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Research Article

Wireless Sensor Networks for Smart Grid Applications: A Case Study on Link Reliability and Node Lifetime Evaluations in Power Distribution Systems

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Recent advances in embedded systems and wireless sensor networks (WSNs) made it possible to realize low-cost monitoring and automation systems for smart grids. This paper presents opportunities and design challenges of WSNs for smart grid applications. WSN-based smart grid applications have been introduced, and some WSN standards and communication protocols have been discussed for smart grid applications. Importantly, node lifetime and link reliability in wireless sensor networking for smart grid applications have been evaluated through case studies based on field tests in electric power system environments.

1. Introduction

The complex and nonlinear nature of electric power distribution networks and the increasing electricity consumption in most countries have caused serious network congestion problems in recent years [1]. Existing power distribution networks suffer from the lack of effective fault diagnostics, monitoring, automation, and communications [2]. These factors, together with the overstressed situation, increase the possibility of system breakdowns. As a result of the increasing demands for clean, abundant, and sustainable electric energy together with the above-mentioned problems, smart grid concept has emerged [1]. Smart grids are modern electric power grid infrastructures, which provide smooth integration of alternative and renewable energy sources through modern communication and sensing technologies and automated control [3, 4]. The potential benefits of smart grids are numerous and they can be outlined as follows [5]:

(i) increased energy consumption information available to consumers,

(ii) improved physical and operational security and resilience against attacks or disasters,

(iii) increased energy efficiency,

(iv) improved reliability and safety,

(v) the integration of a higher percentage of renewable energy sources,

(vi) easy integration of plug-in electric vehicles,

(vii) a reduction in peak energy demand,

(viii) several environmental benefits.

Currently, power grids are deployed with a centralized communication infrastructure. All control entities within a utility are directly connected to the energy management system (EMS), which is the main control center in the power grids. The local control entities cannot communicate with each other directly. In the existing power grids, wide area monitoring and control facilities depend on the data provided by local entities [6]. Hence, flexible adaptation to new control and automation systems is severely restricted and there is a need for a decentralized and data-centric infrastructure to improve system efficiency. Different from the existing power grids, in smart grid, online and reliable information is the main factor for the reliable delivery of energy from the generation units to the users. Generally, a smart grid network consists of the following three segments.

(1) *Home area networks (HANs)* connect smart meters with on-premise appliances, distributed renewable sources, and electrical vehicles.

(2) *Neighbourhood area networks (NANs)* carry information between customer premises and aggregation points.

(3) *Wide area networks (WANs)* serve as the backbone for communication between the utility data center and aggregation points.

Recent advances in embedded systems and wireless sensor networking made it possible to implement low-cost monitoring and diagnostic systems for smart grids [7]. These systems receive information from wireless sensor nodes, which monitor critical smart grid equipments and are used to monitor and respond to the changing conditions in a proactive manner. Hence, WSNs have been recognized as a promising and complementary technology for various smart grid applications [1, 8, 9]. Some of the existing and envisaged applications of WSNs in smart grids include load management and control, wireless automatic meter reading (WAMR), equipment fault diagnostics, remote monitoring, electric fault detection, and distribution automation. However, harsh and complex propagation environments, very common in electric power distribution networks, cause wireless communication challenges in terms of reliability and delay and require special attention during installation in smart grid applications. Also, guaranteeing a specific quality of service (QoS) is a challenging issue in WSNs due to the inherent properties of WSNs, such as unstable topology, unpredictable nature of wireless links, and resource constraints [10]. In addition, in bandwidth-limited and battery-operated WSNs, there is a tradeoff between node lifetime, which requires sensor nodes to follow sleeping schedules with longer periods, and link reliability, which requires sensor nodes to be active in most of their operations in smart grid. Therefore, the relationship between node lifetime and link reliability in smart grid environments needs to be investigated.

This paper presents major opportunities and design challenges of WSNs for smart grid applications. WSN-based smart grid applications are introduced, and main WSN standards and communication protocols are discussed for smart grid applications. Importantly, node lifetime and link reliability in wireless sensor networking for smart grid applications have been evaluated through case studies based on realistic wireless channel models. Note that the channel parameters of these models have been obtained through experimental field tests using IEEE 802.15.4 compliant wireless sensor nodes in electric power system environments, including underground network transformer vault, outdoor 500 kV substation, and indoor power control room environments at Georgia Power, Atlanta, GA, USA [1].

The remainder of this paper is organized as follows. Section 2 explains WSN-based communication infrastructure for different types of smart grid applications. In Section 3, major challenges of WSN-based communications in smart grid environments are given. WSN standards and protocols for smart grid are discussed in Sections 4 and 5, respectively. Emerging amendments to IEEE 802.15.4 which target smart grid applications are given in Section 6. Subsequently, link reliability and lifetime of WSNs and their effects on smart grid applications are explained with case studies in Sections 7 and 8. Energy harvesting methods in smart grid and performance adaptations for efficient use of energy harvesting are described in Sections 9 and 10. Finally, the paper is concluded in Section 11. Future research directions are also given in Section 1.

2. WSN-Based Smart Grid Applications

Generally, WSN-based smart grid applications are divided into three groups: consumer side, transmission and distribution (T&D) side, and generation side WSN-based smart grid applications [17].

(i) *Consumer Side WSN-Based Smart Grid Applications*. Consumer side WSN-based smart grid applications have a direct relationship with different types of customers. Consumer side applications include advanced metering infrastructure, residential energy management, automated panels management, building automation, demand-side load management, process control monitoring, and equipment management and control monitoring.

(ii) *Transmission and Distribution (T&D) Side WSN-Based Smart Grid Applications*. T&D side covers overhead power lines, underground power lines, and substations, and the applications designed for this side play a key role in smart grid, since these systems are responsible for successful power transmission. Some of the transmission and distribution side WSN-based smart grid applications are overhead transmission line monitoring, outage detection, conductor temperature rating systems, underground cable system monitoring, fault diagnostics, overhead and underground fault circuit indicators, cable, conductor and lattice theft, fault detection, and location.

(iii) *Generation Side WSN-Based Smart Grid Applications*. These applications are generally based on monitoring task. Some of them are real-time generation monitoring, remote monitoring of wind farms, remote monitoring of solar farms, power quality monitoring, and distributed generation.

Communication and network requirements of smart grid applications play an important role in implementation of WSN technologies for energy distribution infrastructures. Table 1 lists some of the common smart grid applications and their major requirements in terms of data rate, latency, and reliability [18].

Table 1: Communication and network requirements of common smart grid applications.

Application	Data rate/volume	Latency	Reliability
Smart metering	Low/very low	High	Medium
Interside rapid response	High/low	Very low	Very high
Operations data	Medium/low	Low	High
Distribution automation	Low/low	Low	High
Distributed energy management and control	Medium/low	Low	High
SCADA	Medium/low	Low	High
Mobile workforce	Low/low	Low	High

3. Design Challenges of WSNs in Smart Grids

The major technical challenges for realization of WSN-based smart grid applications can be outlined as follows.

(1) *Resource Limitations of Sensor Nodes*. The design and implementation of a WSN is constrained by the hardware resources of sensor nodes due to limited physical size, such as energy, memory, and processing.

(2) *Harsh Environmental Conditions and Dynamic Topologies*. In power distribution environments, the connectivity and topology of the network may vary due to varying wireless link characteristics and node failures [1]. In addition, sensor nodes may be subject to different environmental conditions which may cause sensor nodes to malfunction [7, 19].

(3) *QoS Requirements of Smart Grid Applications*. Different QoS requirements and specifications in terms of reliability, throughput, and latency are required for different types of existing and envisaged smart grid applications as seen in Table 1.

(4) *Packet Errors and Variable-Link Capacity*. In electric power system environments, due to noisy environment and obstructions, the bandwidth of wireless links depend on the interference level perceived at receivers, and high bit error rates are observed in communication [1]. Therefore, it is very hard to meet QoS requirements in smart grid applications due to the varying characteristics of wireless links [1, 19, 20].

(5) *Security*. Security is an essential feature in the design of WSN-based smart grid applications in order to provide safe communication by preventing intrusion and denial of service (DoS) attacks [21].

Since different WSN-based smart grid applications have different requirements and priorities, the tradeoffs among the different parameters can be balanced.

4. Communication Standards for WSN-Based Smart Grid Applications

This section discusses different communication standards and protocols, such as ZigBee, 6LoWPAN, Z-Wave, WirelessHART, ISA-100 [22], and Wavenis, which can be used in WSN-based smart grid applications.

(i) *ZigBee*. ZigBee was developed by the ZigBee Alliance to meet the specifications of short-range and low-data applications. ZigBee Alliance is very active in the market as an independent organization with more than 340 members. The ZigBee protocol stack consists of 4 layers: the physical (PHY) layer, the medium access control (MAC) layer, the network (NWK) layer, and the application (APL) layer [22]. APL and NWK layers are defined by the ZigBee specification. On the other hand, MAC and PHY layers are defined by the IEEE 802.15.4 standard. The IEEE 802.15.4 operates in the 868 MHz, 915 MHz, and 2.4 GHz bands and provides data rates up to 250 Kbps. ZigBee has many advantages for smart grid applications such as mesh networking support and low duty-cycle operation. Due to the above several advantages and global marketing, ZigBee is currently used in more than 35 million smart meters deployed throughout the world.

(ii) *6LoWPAN*. 6LoWPAN was developed by the IETF IPv6 over Low-Power Wireless PAN (6LoWPAN) Working Group. The mechanisms offered by 6LoWPAN are fragmentation, header compression, IPv6 address autoconfiguration, and IPv6 neighbour discovery for LoWPANs. In the mesh topology, mesh under and route over schemes are used for routing. In mesh under scheme, routing is performed using IEEE 802.15.4 addresses. In route over scheme, routing is performed at the IP layer.

(iii) *RPL*. RPL is a distance vector IPv6 Routing Protocol for LLNs [23] and operates on constrained link layers with a maximum MTU of 127 bytes [24]. RPL creates a directed acyclic graph rooted at the sink and minimizes the cost of reaching the sink from any node in the network based on a combination of metrics and constraints to compute the best path [25, 26]. RPL is optimized for many-to-one and one-to-many traffic patterns.

(iv) *Z-Wave*. Z-Wave was developed by ZenSys for automation in small business and residential environments. Z-Wave was designed to allow transmission of short messages from a control node to other nodes in a wireless network [22] and is composed of PHY, MAC, transfer, routing, and application layers. The Z-Wave radio operates in the 908 MHz in the USA and 868 MHz in Europe and allows transmission rates up to 200 Kbps.

(v) *WirelessHART*. WirelessHART is a wireless network communication protocol which is based on IEEE

802.15.4 for low-power 2.4 GHz operation [19]. WirelessHART is compatible with all existing systems and devices.

(vi) *ISA-100*. ISA-100 is designed for automation and low-data rate monitoring applications. ISA-100 networks operate using 2.4 GHz radio and use channel hopping to minimize interference and increase reliability in mesh and star network topologies.

(vii) *Wavenis*. Wavenis is an emerging wireless communication technology which provides long-range, up to 200 m for indoor applications, and ultra-low-power wireless solutions for machine-to-machine and WSN applications [22, 27]. Many Wavenis-based devices are deployed in various smart grid applications such as automated meter reading (AMR), advanced metering infrastructure (AMI), remote telemetry applications, and utility meter monitoring. A variety of mesh network configurations are supported by Wavenis. Wavenis operates in the 868 MHz, 915 MHz, and 433 MHz bands and has programmable data rates from 4.8 kbps to 100 kbps, typically 19.2 kbps [27].

5. Discussion on Communication Protocols with regard to Smart Grid Applications

Considering the requirements of smart grid communications, the communication protocol stack of WSN standards is briefly discussed in this section. The details of these discussions are omitted to comply with the page limitations.

(i) *Physical Layer*. IEEE 802.15.4 operates in the 915 MHz and 2.4 GHz bands with multichannel support. Therefore, it is possible to operate in smart grid environments with heavy interference by selecting the less interfered channel if IEEE-802.15.4-based protocols are preferred. Another advantage of IEEE-802.15.4-based protocols over other protocols is better signal-to-noise (SNR) ratios due to phase shift keying (PSK) modulations. Additionally, ZigBee avoids the multipath and narrowband interference by using the spread spectrum techniques. ISA-100 networks use channel hopping to increase reliability and minimize interference. All these features help network designers to meet the requirements of WSN-based smart grid applications.

(ii) *Link Layer*. ZigBee and 6LoWPAN use 16-bit checksums, whereas Z-Wave uses 8-bit checksums to provide reliability. Considering end-to-end delay, ZigBee theoretically provides lower expected latency compared to other protocols [22]. All protocols mentioned in the previous section support acknowledgment and retransmission mechanisms aiming to improve reliability in harsh environments.

(iii) *Network Layer*. Link quality (LQ) metric is an important criterion in smart grid environments with multipath and interference. ZigBee uses the link quality indicator (LQI) offered by IEEE 802.15.4. On the other hand, 6LoWPAN does not require the use of LQI. Wavenis uses a received-signal-strength-indicator-(RSSI-) based LQ estimator which may not be accurate in some cases due to multipath and interference. Z-Wave does not take into account LQ. In general, LQ-aware routing protocols are preferred to ensure reliability in smart grid.

(iv) *Application Layer*. ZigBee, Z-Wave, Wireless HART, and ISA-100 have a set of well-defined attributes, commands for various WSN-based smart grid applications. This can be advantageous while deploying WSNs for smart grid applications.

6. Emerging Amendments to IEEE 802.15.4

To promote open standards for smart grid environments and to meet specific national and regional regulations, the IEEE 802.15 Smart Utility Networks (SUN) Task Group 4 g reviewed the IEEE 802.15.4 standards and proposed amendments [28, 29]. These amendments are principally designed for smart metering utility networks, involving large and geographically diverse networks with minimal infrastructure and a great number of fixed endpoints [28]. Initially, the IEEE 802.15.4 standard was designed for low-power wireless PHY and MAC layers which offer low-power consumption with link speeds up to 250 Kbps in the 2.4 GHz ISM frequency band [29]. The amendment, IEEE 802.15.4 g, adds new PHY support and also defines some MAC modifications. The PHY supports multiple data rates in bands ranging from 450 MHz to 2450 MHz in three different modes with data rates of 5–400 Kbps, and PHY frame sizes up to 1500 octets [28, 29]. With this amendment, the IEEE 802.15.4 radio can now operate in one of the dedicated-use or unlicensed bands.

The IEEE 802.15 Low Energy Critical Infrastructure (LECIM) Task Group 4k (TG4k) was also formed to provide an amendment to IEEE 802.15.4 to facilitate point to thousands of points of communications for critical monitoring applications, such as network traffic congestion monitoring, fault circuit indicators, and perimeter security [30, 31]. The amendment addresses minimal network infrastructure and enables schedule-driven and trigger-driven data collection from a great number of battery-powered end points which are widely dispersed or are in challenging environments such as specific smart grid infrastructures [31]. The amendment supports data rates of up to 40 Kbps and minimizes device wake durations and network maintenance traffic to support low energy operation for long battery life. It can also operate in any of the regionally available bands.

7. Link Reliability Analysis

In this section, the results of our reliability analysis are given for different smart grid environments, including indoor power control room, outdoor 500 kV substation, and underground network transformer vault. This analysis is based on experimentally determined log-normal channel parameters obtained in our previous experimental study [1], which was conducted using IEEE 802.15.4 compliant wireless sensor nodes in different power system environments at Georgia

Table 2: Path-loss exponent and shadowing deviation in smart grid environments.

Propagation environment	Path loss (η)	Shadowing deviation (σ)	Noise floor (P_n)
500 kv Substation (NLOS)	3.51	2.95	−93
Underground transformer vault (NLOS)	3.15	3.19	−92
Main power room (NLOS)	2.38	2.25	−88

Power, Atlanta, GA, USA. Experimentally determined log-normal channel parameters for different power system environments in nonline of sight (NLOS) are given in Table 2 [1].

In this case study, we have modelled the wireless channel by the use of a log-normal shadowing path-loss model through a combination of empirical measurements and analytical techniques. Experimental studies show that modelling the wireless channel using a log-normal shadowing path-loss model provides more accurate multipath channel models compared to the Nakagami and Rayleigh models [1, 32]. In this model, signal-to-noise ratio $\gamma(d)$ at distance d from the transmitter can be calculated by the following:

$$\gamma(d)_{dB} = P_t - \mathrm{PL}(d_0) - 10\eta \log_{10}\left(\frac{d}{d_0}\right) - X_\sigma - P_n, \quad (1)$$

where P_t represents the transmit power in dBm, $\mathrm{PL}(d_0)$ represents the path loss at a reference distance d_0, η represents the path-loss exponent, X_σ represents a zero mean Gaussian random variable with standard deviation σ, and P_n represents the noise power (noise floor) in dBm.

In this study, packet reception rate (PRR), the ratio between the number of successful packets and the total number of transmitted packets, is used to evaluate the reliability of wireless links in three different smart grid environments, such as outdoor substation, underground transformer vault, and indoor main power room. For this analysis, an evaluation environment has been developed using ANRG [33]. Experimentally determined log-normal wireless channel parameters for different power system environments are given in Table 2. Using this channel model, we have obtained PRR versus distance in a network, including multiple sensor nodes located in different locations. Figures 1(a), 1(b), and 1(c) show the variation of PRR for different communication distances. In Figure 1, connected region represents the region where PRR is higher than 95%, disconnected region represents the region where PRR is lower than 20%, and the transitional region represents the region between connected and disconnected regions in a PRR versus distance graph.

This case study clearly shows that three different packet reception regions exist in wireless links in smart grid propagation environments, that is, connected, transitional, and disconnected. As it can be seen in Figure 1, even though the distance remains constant for a different pair of nodes, the PRR may significantly change in the transitional region. This is due to the unstable characteristics of the transitional region. Therefore, the unique radio propagation characteristics of smart grid environments require reliable communication solutions integrated with reliable transport layer and error control mechanisms.

Table 3: Common parameters of the case studies.

Parameter	Value
Event duration	1 sec
Unit packet size	128 byte
Radio TX data rate	250 Kbps
Maximum number of retransmissions	5
Duty period	10 sec

8. Node Lifetime Analysis

The lifetime of WSNs mainly depends on the capacity of the battery power of the nodes and packet transmission and reception activities. In this section, to investigate the relationship between data transmission activities and node lifetime, an evaluation environment has been developed using MATSNL [34]. The evaluation environment allows investigating the lifetime performance of the network for schedule-driven and trigger-driven data transmission models. The common parameters of case studies of this section are listed in Table 3.

In schedule-driven model, the processor of a sensor node directly drives the sensors in order to wake the processor up to sample the sensors according to a schedule [34]. For the schedule-driven operation, detection probability (DP) is basically the duty cycle of a schedule-driven sensor node. In WSNs, duty cycle is the ratio between active period and the full active/dormant period of a sensor node [35]. When the schedule-driven model is modelled as a Markov chain, then the average steady-state power consumption of a schedule-driven sensor node can be formulated using the following [36]:

$$\overline{P}_{\mathrm{SD}}(u) = (P_W(\lambda) - P_{S0})u + \left(P_{S0} + \frac{C_P}{T_c}\right), \quad (2)$$

where P_W represents the power consumption at awake period of a schedule-driven node, P_{S0} represents the power at asleep period, C_P represents the wake-up energy cost of the microcontroller, T_c represents duty period, u represents DP, and λ represents the average event interarrival rate.

In trigger-driven model, a sensor coupled to a preprocessor senses the environment and wakes up the rest of the sensor nodes as soon as an event is detected. When the trigger-driven model is modelled as a Markov chain, then the average steady-state power consumption of a trigger-driven sensor node can be formulated using the following [36]:

$$\overline{P}_{\mathrm{TD}}(\lambda) = \frac{P_{S1} + \lambda K_E}{[1 + \lambda K_T]}. \quad (3)$$

The power components of (3) can be broken into two parts. λK_E represents the average power spent for computation and communication for each sensed event, and P_{S1} represents the power spent to monitor the events, where K_E represents

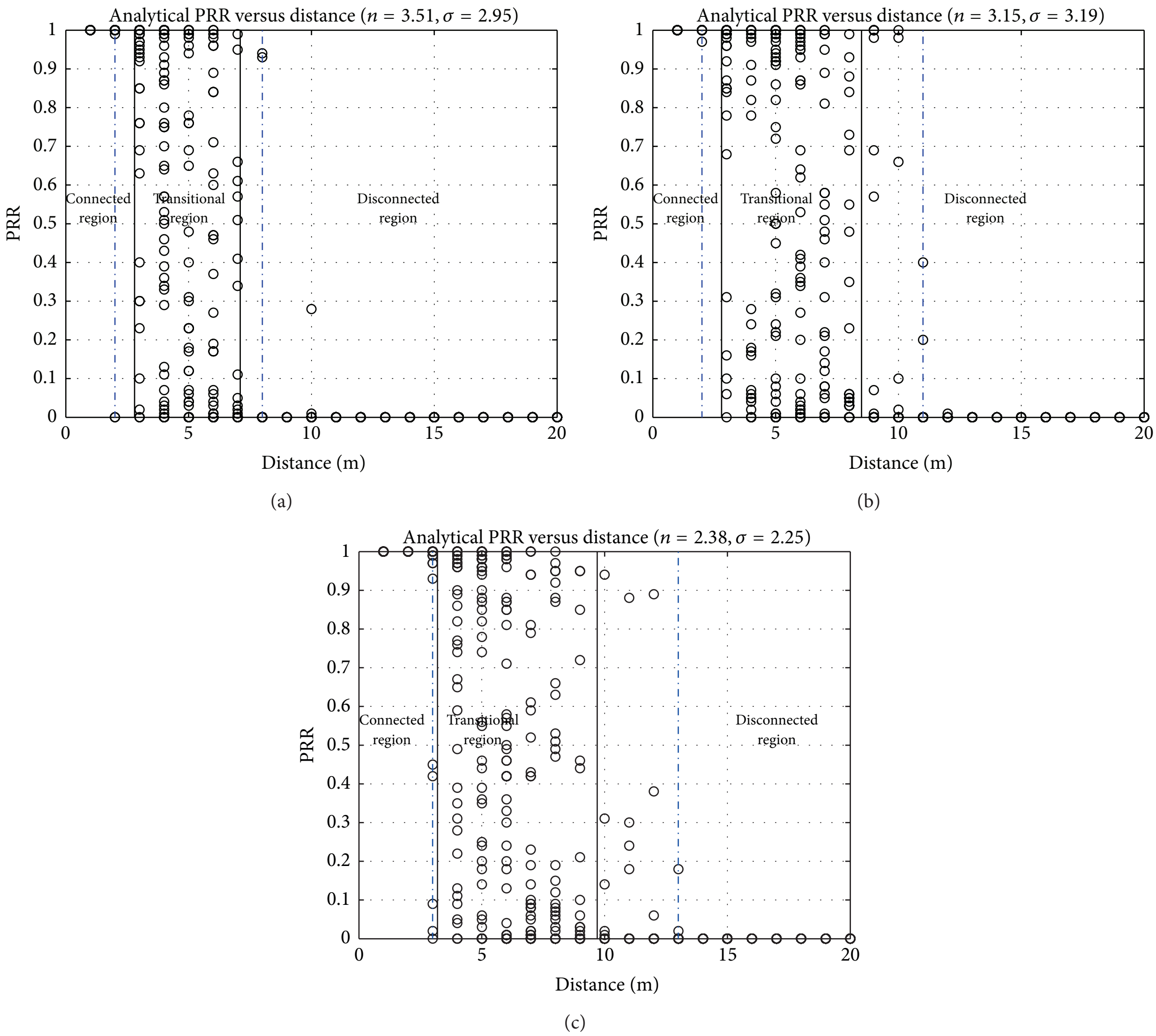

Figure 1: (a) PRR versus distance variation for the 500 kv Substation (NLOS). (b) PRR versus distance variation for the Underground Transformer Vault (NLOS). (c) PRR versus distance variation for the main power room (NLOS).

the energy spent for a sensed event, K_T represents the average time for a sensed event, and λ represents the average event interarrival rate. Detailed information on deriving the equations of the schedule-driven and trigger-driven models can be found in [36].

In the first case study, we have evaluated the lifetime performances of mica2, imote2, and Telos motes in schedule-driven and trigger-driven modes. Table 4 lists a comparison of the transceivers of mica2, imote2, and Telos motes. We have evaluated their lifetimes for detection probabilities between 0.3 and 1 and a fixed interarrival rate of 60 minutes. The resulting plot is shown in Figure 2(a). In the second case study, we have kept DP fixed at 0.5 and varied the event interarrival rate from one minute to one day. The resulting plot is shown in Figure 2(b). We see that for a WSN-based application which allows the use of sensors with DP smaller than a specific point which is a tradeoff point between average power usage and DP, the schedule-driven model is a good choice. For events with larger arrival rates, the situation is the same. The schedule-driven model is suitable for frequent and noncritical detections. On the other hand, the trigger-driven model is better for WSN-based applications requiring high accuracy. The reason of this lies in the principles on which the models are based. For the trigger-driven model, the sensor and preprocessor are always on. This results in added power cost for the preprocessor. However, the schedule-driven model does not take such toll on power but takes so at the expense of event DP. As a result of these case studies, we can conclude that Telos motes are more suitable for long-term WSN-based smart grid applications due to their longer lifetimes and their support for low-power IEEE 802.15.4 protocol. We believe that the

Table 4: A comparison of Texas instruments CC1100 and CC2420 transceivers.

	Texas instruments CC1100	Texas instruments CC2420
Platforms	Mica2Dot, Mica2, and BTnode	MicaZ, TelosB SunSPOT, and Imote2
Data rate (Kbps)	38.5	250
Modulation	FSK	O-QPSK
Radio frequency (MHz)	315/433/868/915	2.4 GHz
Supply voltage (V)	2.1–3.6	2.1–3.6
TX maximum (mA/dBm)	26.7/10	17.4/0
TX minimum (mA/dBm)	5.3/−20	8.5/−25
RX (mA)	7.4–9.6	18.8
Sleep (μA)	0.2–1	0.02
Startup (ms)	1.5–5	0.3–0.6

lifetime of a battery-operated sensor node can be further extended through adaptive sleeping algorithms and dynamic transmission power control algorithms.

In the third case study, to show the effect of transmit power on node lifetime, we have examined the lifetime performances of imote2 and Telos motes in schedule-driven and trigger-driven modes for 0 dBm and −25 dBm transmit powers. Different from mica2 motes, imote2 and Telos motes have CC2420 radios which allow setting different transmit modes including 0 dBm, −5 dBm, −10 dBm, −15 dBm, −20 dBm, and −25 dBm which in turn can be used to increase sensor lifetime. In this study, we have kept DP fixed at 0.5 and varied the event interarrival rate from one minute to one day. The resulting plot is shown in Figure 2(c). We see that reducing transmission power slightly increases the lifetime expectations of both imote2 and Telos motes. On the other hand, it is well known that reducing transmission power reduces effective transmission range and affects network connectivity. Therefore, adaptive transmission power approaches are required to balance the tradeoff between network connectivity and node lifetime.

9. Energy Harvesting for WSN-Based Smart Grid Applications

Main power might be available in some WSN-based smart grid applications. On the other hand, in most implementations, sensor nodes are usually deployed in high voltage environments and require low-voltage power sources due to inappropriate power levels and high costs of wiring and necessary transformers. Due to that the use of batteries as main power sources for the sensor nodes makes periodic battery replacements unavoidable [19], energy harvesting methods play an important role in the lifetime of WSNs. If there are many battery-operated sensor nodes in the network, then an additional maintenance expense is required to change batteries periodically. Although many solutions exist, major energy harvesting techniques that can be used in smart grid applications can be summarized as follows.

(i) *Solar Energy Harvesting*. Solar energy harvesting technique has been around for a long time. With the help of a photo voltaic system, sunlight is converted into electricity. The open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) characterize solar panels. Although the value of I_{sc} depends on the amount of incident solar radiation, V_{oc} remains almost constant. Hence, various energy storage elements are used to store the harvested energy and to provide a stable voltage. The problem with this technique is that a continuous supply of sunlight may not be available all the time and solar cells suffer from low energy conversion efficiency. However, various cells are available in the market for both outdoor and indoor environments. Solar energy harvesting can be utilized effectively in outdoor smart grid environments including outdoor substations, transmission and distribution lines, solar farms, and wind farms.

(ii) *Thermal Energy Harvesting*. Thermo generators harvest energy from objects or environments at different temperatures through heat transfer and produce an electrical voltage across difference in temperature between the cold and the hot junctions [37]. Though thermal energy harvesting sounds promising, the maximum efficiency of this method is governed by the Carnot cycle. For instance, a difference of 17°C yields only 5.5% efficiency [37]. This technique may be feasible in the future if thermal energy harvesting for smaller temperature differences is possible.

(iii) *Vibration-Based Energy Harvesting*. Electrical energy can be produced from mechanical vibrations. Techniques in the literature for this conversion are categorized into three groups: piezoelectric technique, inductive spring mass system, and electrostatic method [37]. Vibrational magnetic power generators based on moving magnets and coils can yield powers ranging from tens of microwatts to over a milliwatt. Vibrational power generators based on charged capacitors with moving plates can yield power on the order of 10 μW. Piezoelectric technique-based methods can generate power of 100–330 $\mu W/cm^3$ [19].

(iv) *Air Flow Energy Harvesting*. Air flow can be used to produce electric energy. There are different approaches in the literature including micro wind turbines, oscillating wings, and flapping wings for this technique. The effectiveness of this technique depends on the collector area which is a function of required power output, air density, air speed, and conversion efficiency. For practical implementations, it may not be possible to design very small scale and effective converters.

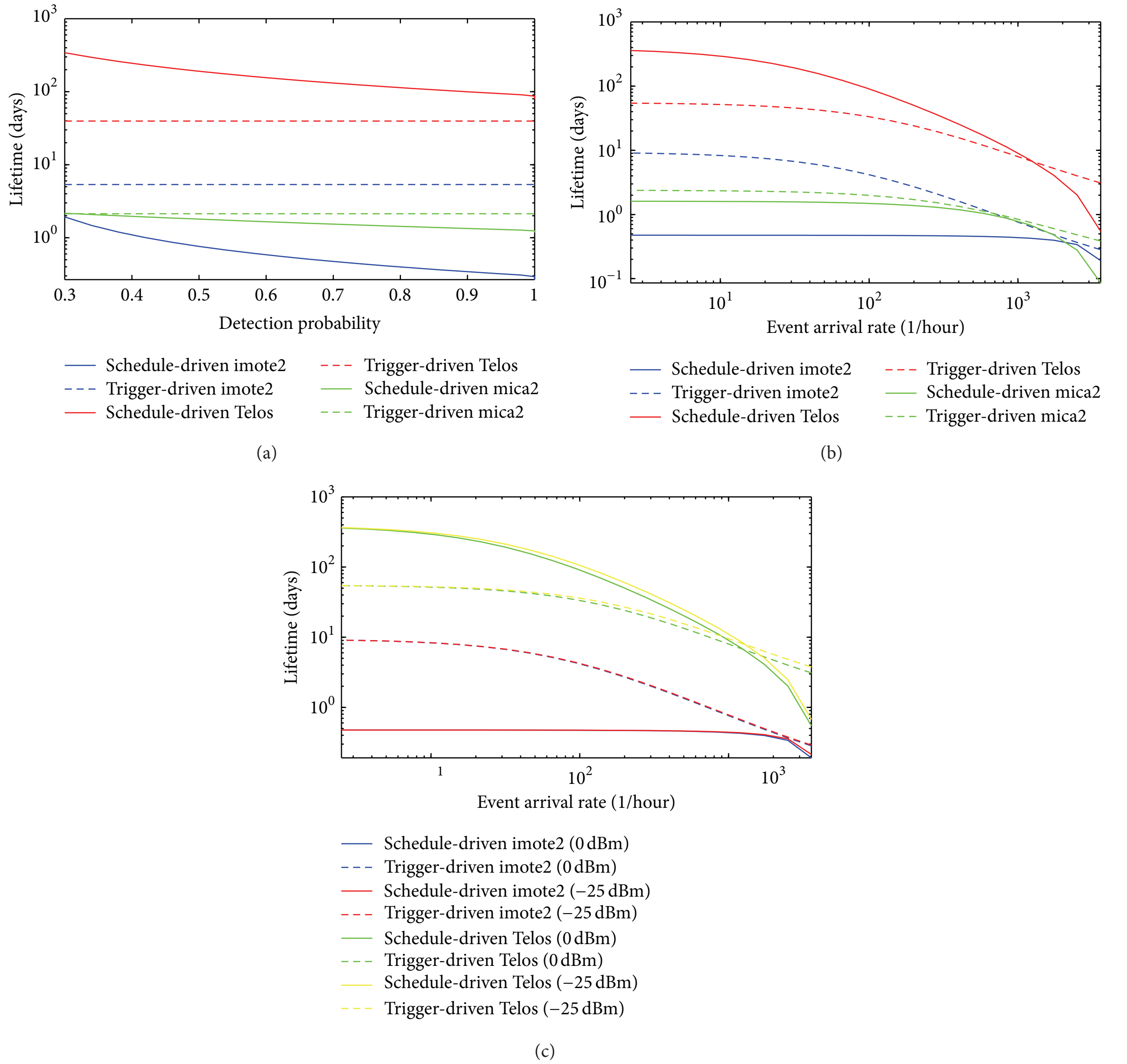

FIGURE 2: (a) Lifetime comparison of mica2, imote2, and Telos motes for schedule-driven and trigger-driven models (variable detection probability and fixed interarrival rate). (b) Lifetime comparison of mica2, imote2, and Telos motes for schedule-driven and trigger-driven models (fixed detection probability and variable event interarrival rate). (c) Lifetime comparison of imote2 and Telos motes for 0 dBm and −25 dBm transmit powers for schedule-driven and trigger-driven modes.

(v) *Electromagnetic Wave Energy Harvesting*. Theoretically, an electric field of 1 V/m yields 0.26 μW/cm^2. However, such electric fields may only be encountered close to powerful transmitters. Although smart grid environments are energy rich, sensors must be located further away from high voltage conductors to function properly. Instead of this, RF energy can be broadcasted to power electronic devices. But this approach is limited by legal limits set by safety and health implications [19]. This approach is already used in passive Radio Frequency Identification Systems (RFIDs) [37].

(vi) *Modulated Backscattering*. Data transmission is one of the major battery-consuming processes in sensor nodes. A design technique called modulated backscattering (MB) is very promising since by using this technique, wireless sensor nodes send their data just by switching the impedance of their antennas and reflecting the incident signal coming from an RF source [38]. The source of energy is an RF power source which is AC/DC powered. In this technique, an RF source transmits RF power to run wireless passive sensor network (WPSN) nodes and transmits and receives information from the nodes simultaneously. Hence, the expected lifetime of WPSNs utilizing MB is longer than WSNs. On the other hand, the RF coverage provided over the field directly affects the communication performance of WPSNs. Another advantage of MB-based WPSNs is that theoretically long-range communication with the WPSN nodes is achievable without increasing the power consumption of the nodes. An important criterion which affects the design of WPSNs is the number of RF sources required for effective MB-based communication [38].

(vii) *Magnetic Field Energy Harvesting*. The magnetic field near T&D lines can be harvested to power sensor nodes [37]. Most of the magnetic field energy harvesters are based on transformer action, which requires a clamp around the conductor for energy harvesting. This requirement may limit their application.

(viii) *Biochemical Energy Harvesting*. The chemical energy of glucose and oxygen in biofluid can be converted into electricity using an enzymatic biofuel cell (BFC) [39]. The highest theoretical voltage which can be obtained from a BFC depends on thermodynamics, and the maximum energy density of a BFC is up to 1 mW/cm^2 [16].

10. Discussion on Energy Harvesting and Performance Adaptations in Smart Grids

Generally, WSN-based applications are optimized for various parameters in order to meet design goals. For instance, WSNs optimized for increased network lifetime may operate at low-duty cycles and compromise sensing reliability in the application. Otherwise, WSNs optimized for coverage and sensing reliability need high capacity batteries or involve periodic human effort for maintenance. In this respect, energy harvesting methods play an important role in extending the lifetime of sensor nodes.

The aim of energy harvesting is to generate power between tens of microwatts and several hundred milliwatts to supply one or more wireless sensor nodes [40]. Considering the effectiveness and availability of products for different energy harvesting methods, vibration-based energy harvesting might be used in smart grid applications. There are a lot of small-sized commercial products (piezoelectric, electrostatic, and electromagnetic) in the market for both micro and macro systems. Solar energy harvesting is a mature technology and can be used in outdoor environments. Silicone, thin film, and plastic-based solar cells are commercially available in the market. Electromagnetic wave energy harvesting is questionable considering safety- and health-related concerns. Another problem with electromagnetic wave energy harvesting is that some sensors may not function properly if they are exposed to interference. Thermal energy harvesting is another promising technology, but most commercial products require a temperature difference of 10–200°C. The comparison of energy harvesting solutions explained in this paper is given in Table 5.

To exploit the benefits of energy harvesting methods in smart grid, sensor nodes need to carry out additional tasks. For increased capability and performance, various node-level system parameters including transmission power, duty cycle, sampling rate, data processing, and sensing reliability need to be carefully set by taking the next recharge cycle into consideration [20]. An energy harvesting sensor node can tune several parameters for performance optimization, provided that it is able to predict the harvestable energy by a prediction module [40]. Another node-level optimization is achieved by tuning sensing-related parameters using various mechanisms including changing the bit resolution of samples, changing the sampling rate, sampling interesting regions of space and intervals of time, predicting measurements instead of making them, and hierarchical sensing. Besides node-level design adaptations, routing protocols incorporating metrics to account for residual energy levels at nodes, mechanisms to route packets through formation of clusters, energy-efficient data collection methods, which use data aggregation techniques, and MAC protocols to use the harvested energy efficiently to maximize throughput and minimize delays [41] are some major network-level solutions for energy harvesting [40].

While the node-level adaptations keep each sensor node within permissible limits, designers try to meet the requirements of applications at all times. Thus, it is required to balance the tradeoff between tuning system parameters for coordination and cooperation among sensor nodes to meet application requirements and node-level design adaptations.

11. Conclusions

This paper presents major opportunities and design challenges of WSNs for smart grid applications. WSN-based smart grid applications are introduced, and main WSN standards and communication protocols are discussed for smart grid applications. Importantly, node lifetime and link reliability in wireless sensor networking for smart grid applications have been evaluated through case studies. Overall, this paper explains research challenges resulting from inherent properties of WSNs and smart grid propagation environments. In addition, our experimental studies show that network designers planning to use WSNs for smart grid applications need to consider important sensor node parameters including transmission power, range, and channel parameters. Future work includes the development of cross-layer communication protocols to address link-quality variations in smart grid environments, QoS provisioning, and coordinated network management for different application types of smart grid. In addition, in order to prove the advantages of energy harvesting techniques for WSN-based smart grid applications, a set of experiments will be conducted and statistical evaluations will be done. A group of field tests will be conducted in a main power room and near a substation. In the same locations, another group of field tests will be conducted to examine the relation between link reliability and node lifetime.

Table 5: The comparison of energy harvesting solutions.

Solution	Applicability	Energy density	Commonly available in the market	Safe
Solar energy harvesting	Outdoor/indoor	15 mW/cm^2 (outdoor) [11], 100 μW/cm^2 (indoor at 10 W/cm^2 light density) [12]	Yes	Yes
Thermal energy harvesting	Outdoor/indoor	100 μW/cm^2 at 5°C gradient, 3.5 mW/cm^2 at 30°C gradient [12]	Yes	Yes
Vibration-based energy harvesting	Outdoor/indoor	3.5–500 μW/cm^2 depending on the technique [13]	Yes	Yes
Electromagnetic wave energy harvesting—RF energy harvesting	Outdoor/indoor	15 mW (with a transmitted power of 2-3 W at a frequency of 906 MHz at a distance of 30 cm) [14]	Yes	Questionable
Air flow energy harvesting	Outdoor/indoor	3.5 mW/cm^2 (at air flow speed of 8.4 m/s) [15]	No	Yes
Magnetic energy harvesting	Outdoor/indoor	N/A	No	Yes
Biochemical energy harvesting	Outdoor/indoor	0.1–1 mW/cm^2 [16]	No	Yes

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References

[1] V. C. Gungor, L. Bin, and G. P. Hancke, "Opportunities and challenges of wireless sensor networks in smart grid," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, pp. 3557–3564, 2010.

[2] T. Sauter and M. Lobashov, "End-to-end communication architecture for smart grids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1218–1228, 2011.

[3] V. C. Gungor, D. Sahin, T. Kocak, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: communication technologies and standards," *IEEE Transactions on Industrial Informatics*, vol. 7, no. 14, pp. 529–539, 2011.

[4] S. M. Amin and B. F. Wollenberg, "Toward a Smart Grid: power delivery for the 21st century," *IEEE Power and Energy Magazine*, vol. 3, no. 5, pp. 34–41, 2005.

[5] DOE, "Communications requirements of smart grid technologies," Tech. Rep., U.S. Department of Energy, Washington, DC, USA, 2010.

[6] Y. J. Kim, M. Thottan, V. Kolesnikov, and W. Lee, "A secure decentralized data-centric information infrastructure for smart grid," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 58–65, 2010.

[7] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Computer Networks*, vol. 50, no. 7, pp. 877–897, 2006.

[8] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[9] C. Cano, B. Bellalta, A. Sfairopoulou, and M. Oliver, "Low energy operation in WSNs: a survey of preamble sampling MAC protocols," *Computer Networks*, vol. 55, no. 15, pp. 3351–3363, 2011.

[10] M. A. Yigitel, O. D. Incel, and C. Ersoy, "QoS-aware MAC protocols for wireless sensor networks: a survey," *Computer Networks*, vol. 55, no. 8, pp. 1982–2004, 2011.

[11] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," in *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN '05)*, pp. 457–462, April 2005.

[12] Z. G. Wan, Y. K. Tan, and C. Yuen, "Review on energy harvesting and energy management for sustainable wireless sensor networks," in *Proceedings of the IEEE International Conference on Communication Technology*, pp. 362–317, 2011.

[13] B. H. Calhoun, D. C. Daly, N. Verma et al., "Design considerations for ultra-low energy wireless microsensor nodes," *IEEE Transactions on Computers*, vol. 54, no. 6, pp. 727–740, 2005.

[14] R. J. M. Vullers, R. V. Schaijk, H. J. Visser, J. Penders, and C. V. Hoof, "Energy harvesting for autonomous wireless sensor networks," *IEEE Solid-State Circuits Magazine*, vol. 2, no. 2, pp. 29–38, 2010.

[15] Y. K. Tan and S. K. Panda, "Self-autonomous wireless sensor nodes with wind energy harvesting for remote sensing of wind-driven wildfire spread," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 4, pp. 1367–1377, 2011.

[16] B. E. Logan, B. Hamelers, R. Rozendal et al., "Microbial fuel cells: methodology and technology," *Environmental Science and Technology*, vol. 40, no. 17, pp. 5181–5192, 2006.

[17] V. C. Gungor, D. Sahin, T. Kocak et al., "A survey on smart grid potential applications and communication requirements," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 28–42, 2013.

[18] Alcatel-Lucent, "Smart choices for the smart grid," White Paper, Alcatel-Lucent, Murray Hill, NJ, USA, 2010.

[19] V. C. Gungor and G. Hancke, "Industrial wireless sensor networks: challenges, design principles, and technical approaches," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4258–4265, 2009.

[20] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: survey and implications," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, 2011.

[21] M. Erol-Kantarci and H. T. Mouftah, "Wireless multimedia sensor and actor networks for the next generation power grid," *Ad Hoc Networks*, vol. 9, no. 4, pp. 542–551, 2011.

[22] C. Gomez and J. Paradells, "Wireless home automation networks: a survey of architectures and technologies," *IEEE Communications Magazine*, vol. 48, no. 6, pp. 92–101, 2010.

[23] http://tools.ietf.org/id/draft-ietf-roll-rpl-19.html, 2011.

[24] J. W. Hui and D. E. Culler, "IPv6 in low-power wireless networks," *ProceedIngs of the IEEE*, vol. 98, no. 11, pp. 1865–1878, 2010.

[25] T. Clausen, U. Herberg, and M. Philipp, "A critical evaluation of the IPv6 routing protocol for low power and lossy networks (RPL)," in *Proceedings of the 7th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob '11)*, pp. 365–372, 2011.

[26] J. Tripathi, J. C. de Oliveira, and J. P. Vasseur, "Applicability study of RPL with local repair in smart grid substation networks," in *Proceedings of the 1st IEEE International Conference on Smart Grid Communications*, pp. 262–267, 2010.

[27] http://www.wave2m.com/the-specification/the-platform-in-depth?view=item, 2012.

[28] http://www.ieee802.org/15/pub/TG4g.html, 2011.

[29] "A standardized and flexible IPv6 architecture for fieldarea networks," Tech. Rep., 2011, http://www.cisco.com/web/strategy/docs/energy/ip_arch_sg_wp.pdf.

[30] http://www.ieee802.org/15/pub/TG4k.html, 2011.

[31] https://mentor.ieee.org/802.15/dcn/11/15-11-0607-00-004k-a-mac-proposal-for-lecim.pdf, 2011.

[32] M. Zuniga and B. Krishnamachari, "An analysis of unreliability and asymmetry in low-power wireless links," *ACM Transactions on Sensor Networks*, vol. 3, no. 2, pp. 1–30, 2007.

[33] "Realistic Wireless Link Quality Model and Generator, Autonomous Network Research Group (ANRG), University of Southern California," 2012, http://anrg.usc.edu/www/index.php/Downloads.

[34] D. Jung, T. Teixeira, A. Barton-Sweeney, and A. Savvides, "Model-based design exploration of wireless sensor node lifetimes," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 4373, pp. 277–292, 2007.

[35] F. Wang and J. Liu, "Duty-cycle-aware broadcast in wireless sensor networks," in *Proceedings of the IEEE (INFOCOM '09)*, pp. 468–476, 2009.

[36] D. Jung, T. Teixeira, and A. Savvides, "Sensor node lifetime analysis: models and tools," *ACM Transactions on Sensor Networks*, vol. 5, no. 1, p. 3, 2009.

[37] R. Moghe, Y. Yang, F. Lambert, and D. Divan, "A scoping study of electric and magnetic field energy harvesting for wireless sensor networks in power system applications," in *Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE '09)*, pp. 3550–3557, San Jose, Calif, USA, September 2009.

[38] A. Bereketli and O. B. Akan, "Communication coverage in wireless passive sensor networks," *IEEE Communications Letters*, vol. 13, no. 2, pp. 133–135, 2009.

[39] B. J. Hansen, Y. Liu, R. Yang, and Z. L. Wang, "Hybrid nanogenerator for concurrently harvesting biomechanical and biochemical energy," *ACS Nano*, vol. 4, no. 7, pp. 3647–3652, 2010.

[40] G. Tuna and K. Gulez, "Energy harvesting techniques for industrial wireless sensor networks," in *Industrial Wireless Sensor Networks: Applications, Protocols, Standards, and Products*, V. C. Gungor and G. P. Hancke, Eds., CRC Press, New York, NY, USA, 2013.

[41] D. Niyato, M. M. Rashid, and V. K. Bhargava, "Wireless sensor networks with energy harvesting technologies: a game-theoretic approach to optimal energy management," *IEEE Wireless Communications*, vol. 14, no. 4, pp. 90–96, 2007.