average age of power-grid transmis-sion lines is beyond 50–60 years [29]. Over the last 20 years, the electricity demand and consumption have increased contin-uously by 2.5% annually according to a U.S. Department of Energy report [8]. The increasing electricity demand, together with the complex and nonlinear nature of the electric power distribution network, have caused serious network congestion issues. The network congestion and safety-related factors have become the main causes of several major blackouts that hap-pened in recent years. In addition to the overstressed situation, the existing power grid also suffers from the lack of perva- sive and effective communications, monitoring, fault diagnos-tics, and automation, which further increase the possibility of region-wide system breakdown due to the cascading effect initiated by a single fault. Furthermore, the global increasing adaptation of renewable and alternative energy sources in the 21st century also introduced new issues, such as power-grid integration, system stability, and

energy storage, which also need to be addressed as additional challenges.

To address these challenges, a new concept of next- generation electric power system, a *smart grid*, has emerged. The smart grid is a modern electric power-grid infrastructure for improved efficiency, reliability, and safety, with smooth integra- tion of renewable and alternative energy sources, through au- tomated control and modern communication technologies [2], [5]. In the smart grid, reliable and online information becomes the key factor for reliable delivery of power from the generation units to the end users. The impact of equipment failures, capac-ity limitations, and natural accidents and catastrophes, which cause power disturbances and outages, can be largely avoided by online power system condition monitoring, diagnostics, and protection. In this respect, the intelligent and low-cost moni- toring and control enabled by online sensing technologies have become essential to maintain safety, reliability, efficiency, and uptime of the smart grid [11], [13], [19], [30].

Traditional electric-power-system monitoring and diagnostic systems are typically realized through wired communications. However, the wired monitoring systems require expensive com-munication cables to be installed and regularly maintained, and thus, they are not widely implemented today because of their high cost [7]. Hence, there is an urgent need for cost-effective wireless monitoring and diagnostic systems that improve system reliability and efficiency by optimizing the management of electric power systems [11], [13].

As one of the main objectives, this paper gives a first glimpse and opens up future work in many unexploited research areas of applying wireless sensor networks (WSNs) in smart grid by providing an overview of the opportunities and challenges. The collaborative operation of WSNs brings significant advantages over traditional communication technologies, including rapid deployment, low cost, flexibility, and aggregated intelligence via parallel processing. The recent advances of WSNs have

made it feasible to realize low-cost embedded electric utility monitoring and diagnostic systems [1], [4], [9], [11], [19], [30]. In these systems, wireless multifunctional sensor nodes are installed on the critical equipment of the smart grid and monitor the parameters critical to each equipment's condition. Such information enables the smart-grid system to respond to the changing conditions in a more proactively and timely manner. In this regard, WSNs play a vital role in creating a highly reliable and self-healing smart electric power grid that rapidly responds to online events with appropriate actions. The existing and potential applications of WSNs on smart grid span a wide range, including wireless automatic meter reading (WAMR), remote system monitoring, equipment fault diagnos- tics, etc. However, the realization of these currently designed and envisioned applications directly depends on efficient and reliable communication capabilities of the deployed WSNs [11], [13]. However, harsh and complex electric-power-system environments pose great challenges in the reliability of WSN communications in smart-grid applications.

Research activities related to the reliability of WSNs, such as wireless channel modeling and link-quality characterization, in harsh environments are extremely important when designing and deploying a reliable WSN in the smart grid. These channel models provide power system designers the ability to predict the performance of the communication network for a specific propagation environment, channel modulation, and frequency band. Although there exist radio propagation measurements in urban areas, office buildings, and factories [22], [28], [33], link- quality characterization in power generation, distribution, and industrial facility environments are yet to be efficiently studied and addressed.

To address this need, this paper presents a comprehensive experimental study on the statistical characterization of the wireless channel in different electric-power-system environ- ments. Field tests have been performed on IEEE 802.15.4- compliant wireless sensor nodes (using CC2420 radio chips) in real-world power delivery and distribution systems, including a 500-kV substation, an industrial power control room, and an un- derground network transformer vault, to measure background noise, channel characteristics, and attenuation in the 2.4-GHz frequency band. Various communication links, including both line-of-sight (LOS) and non-LOS (NLOS) scenarios, are also considered.

The remainder of this paper is organized as follows. In Sections II and III, the opportunities and challenges of applying WSNs in smart grid are reviewed, respectively. In Section IV, an overview of the related work on wireless link-quality mea- surements in WSNs is presented. The channel measurements and the field experiments are presented in Section V. Finally, this paper is concluded in Section VI.

II. OPPORTUNITIES TO APPLY WSNs IN SMART GRID

Electric power systems contain three major subsystems, power generation, power delivery, and power utilization. Re- cently, WSNs have been widely recognized as a promising technology that can enhance all these three subsystems, making WSNs a vital component of the next-generation electric power

system, the *smart grid*. In this section, an overview of a few potential opportunities of applying WSNs in smart grid is dis- cussed. Note that, depending on the application requirements, other wireless technologies, such as Wi-Fi and WiMAX, and power line communications can also be utilized in some of the smart-grid applications, such as in long-range backhaul communications in advanced metering applications.

A. WAMR

Recently, WSNs have provided a low-cost solution that enables WAMR systems for electric utilities. Overall, WAMR systems offer several advantages to electric utilities, including reduced electric utility operational costs by eliminating the need for human readers and online pricing models based on the online energy consumption of the customers [20] and for asset protection through advanced remote monitoring [11], [23]. However, WAMR systems require reliable two-way communi- cations between electric utilities and the customer's metering devices. WSN technology addresses this requirement efficiently by providing low-cost and low-power wireless communica- tions. Most utility and billing companies have recognized that, with the invention of low-cost low-power radio sensors, wire- less communication is one of the most cost-efficient way to collect utility meter data.

B. Remote System Monitoring and Equipment Fault Diagnostics

In electric power systems today, safety and reliability have become the most critical tasks among all other tasks. System breakdown caused by component faults, environmental factors, or misoperation could cause huge economical losses and public concerns. For example, the August 2003 blackout that happened in U.S. and Canada left over 50 million people out of electricity and caused between 7 and 10 billion U.S. dollars of economical losses to the national economy for U.S and Canada [17]. Moving down to the facilities, the average unscheduled system downtime caused

by unexpected equipment failures in various industries range from 70 000 to 200 000 U.S. dollars per hour [10]. It is commonly known that many of these power-grid and facility breakdowns could be avoided or at least largely allevi- ated if the critical system components are better monitored and the protection devices are better coordinated. However, the fact is that most of today's electric power infrastructure has only the minimal level of monitoring and automation and the majority of industries' critical equipment, such as motors less than 200 hp, are not even monitored. One of the main reasons of such dilemma is that the existing remote sensing, monitoring, and fault diagnostic solutions are still too expensive to be applied in a large-scale and pervasive basis.

With its low cost as one of the main advantages, WSNs provide a feasible and cost-effective sensing and communi- cation solution for remote system monitoring and diagnosis systems. Efficient monitoring systems constructed by large- scale deployment of smart sensor nodes can provide complete information on the conditions of system components, including generation units, transformers, transmission lines, motors, etc., in a remote and online manner [11], [12], [18], [24], [27]. With the online system monitoring and system-level coordinating controls and protections, a single system contingency in the power grid or facility could be detected and isolated before it causes cascading effects and results to more catastrophic system breakdowns.

III. CHALLENGES TO APPLY WSNs IN SMART GRID

The major technical challenges of WSNs in smart-grid appli-cations can be outlined as follows.

1) *Harsh environmental conditions.* In electric-power- system environments, the topology and wireless con- nectivity of the network may vary due to link failures. Furthermore, sensors may also be subject to RF inter- ference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other condi- tions that challenge performance [7], [13]. These harsh environmental conditions and dynamic network topolo- gies may cause a portion of sensor nodes to malfunction or render the information they gather obsolete [11].

2) *Reliability and latency requirements.* The wide variety of applications envisaged on WSNs for smart grid will have different quality-of-service (QoS) requirements and specifications in terms of reliability, latency, network throughput, etc. In addition, since sensor data are typi- cally time sensitive, e.g., accidents in the electric power systems, it is important to receive the data at the controller node in a timely manner [11].

3) *Packet errors and variable link capacity.* In WSNs, the bandwidth of each wireless link depends on the interference level perceived at the receiver, and high bit error rates (BER $=10^{-2}$ 10^{-6}) are observed in communication. In addition, wireless links exhibit widely varying characteristics over time and space due to obstructions and noisy environment in electric power systems. Hence, the bandwidth and communication latency at each wireless link are location dependent and can vary continuously. This makes it very hard to meet QoS requirements [11].

4) *Resource constraints.* The design and implementation of WSNs are constrained by three types of resources:
   a) energy; b) memory; and c) processing. In general, sensor nodes have limited battery energy supply [11]. For this reason, communication protocols for WSNs are mainly tailored to provide high energy efficiency.

Overall, in WSN-based smart-grid applications, a good link- quality metric is essential to a

reliable and energy-efficient system operation. However, in harsh electric-power-system environments, rapid variations in the wireless channel preclude an efficient mechanism for knowing instantaneous link quality at the time of transmission, thus making it difficult to estimate the instantaneous value of the wireless link quality. In this paper, the focus of the field tests is on how to characterize wireless link quality in different electric power system environments based on a few radio-hardware measurements.

IV.   RELATED WORK ON WIRELESS LINK
                     ASSESSMENTS IN WSNs

There have been numerous experimental studies on WSNs [25], [26], [31]–[33]. These studies have been performed either outdoors in open fields of different terrains or indoors in office settings and factory environments. In addition, the problem of coexistence between IEEE 802.11b and IEEE 802.15.4 networks has received a significant interest from the research community [3]. Different sensor platforms have been adopted, and each of them has had their respective radio protocols, fre- quency bands, channel modulation, and power levels. Despite their differences, their observations have mostly agreed on the following three aspects.

First, these studies have revealed the existence of three distinct reception regions in a wireless link: connected, tran- sitional, and disconnected [31], [33]. The transitional region is often quite significant in size and is generally characterized by high variance in packet reception rates (PRRs).

Second, wireless link quality varies over space and time, deviating to a large extent from the idealized unit disk graph models used in network simulation tools [26], [33]. Based on these empirical studies and measurements, it is also found that the coverage area of sensor radios is neither circular nor convex, and packet losses due to fading and obstacles are common at a wide range of distances and keep varying over time.

Third, link asymmetry and radio irregularity were observed in several studies [25], [31]–[33]. Link asymmetry occurs when a node can successfully send packets to another node but not vice versa, even if both nodes are set to the same transmit power. In [32], the authors observed a significant percentage of radio links suffering asymmetry when the communication distance is large or the transmit power is low, which was confirmed by other researchers [25], [31], [33].

Although all these studies provide a valuable and solid foundation in WSNs, none of them addresses a statistical char- acterization of the wireless channel and link quality in indoor, outdoor, and underground electric-power-system environments [5], [26]. Consequently, the advances in sensor radio hardware as well as spatiotemporal link-quality variations in electric power systems call for new empirical measurements and analy- sis on IEEE 802.15.4-compliant sensor platforms deployed in different electric-power-system environments.

V.   LINK-QUALITY MEASUREMENTS AND
                       EXPERIMENTAL SETUP

In this paper, we first focused on how to characterize and measure link quality in WSNs. We conducted experiments with Tmote Sky sensor nodes to obtain insights to answer this question. Tmote Sky nodes use the CC2420 radio com- ponent and support IEEE 802.15.4 [15]. Specifically, Tmote Sky motes operate in the 2.4-GHz industrial, scientific, and medical band with an effective data rate of 250 kb/s. The higher data rate allows shorter active periods, further reducing energy consumption. Tmote Sky motes also integrate programming, computation, communication, and sensing onto a single device [21]. The integrated design provides an easy-to-

use sensor mote

Fig. 1. Experimental sites. (a) Outdoor 500-kV substation environment, (b) indoor main power room, and (c) underground network transformer vault environments.

TABLE I
MEAN POWER LOSS AND SHADOWING DEVIATION IN ELECTRIC POWER ENVIRONMENTS

Propagation Environment	Path Loss (n)	Shadowing Deviation (σ)
500 kv Substation (LOS)	2.42	3.12
500 kv Substation (NLOS)	3.51	2.95
Underground Transformer Vault (LOS)	1.45	2.45
Underground Transformer Vault (NLOS)	3.15	3.19
Main Power Room (LOS)	1.64	3.29
Main Power Room (NLOS)	2.38	2.25

with increased robustness, which is crucial for electric sys-tem automation applications. In our measurements, the packet length and buffer size are selected as 30 B and 64 packets, respectively.

Specifically, field tests have been performed to measure background noise, wireless channel characteristics, and atten- uation in an indoor power control room, a 500-kV substation, and an underground network transformer vault. In Fig. 1, we present our experimental sites [20]. In these field tests, various communication links, including both line-of-sight (LOS) and non-LOS (NLOS) scenarios, are also considered.

A. Wireless Channel Model

In this paper, we modeled the wireless channel using a log-normal shadowing path-loss model through a combination of analytical and empirical methods. This model is used for large and small coverage systems, and moreover, experimental studies have shown that it provides more accurate multipath channel models than Nakagami and Rayleigh models for indoor wireless environments with obstructions [33]. In this model, the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by

measured data in electric-power-system environments, using linear regression such that the difference between the measured and estimated path losses is minimized in a mean square error sense over a wide range of measurement locations and transmitter–receiver separations. These experiments were con- ducted over a period of several days for various locations and network

configurations, including LOS and NLOS scenarios.

B. *Noise and Interference Measurements*

In this section, we first investigate the impact of background noise on the overall performance of 802.15.4 sensor networks in different electric-power-system environments. Then, we show the effect of electronic appliances on 802.15.4 sensor networks. To measure background noise, we wrote a TinyOS applica- tion that samples RF energy at 62.5 Hz by reading the received signal strength indicator (RSSI) register of the CC2420 radio. The register contains the average RSSI over the past eight sym-bol periods. We sampled noise on different radio channels in a wide range of environments, including an indoor power con-trol room, a 500-kV substation, and an underground network transformer vault. Fig. 2 shows our noise measurements and the effect of an electric appliance (microwave oven) on an 802.15.4 network. From the field measurements, the average noise level

$$
\gamma(d)_{dB} = P_t - P L(d_0) - 10\eta \log_{10}\frac{d}{d_0} - X_\sigma - P_n \tag{1}
$$

is found to be around 90 dBm, which is significantly higher than that of outdoor environments, i.e., 105-dBm background noise is found in outdoor environments. We also observe that where P_t is the transmit power in dBm, $P L(d_0)$ is the path loss at a reference distance d_0, η is the path-loss exponent, X_σ is a zero mean Gaussian random variable with standard deviation σ, and P_n is the noise power in dBm.

In Table I, we present the radio propagation parameters for different electric-power-system environments. Note that, in Table I, the values of n and σ were calculated from the background noise continuously changes over time, which can be caused by temperature changes and interference levels. In Fig. 2(d), we also show the effect of microwave-oven interfer-ence on the noise floor measured by the Tmote Sky module [20]. As shown in Fig. 2, the interference from an existing microwave oven leads to a 15-dBm interference in the 2.4-GHz frequency band.
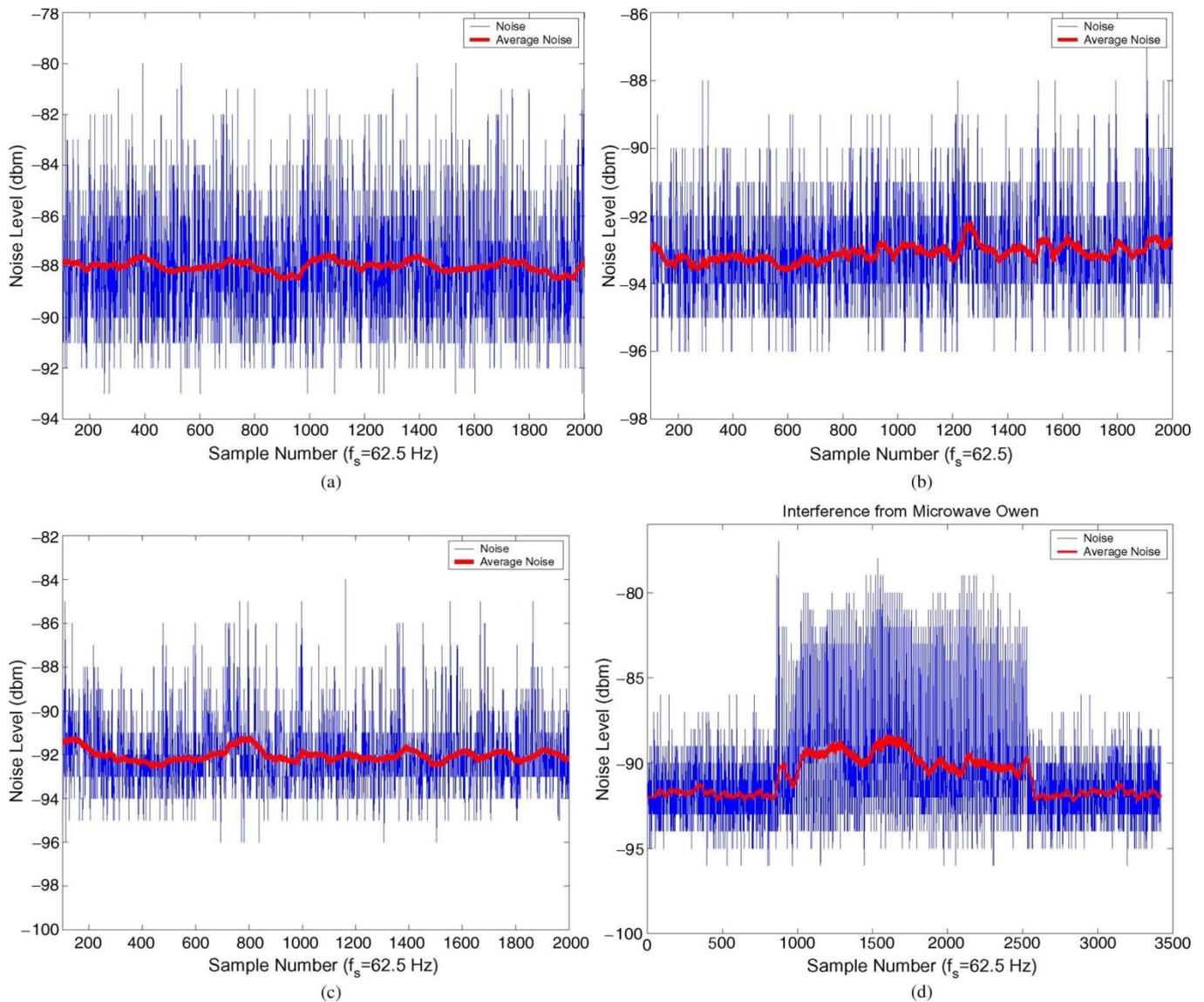
Fig. 2. Background noise measurements in (a) an indoor power control room, (b) a 500-kV substation, (c) an underground transformer vault, and (d) an indoor room, when a microwave oven is on.

To decrease the effect of noise and interference problems in the 2.4-GHz frequency band, Tmote Sky nodes use the direct sequence spread spectrum (DSSS) encoding scheme. To eval- uate the DSSS's strength in real situations, we also measured the PRR when a pair of Tmote Sky motes are deployed close to a microwave oven operating in 2.4 GHz. The performance measurements show that the PRR varies from 35% to 100%, when the microwave oven is turned on and off, respectively.

This experimental observation reveals that DSSS addresses the crowded spectrum issue in some degree, but is still far from enough. Here, it is important to note that some of the 802.15.4

frequencies overlap with 802.11b frequencies, increasing the effects of external interference on link quality [3], [14]. In our performance measurements, we observe that only channel 26 in the 802.15.4 spectrum is not affected by 802.11b interfer- ence. Thus, to minimize 802.11b interference in electric util- ity automation applications, e.g., WAMR systems, the default 802.15.4 channel can be set to 26. However, it is important

to note that multichannel radios are often optimized for the center channel; therefore, selecting by default a channel at one extreme may significantly lower the radio performance. Hence, the utilities need to conduct large-scale field tests to decide the optimal channel for 802.15.4 sensor networks.
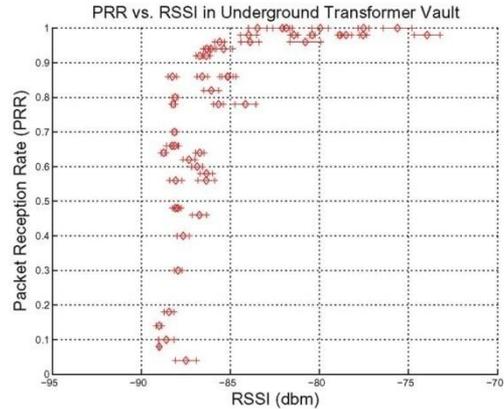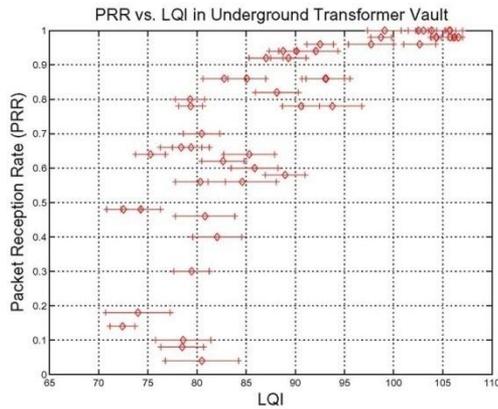
C. Link-Quality Measurements

In this section, we focused on how to characterize and mea-sure link quality in sensor networks deployed in electric-power- system environments. We have conducted experiments with Tmote Sky nodes. In our experiments, to measure the radio link quality, two useful radio-hardware link-quality metrics were used: LQI and RSSI. Specifically, RSSI is the estimate of the signal power and is calculated over eight symbol periods, while LQI can be viewed as chip error rate and is calculated over eight symbols following the start frame delimiter. LQI values are usually between 110 and 50 and correspond to maximum
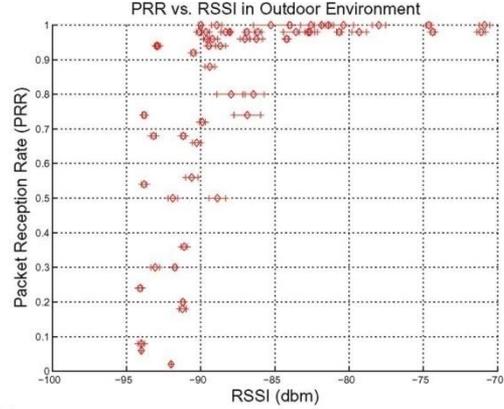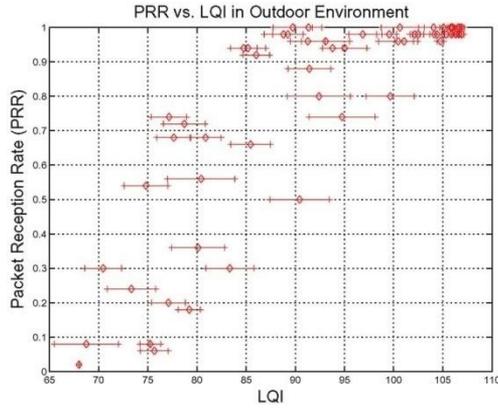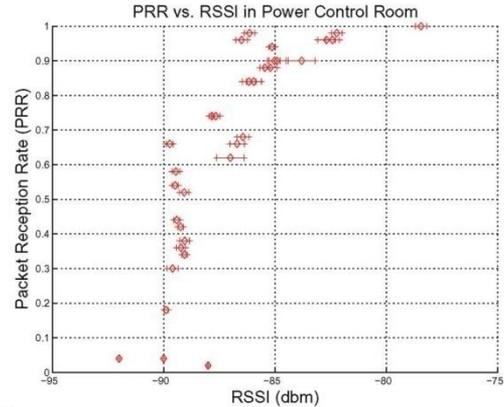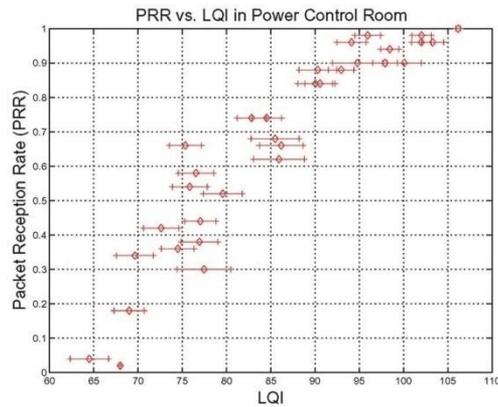
(a)
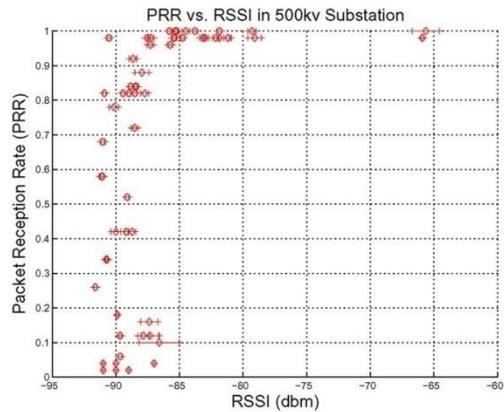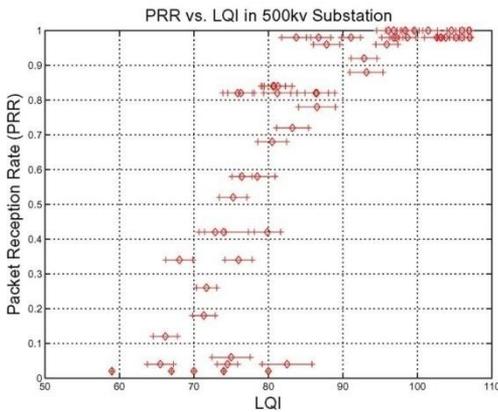
(b)

(c)

(d)

Fig. 3. PRR versus LQI and PRR versus RSSI measurements in (a) an outdoor environment, (b) a 500-kV substation, (c) an underground transformer vault, and (d) an indoor power control room.

and minimum quality frames, respectively. The details of LQI metric can be found in the IEEE 802.15.4 standard [15].

In our experiments, we use a pair of Tmote Sky nodes in different utility environments and outdoor environment, one as the sender and the other as the receiver. We vary the distance from the receiver to the sender from 1 to 20 m, in steps of 1 m. The output power level of each sensor node and the packet size were set to be 25 dBm and 30 B, respectively. At each distance, the transmitter sends 200 data packets with a rate of 2 packets/s. We deliberately chose a low rate to avoid any potential interference, so that the effect of unreliable links can be isolated from that of congestion. In addition, various NLOS communication links are also considered.

In Fig. 3, we present our preliminary experiment results to elaborate the relationship between PRR and link-quality metrics. Here, PRR represents the ratio of the number of suc- cessful packets to the total number of packets transmitted over a certain number of transmissions. Specifically, Fig. 3 shows 95% confidence intervals. In this figure, we observe a strong correlation between the average LQI values and PRRs at the receiver. Statistical analysis shows that the Pearson correlation coefficient is around 0.70 between these two variables for the indoor main power room. This correlation implies that average LQI is a good measurable indicator of the packet reception probability. This observation is also consistent with the results in the related literature [20].

In Fig. 3, we also observe that there is a much smaller correlation between RSSI and the packet reception probability. The Pearson correlation coefficient is only 0.50 between the packet reception probability and the RSSI value. Furthermore, it is found that when the signal is weak [particularly when it is around the sensitivity threshold of CC2420(94 dBm)], even though there is a considerable variation in the packet loss rate, RSSI does not provide any correlated behavior with PRR. Here, it is also important to note that all these measurements should be used as a reference. The exact values for a particular site are likely to vary depending on the actual environment propagation characteristics, RF interference, etc.

VI. CONCLUSION

In this paper, a statistical characterization of the wireless channel in different electric-power-system environments has been presented. Field tests have been performed on IEEE 802.15.4-compliant sensor nodes (using CC2420 radio chips) in a 500-kV substation, a main power control room, as well as an underground network transformer vault to measure background noise, channel characteristics, and attenuation in the 2.4-GHz frequency band. Various communication links, including both LOS and NLOS scenarios, are also considered. In summary, the following major contributions have been made in this paper.

1) The potential applications of WSNs in smart grid are summarized. The WSN design and deployment chal- lenges on wireless communication reliability are identi- fied and experimentally studied.

2) The spatiotemporal impacts of electric-power-system en- vironments on low-power wireless communications have been revealed. The relationship between the dynamics of

link-quality and radio-hardware measurements has been identified based on extensive sets of link-quality measure- ments on IEEE 802.15.4-compliant sensor nodes (using CC2420 radio

chips).

3) The empirical measurements in the field have demon- strated that average LQI values provided by WSN radio components are closely correlated with PRR and can be used as a reliable metric for wireless link-quality assessment during the operation of WSNs.

4) The wireless channel in different electric-power-system environments has been modeled using a log-normal shadowing path-loss model through a combination of analytical and empirical methods. Upon request, the complete experimental data will be made available. These can help the research community develop real- istic link-quality models of WSNs for simulation-based studies.

Overall, the empirical measurements and experimental re- sults in this paper provide valuable insights about IEEE 802.15.4-compliant sensor network platforms and guide design decisions and tradeoffs for WSN-based smart-grid applications. Future work includes developing adaptive and cross-layer com- munication protocols for smart grid applications.

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