Spectrum-Aware and Cognitive Sensor Networks for Smart Grid Applications

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ABSTRACT

Recently, wireless sensor networks have been considered as an opportunity to realize reliable and low-cost remote monitoring systems for smart grid. However, interference due to nonlinear electric power equipment and fading as a result of obstacles in various smart grid environments from generation to end-user sides make realization of reliable and energy-efficient communication a challenging task for WSNs in smart grid. In this article, spectrum-aware and cognitive sensor networks (SCSNs) are proposed to overcome spatio-temporally varying spectrum characteristics and harsh environmental conditions for WSN-based smart grid applications. Specifically, potential advantages, application areas, and protocol design principles of SCSN are introduced. The existing communication protocols and algorithms devised for dynamic spectrum management networks and WSNs are discussed along with the open research issues for the fulfillment of SCSNs. A case study is also presented to reveal the reliable transport performance in SCSNs for different smart grid environments. Lastly, different energy harvesting techniques for SCSN-based smart grid applications are reviewed. Here, our goal is to envision potentials of SCSNs for reliable and low-cost remote monitoring solutions for smart grid.

INTRODUCTION

Smart grid has been conceived as the evolution of electric power systems to enhance the efficiency, reliability, and safety of the existing power grid. The need for the next-generation electricity network has arisen with the increasing demand for electricity, aging grid equipment, advancement of alternative energy resources, and climate changes to provide reliable, safe, and economical power delivery [1–4]. To this end, remote and timely information gathering from smart grid equipment about failures, capacity limitations, and natural accidents is extremely crucial for ensuring proactive and real-time diagnosis of possible blackouts and transient faults in the smart grid. This makes cost-effective remote monitoring and control technologies vital for safe, reliable and efficient power delivery in smart grid [5, 6]. An illustrative architecture of the smart grid is shown in Fig. 1.

Recently, wireless sensor networks (WSNs), which are mainly characterized by their collaborative, low-cost, and energy-limited nature, have gained attention for electric power network monitoring instead of wired systems. Reliable and efficient management of smart grid can be accomplished with the installation of wireless sensor nodes on critical power grid equipment [5, 6]. Gathered information from this equipment can help in responding to changing conditions and malfunctions of the electric grid in a proactive manner. Moreover, obtained information from sensors can be used to diagnose arising problems rapidly, and hence, autonomous and reliable operation can be achieved in smart grid. However, the realization of smart grid literally depends on the communication capabilities of sensor networks in harsh and complex electricity network environments that bring out great challenges for reliability and energy efficiency in WSNs.

To this end, the dynamic and opportunistic spectrum access capabilities of cognitive radio can be benefited to address many of the unique requirements and challenges of smart grid for WSNs: heterogeneous spectrum characteristics changing over time and space, reliability and latency requirements, harsh environmental conditions, and energy constraints of low-power sensor nodes. With their adaptability to existing spectrum utilization and characteristics in the deployment field, spectrum-aware and cognitive sensor networks can enhance overall network performance and spectrum utilization [7]. Promising advantages of spectrum-aware and cognitive radio equipped sensor nodes in smart grid can be outlined as follows.

Minimization of environmental effects: Field tests in [5] show that wireless links in smart grid are exposed to spatio-temporally varying spectrum characteristics due to electromagnetic interference, equipment noise, dynamic topology changes, and fading due to obstructions and hindrances. This leads to both time- and location-dependent delay and capacity variations of wireless links in smart grid environments. There-

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fore, to overcome varying link conditions in time and space domains, sensor nodes must be capable of reconfiguring themselves autonomously without hardware modifications. With the ability of dynamic and opportunistic access to spectrum, sensor nodes can mitigate these effects while minimizing energy consumption.

Access to licensed and unused spectrum bands: Different services operating in licensed bands of spectrum can be accessed by users in smart grid. Cognitive radio capability empowers sensor nodes to detect spectrum holes and access them without interfering with licensed users. Therefore, cognitive radio equipped sensor nodes can dynamically access vacant bands based on spectrum opportunities, and achieve higher capacity levels with the same amount of power consumption.

Adaptation to different spectrum utilization patterns: Smart grid is distributed over a large geographic area, and different spectrum utilization patterns can be experienced in these areas. Sensor nodes equipped with cognitive radio can continue reporting of sensed phenomena under different spectrum characteristics. Therefore, cognitive capability not only increases overall spectrum utilization, but also facilitates adaptation to different spectrum utilization patterns in smart grid as well.

Overlay deployment of multiple sensor networks: The existing WSN deployments are based on static spectrum apportionment. Since multiple nodes from different sensor networks try to send its information simultaneously, sensor nodes are subject to interference and collisions. Cognitive radio can provide efficient spectrum sharing between coexisting sensor networks in a fair manner.

In general, spectrum-aware and cognitive sensor networks (SCSNs) for smart grid can be specified as a distributed wireless network of spectrum-aware sensor nodes, which monitor the critical smart grid equipment and send their information dynamically over available spectrum bands in a multihop fashion to meet the application-specific requirements. Albeit the recent interest in power grid monitoring based on WSNs, the SCSN for smart grid is a vastly unexplored area. To the best of our knowledge, there is no comprehensive work on employment of cognitive radio sensor networks for smart grid applications. In addition to study of potential applications and communication algorithm needs of SCSNs, in this article we also investigate incorporation of energy harvesting techniques for different power grid segments to extend the limited lifetime of sensor nodes. Here, our objective is to envision the potential of SCSNs for smart grid applications, and discuss the open research issues in this timely and exciting field. The remainder of the article is organized as follows. The potential applications of SCSNs in smart grid are briefly discussed. The spectrum management functionalities in SCSNs are presented. The specific technical challenges and open research directions for the communication layers of SCSNs are summarized, and reliable transport performance in SCSNs for various smart grid environments is asses via a case study. Different energy harvesting solutions for SCSN-based smart grid applications are reviewed. Finally, the article is concluded.

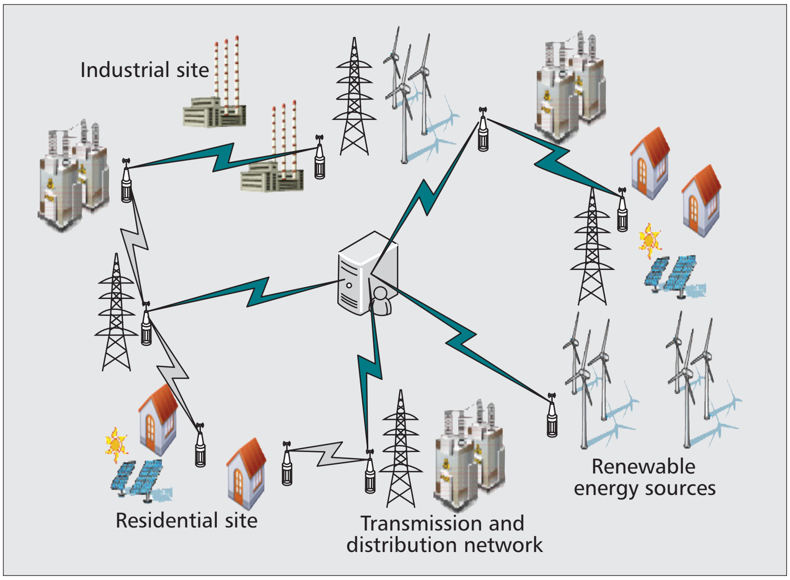

Figure 1. *An illustrative architecture of smart grid using sensor networks. Smart grid can be defined as a modernized electric power T&D network using robust two-way communications, advanced sensors, and distributed computing technologies to improve efficiency, reliability, and safety of power delivery and use.*

Potential Applications of SCSN in Smart Grid

WSNs have already started to be used in a diverse range of power grid applications from home area networks to power transmission and distribution (T&D) network monitoring [1, 5, 6, 8, 9]. In Table 1, an overview of some of these potential applications and their corresponding power grid segments are given [1, 5, 6, 8, 9]. In general, the electric power systems contain three major subsystems: power generation, T&D, and consumer facilities.

Remote Monitoring for Electric Power Generation Systems

A wide variety of sensors, such as current, voltage, and temperature, have been used in conventional electric power generation systems (EPGSs). Lately, green energy resources, such as wind power and solar energy, have been gaining popularity in electricity generation since such green electricity generation techniques meet environmental regulations by producing lower carbon emissions in contrast to conventional EPGSs. Due to variations and limitations on the availability of solar and wind power, real-time information obtained from green EPGS is crucial for electrical energy storage units.

Recently, employing wireless sensors in EPGS has been an active research field due to the collaborative nature and flexibility of WSNs [8]. However, realization of wireless remote monitoring applications in EPGSs is challenging due to the crowded spectrum problem in unlicensed bands. Moreover, performance of WSNs in smart

Applications	Power grid segment
Wireless automatic meter reading	Consumer side
Real-time pricing and demand response	Consumer side
Residential energy and load management	Consumer side
Line fault and power theft detection	T&D side
Outage detection	T&D side
Underground cable system monitoring	T&D side
Tower and pole monitoring	T&D side
Animal and vegetation control monitoring	T&D side
Conductor temperature and dynamic thermal rating systems	T&D side
Traditional power pant monitoring	Generation side
Wind farm monitoring	Generation side
Solar farm monitoring	Generation side

Table 1. *Summary of SCSN applications for smart grid vs. power grid segment.*

grid is severely restricted by packet losses, collisions, and contention delays due to spatio-temporally varying heterogeneous spectrum characteristics [10]. In this regard, the SCSN nodes can access the spectrum opportunistically to improve the overall network performance in terms of reliability and communication latency. In addition to remote monitoring of EPGS equipment, SCSNs can also be deployed for monitoring the workspace for the safety of staff.

Remote Monitoring for Electricity T&D Network

Transmission and distribution power networks are very critical power grid assets, where an equipment failure can result in electricity blackouts and various accidents. In T&D equipment monitoring, several variables, such as temperature, conductor thermal capacity, faulted circuit indicators, conductor sag, and conductor vibration, can be monitored [6]. Since transmission power lines are distributed over a large geographic area, different spectrum utilization patterns are exposed in these areas. Cognitive capability helps to adapt different spectrum patterns in smart grid easily. Substation monitoring and control is also important for the power grid [6]. The SCSN nodes can overcome challenges due to electromagnetic interference and fading in substations with their spectrum-aware nature. Moreover, the SCSN can achieve higher throughput with its DSA capability, and hence, surveillance of power lines and substations can be achieved with enhanced real-time communication capability of the SCSN, and bandwidth-greedy multimedia applications can be realized (e.g., power grid infrastructure security via video surveillance in smart grid).

Remote Monitoring for Consumer Facilities

Unlike the conventional power grid, effective power demand control of consumer facilities can be achieved in smart grid. With the opportunistic spectrum access capability of SCSNs, monitoring of consumer facilities' power consumption can be incorporated into smart grid without interfering with the existing communication infrastructure at the consumer side. Moreover, DSA capability can help to overwhelm environmental interference and fading. Based on gathered information from different users with various power consumption characteristics, such as industrial and home users, predictive and robust electrical power load balancing strategies can be developed [5].

As part of the end-user facilities, advanced metering infrastructures (AMIs) can also be efficiently realized with the use of SCSNs. SCSNs can contribute to AMI technology for self-configuration and easy deployment in coexisting wireless networks at different customer premises. With the spectrum-aware communication capability, AMI meters and equipment can be easily deployed at the remote sides to achieve seamless and reliable communication between a utility control center and AMIs. The SCSN nodes designed with consideration of energy and price limitations in remote monitoring can be the main components for efficient realization of wireless AMI.

Spectrum Management Requirements and Challenges of SCSNs

Minimization of environmental effects, adaptation to different spectrum utilization patterns, and overlay deployment of multiple sensor networks are some of the promising advantages of SCSNs in smart grid. However, the realization of SCSNs for smart grid mainly requires efficient spectrum management functionalities to dynamically manage the spectrum access of sensor nodes in harsh smart grid environments. Requirements and research challenges for main four spectrum management functionalities in cognitive radio, i.e., spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility, are explored below for SCSNs.

Spectrum Sensing

To take advantage of spectrum sensing in the SCSN, an efficient solution is needed considering both sensor network resource limitations and DSA network challenges. Considering the high numbers of sensor nodes in large-scale smart grid systems and low-cost requirements, it may not be feasible to equip sensor nodes with multiple radios and highly capable processors. Therefore, sophisticated spectrum sensing algorithms cannot be used. Spectrum sensing should be performed with limited node hardware, possibly using a single radio. Assuming that deployed sensor nodes in smart grid environments have single radios due to their scalability and low-cost requirements, sensing durations should be minimized as much as possible with the consideration of possible transmission activities and energy efficiency. There are various spectrum sensing methods, such as energy detection, feature detection, matched filter, and interference temperature [11]. Incorporating of one (or hybrid) of these techniques, detection of dynamically changing noise components in smart grid, and modeling of their interference with respect to time and space can be achieved.

Overall, the benefits of DSA, such as lower packet collisions due to the capability of switching to the best available channel, less contention delay and more bandwidth, come with the additional energy consumption caused by spectrum sensing and distribution of these sensing results. The trade off between energy efficiency and sensing accuracy is should be addressed and a detailed analysis of cost vs. benefits for a specific smart grid environment should be performed.

Spectrum Decision

With the DSA capability, sensor networks have ability to change their operating spectrum band when they decide that communication can be done in an another band with increased efficiency and QoS. Selecting one radio frequency as network-wide cannot yield the expected performance gain due to spatio-temporally varying spectrum characteristics. For example, power grid equipment may work periodically, since they may not be required to always work, and hence, their RF interference can also vary with time. In addition, some licensed band users, such as TV and cellular phones, may exist around, especially in consumer sites.

Parameter selection is crucial for efficiency of spectrum decision. These parameters include but not limited to spectrum sensing duration to data transmission ratio, transmission power, expected duration to spend in a channel without spectrum handoff, predictive capacity and delay, energy-efficiency and error rate. For underlay approaches and existing smart grid equipment RF interference, the trade-off between spectrum handoff and adaptation to ongoing channel must be investigated. Overall, this yields an optimization problem as to handoff or not to handoff based on channel conditions.

In distributed coordination approaches for spectrum decision, sensor nodes sense the radio spectrum and communicate their spectrum sensing and decision results to their neighbors in order to overcome the spectrum decision problems caused by the limited knowledge of spectrum availability and network topology [11]. Overall, energy efficient and scalable methods of spectrum decision mechanisms are yet to be investigated in order to efficiently realize the proposed SCSN for smart grid.

Spectrum Sharing

The transmissions in smart grid environments should be coordinated by spectrum sharing functionality to prevent packet collisions and multi-user colliding in crowded radio spectrum environments of the smart grid [11]. Importantly, different applications in smart grid may co-exist, and to satisfy their reliability and latency requirements, quality of service (QoS)-aware spectrum sharing schemes are essential for the proposed SCSN. To achieve this objective and thus overcome dynamically varying spectrum characteristics, the temporal and spatial reuse of spectrum must be benefited. In general, spectrum sharing functionality is closely related to medium access control (MAC) layer functionalit; thus, it can be incorporated into the MAC layer. Some of the main challenges against efficient spectrum sharing schemes include time-synchronization, distributed power allocation and spectrum utilization, and topology discovery. Overall, an effective spectrum sharing scheme helps to meet QoS requirements of smart grid applications by allocating network resources adaptively.

Spectrum Mobility

In SCSN for smart grid, spectrum handoff (or mobility) can be triggered by excessive interference caused by smart grid equipment. In case of excessive radio frequency (RF) interference and noise, ongoing communication should be carried onto an another channel selected by a spectrum decision algorithm. To have effective spectrum mobility functionality, the trade-offs between communication parameters must be well understood. Moreover, since spectrum mobility brings interruptions to ongoing communication, the schemes to prevent buffer overflows and minimize communication delay should be developed in order to allow reliable and real-time remote monitoring in SCSN. Based on changes in spectrum characteristics in time and space domains, spectrum handoff can be performed heterogeneously, which will yield heterogeneous link conditions on the way to the sink node. Since smart grid is spread over a large geographic area, spectrum mobility functionality is also critical for adapting to different spectrum regulations.

SCSN Communication Protocol Suite

Efficient operation of the proposed SCSN is tightly coupled with the running communication protocol suite. In addition to dynamic spectrum access, dense deployment, the event-driven nature, and energy efficiency concerns of the SCSNs, harsh environmental conditions and variable link capacity arise in smart grid environments. In this section, the SCSN-specific challenges for communication layers are briefly investigated due to space limitations, and then adaptive reliability control in SCSNs is addressed.

Physical Layer

To overcome spatio-temporally varying spectrum characteristics and fading, an SCSN node's physical layer must be configurable in terms of operating frequency, modulation, channel coding, transmission power, and spectrum sensing duration. This configuration should be based on spectrum sensing and decision results. Due to resource-limited nature and low-cost requirement of sensor nodes, implementing an RF front-end for an SCSN node is a challenging task. Importantly, the SCSN physical layer must

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be capable of providing statistical information about channel conditions to upper layers for empowering spectrum-awareness. Therefore, effective, energy-efficient, and yet practical cognitive radio for sensor nodes is essential for the realization of SCSN. Existing fundamental open research issues for the realization of physical layer of SCSN can be outlined as follows:

- In order to overwhelm temporally and spatially varying environmental RF interference in smart grid, adaptive power allocation schemes are essential. Interference problem due to dense deployment in sensor networks should also be considered. Designed solution must maximize energy usage efficiency.
- Adaptive modulation should be employed to maximize network life time and map application-specific QoS requirements to configurable parameters of the physical layer. An SCSN node's physical layer must be configurable without hardware modification. Thus, software-defined radios ensuring efficient DSA are needed for SCSN.
- Cooperative transmission schemes must be investigated to benefit from sender diversity in SCSN. Cooperative relaying can help to realize energy-efficient communication in such a harsh RF interference environment as SCSN.
- Statistical methods are required to help channel information gathering in physical layer. Considering limited processing capabilities and low-cost requirements of sensor nodes, practical signal processing algorithms should be developed to enable effective spectrum management, and spectrum awareness at upper layers.

DATA LINK LAYER

Efficient MAC and error control are the main functionalities of the data link layer. In the proposed SCSN, these objectives must be achieved in an energy-efficient manner with consideration of dynamic spectrum management challenges. We investigate MAC and error control in SCSNs separately as follows.

Medium Access Control — Resource limitations, dense deployment, and application-specific QoS requirements of sensor networks are exacerbated by spatially and temporally varying channel conditions in smart grid. Furthermore, event estimation, spectrum sensing, and channel identification requirements should be considered jointly to determine sleep schedules to reduce energy consumption in the network.

Additional challenges the MAC layer in SCSN must handle to empower DSA are outlined as follows:

- Solutions with minimum control overhead and no additional hardware requirements, such as an additional transceiver, should be developed.
- Joint consideration of spectrum sensing and duty cycling is required to balance the trade-off between energy efficiency and spectrum efficiency.
- A novel spectrum-aware MAC protocol should be developed. It must jointly consider spatial correlation of sensed phenomena, energy efficiency requirement of sensor nodes, and contention due to dense deployment.

Error Control — With its multiple channel access ability, and dynamically varying spectrum conditions, a fixed forward error correction (FEC) scheme may not yield optimal results for every channel. Hence, the error correction mechanism must consider this trade-off, and adaptive FEC schemes or hybrid automatic repeat request (ARQ) mechanisms can be employed. Enabling spectrum-aware energy-efficient error control mechanisms can be made possible with the consideration of the following additional challenges.

- Cooperative schemes based on HARQ can be developed to help lost packet recovery. Nodes receiving the transmitted information can keep this information for a while although they are not the destination node, and can retransmit based on loss prediction or ARQ. Moreover, cooperative relaying schemes may be employed by relay nodes to increase probability of successful packet forwarding. However, efficient synchronization of sensor nodes is required in this case.
- Repetitive ARQs due to harsh smart grid environmental interference can block packet forwarding and cause congestion due to excessive incoming packets. Added redundancy by FEC employment must be spectrum-aware and predictive such that it must adapt to spatially and temporally varying environmental interferences, and rapidly react to spectrum handoffs.
- Cost vs. benefit analysis of employing FEC, ARQ, hybrid, and cooperative schemes should be well investigated with consideration of spectrum handoff and licensed user activity to provide energy conservation maximization.

ROUTING LAYER

DSA capability provides interference minimizing opportunity in route selection through the sink node. Moreover, spectrum sensing durations are a limiting factor for the throughput of sensor nodes. Moreover, in order to detect variations in the environmental interference, spectrum sensing durations also vary depending on spatially varying characteristics of RF interference sources on the path to sink. Open research issues in SCSN for routing layer are stated below.

- Multipath routing can be employed to benefit from path diversity for interference mitigation.
- Cooperative routing schemes, such as diffusion-based cooperative routing protocols, can be developed to increase energy efficiency on packet forwarding.
- Depending on spatial variation of environmental interference, different channels can be benefited for forwarding on the event-to-sink path. To this end, s spectrum-aware multichannel routing algorithm can be developed that is maximizing spectrum usage efficiency while minimizing exposed event-to-sink delay.
- Moreover, spectrum decision mechanism should be in contact with the routing layer; that is, spectrum decisions must be performed after investigation of trade-off between spectrum handoff and adaptation of the routing layer to the concurrent operating channel.

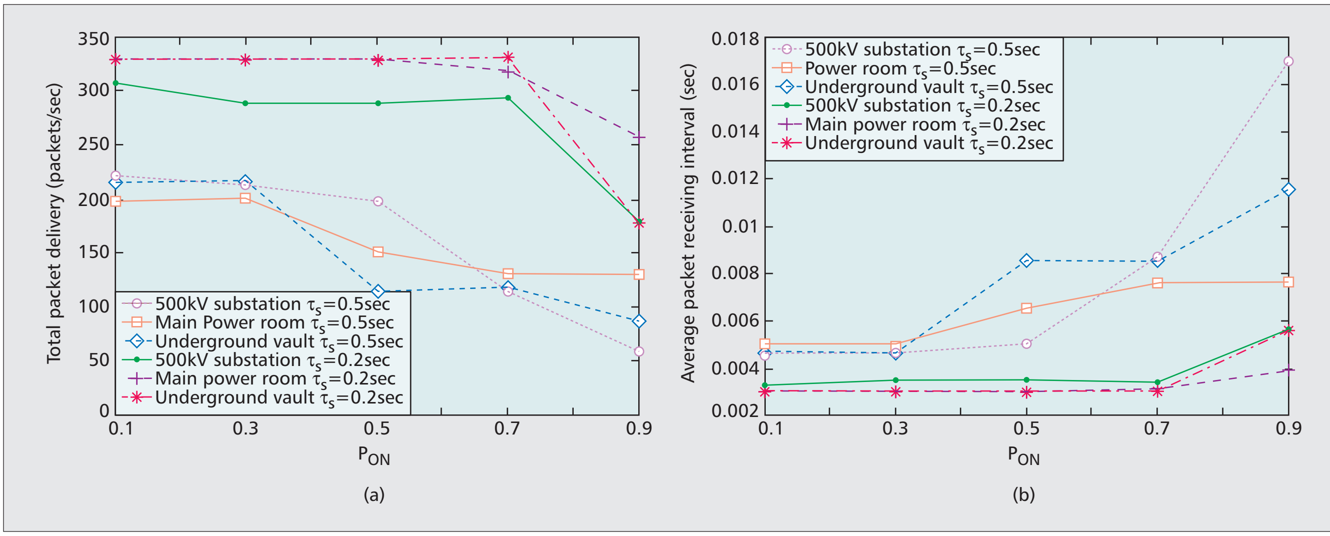

Figure 2. *Variation of: a) packet delivery; b) packet receiving interval with respect to licensed user ON probability (P_{ON}).*

Transport Layer

Reliability and congestion control become an extremely challenging task with integration of cognitive radio and sensor networks [10, 12]. In SCSNs, congestion control algorithms must be aware of the cognitive cycle, and should perform load balancing in a distributed manner. Spatially and temporally varying lossy links make rate control a very challenging task, requiring careful design for congestion avoidance. Moreover, control packet exchanges must be minimized and congestion control mechanism must be proactive to help energy harvesting. Furthermore, in SCSNs, environmental RF interference further amplifies the challenges emerging from union of those. Open research directions for reliability and congestion control in SCSNs are summarized as follows.

- Statistical rate control schemes must be developed to provide reliable event transport under varying spectrum characteristics and spectrum sensing durations. Obviously, a rate control algorithm must not aim to maximize rate and reach maximum bandwidth utilization; instead, it must aim to maximize reliability.
- Furthermore, real-time requirements of time-critical applications should be considered; as well as maximizing reliability, real-time transport protocols must minimize delay. This requires additional information at source nodes to determine event-to-sink path characteristics, and apply rate control to minimize delay while satisfying reliability.

A Case Study of Reliable Transport in Different Smart Grid Environments

We have performed simulation experiments to reveal the reliability performance of cognitive radio equipped sensor nodes in smart grid [10]. A wireless channel model and parameters that were determined in our previous study via field test experiments in different spectrum environments of a power grid (e.g., 500 kV substation, main power room, and underground network transformer vaults [5]) are used in simulations. Experimentally determined log-normal channel parameters for different power system environments are given in Table 2. Two hundred nodes and a sink are placed randomly in a 100 m × 100 m field. Ten source nodes are randomly selected within an event area of radius 15 m, and transmit power (P_t) is set to 10 dBm. Sensor nodes activity pattern with time consists of data transmission (τ_t), spectrum sensing (τ_s), and spectrum handoff (τ_h) intervals. Transmission interval τ_t is 1.5 sec in simulations. As licensed user communication is detected, an accessed channel is vacated and spectrum handoff is performed. For the smart grid environment, licensed user activity can be perceived as wireless channel conditions that restrict communication of sensor nodes. TFRC [13] is used as the transport protocol in the simulation experiment, and packet size is limited to 100 bytes. Ten channels are created for each power grid spectrum environment (e.g., 500 kV substation, main power room, and underground network transformer vault), given in Table 2.

In Figs. 2a and 2b, to gain more insight regarding the challenges of reliable transport in SCSNs, comparative performance evaluations in terms of packet delivery rate and average packet receiving interval are presented, respectively. Increase in the spectrum sensing duration caused a downswing in the packet delivery performance of about 30 percent for each environment. Moreover, with increasing P_{ON} packet delivery performance decays. Average packet receiving interval increases four times with increasing licensed user activity. Extended simulations and their detailed discussions for delay-sensitive and multimedia communications can be found in [10].

Energy Harvesting in SCSN

While communicating a sensor node's power consumption is on the order of a few milliwatts, it reduces to a few microwatts in sleeping periods. In addition to transmission distance, power consumption of SCSN nodes alter based on the spectrum conditions and different factors, such as employed frequency band, environmental

Power system environment	Path loss (η)	Shadowing deviation (s)	Noise level (dBm)
500 kV substation	2.42	3.12	–93
Main power room	1.64	3.29	–88
Underground network transformer vault	1.45	2.45	–92

Table 2. *Log-normal shadowing path loss model parameters for different smart grid environments.*

noise, licensed user interference limitations, and spectrum sharing policies with other unlicensed networks. Since battery maintenance and wiring for densely deployed sensor networks in smart grid is not a feasible solution, extending battery lifetime is a significant challenge. Meanwhile, mains power might be available in some of the WSN-based smart grid applications, such as in residential energy management. However, sensor nodes, which are deployed in high voltage smart grid environments, will still need appropriate power sources. Recently, a few energy harvesting techniques have been introduced [14]. Energy harvesting can enhance the performance of SCSNs with self-charging (i.e., self-healing) capability. Unattended energy in the environment, such as solar, mechanical, thermal, and magnetic, can be scavenged to energize sensor nodes. Possible energy harvesting techniques for SCSNs are summarized in Table 3, and explained below.

Magnetic induction: Generated magnetic field by the AC current carrying power lines can be used to induce electric current, and hence, power for sensor nodes. Sensors nearby power lines can benefit from magnetic flux linkage opportunity, and harvested energy can be used for battery recharging purposes.

Modulated backscattering: Recently, modulated backscattering is proposed for sensor networks, in which radiated wave is backscattered by a source node and modulated accordingly [15]. With modulated backscattering, only the receiver node is required to consume power, since the source node only modulates the received signal. If the receiver node has battery charging opportunity, such as a node that has energy harvesting opportunity and capability by magnetic induction, network lifetime can be greatly extended by the employment of modulated backscattering at the source node.

Other energy harvesting opportunities: Apart from magnetic induction and modulated backscattering, there are piezoelectric, pyroelectric, thermoelectric, solar, and electrostatic energy harvesting techniques that can also be employed in SCSNs for smart grid. While solar harvesting techniques are only applicable to sensors placed on outdoor equipment, pyroelectric and thermoelectric are applicable to sensors placed on both outdoor and indoor equipment. Piezoelectric and electrostatic harvesting techniques exploit mechanical strain deformation and vibration motion to acquire electrical energy, respectively.

CONCLUSION

Recent field tests show that reliable communication in smart grid is a challenging task for WSN-based smart grid applications due to electromagnetic interference, equipment noise, dynamic topology changes, and fading. In this article, spectrum-aware and cognitive sensor networks (SCSNs) are introduced to provide reliable and efficient communication for remote monitoring applications in smart grid. First, SCSN-based applications are explored for power generation systems, T&D networks, and consumer facilities. Then the challenges and requirements of spectrum management functionalities (i.e., spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility) are discussed from the perspective of SCSNs. The communication protocol suite is discussed from the perspective of SCSNs, while putting emphasis on open research directions. A case study is presented to uncover reliable transport performance in SCSNs for various smart grid environments. Lastly, different energy harvesting techniques for SCSN-based smart grid applications are reviewed. We have provided a contemporary perspective on the current state of the art in remote monitoring and control of smart grid via SCSNs.

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Energy harvesting technique	Effect	Energy source	Principle
Magnetic induction	Electromagnetic	Current passing lines	Magnetic fields
Modulated backscattering	Wave backscattering	RF source	Sender modulates received wave
Piezoelectric	Piezoelectric materials	Vibrations	Deformation of piezoelectric materials
Pyroelectric	Pyroelectric materials	Heat	Temperature increase or decrease
Thermoelectric	Seebeck effect	Heat	Thermal gradients
Solar	Photovoltaic effect	Sun	Cells with reverse biased pn+ junction
Electrostatic	Mechanical	Vibrations	Oscillation based varactor plate movements

Table 3. *Summary of existing energy harvesting techniques for SCSN.*

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