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Spectrum-aware bio-inspired routing in cognitive radio sensor networks for smart grid applications

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ABSTRACT

Cognitive radio sensor networks (CRSNs) have been proposed to serve as a reliable, robust, and efficient communications infrastructure that can address both the existing and future energy management requirements of the smart grid. The existing and envisioned applications of CRSN-based smart grid include substation automation, overhead transmission line monitoring, home energy management, advanced metering infrastructure, wide-area situational awareness, demand response, outage management, distribution automation, asset management. To realize these applications, in this paper, honey bee mating optimization-based routing and cooperative channel assignment algorithms have been proposed. The developed framework significantly decreases the probability of packet loss and preserves high link quality among sensor nodes in harsh smart grid spectrum environments. The proposed approach performance has been evaluated in terms of packet delivery ratio, delay, and energy consumption demonstrating that it has successfully addressed the QoS requirements of most of the SG applications presented.

1. Introduction

The existing power grid is built a century ago, which means its outdated and does not meet the new power demands. Wireless sensor networks (WSNs) have been proposed to effectively monitor, control and operate the power grid [1]. The existing and envisioned applications of WSN-based smart grid include substation automation, overhead transmission line monitoring, home energy management, advanced metering infrastructure, wide-area situational awareness, demand response, outage management, distribution automation, asset management. It is evident that these applications have different quality of service (QoS) requirements in terms of bandwidth, reliability and latency as shown in Table 1 [1]. However, recent field tests have shown that wireless links in smart grid environments have high packet loss rates and varying link qualities because of power grid equipment noise, obstructions, electromagnetic interference, multipath effects, and fading [3]. In these field tests, it has been observed that the average noise level varies between −89 dBm and − 93 dBm in outdoor 500 kV substation environments. Please note that this noise level is much higher than that of outdoor noise levels, which has been observed as − 105 dBm. Thus, the main design challenge of WSN-based smart grid applications is to enable reliable and energy-efficient data delivery under adverse wireless communication conditions of smart grid propagation environments [4].

To this end, cognitive radio sensor networks (CRSNs) can resolve the bandwidth scarcity issues in smart grid by permitting a sensor node to transmit in unused spectrum holes without causing harmful interference to neighboring nodes. In CRSN, if a secondary user (SU) encounters the high noise and/or primary user (PU), it changes its spectrum band or stays in the same band without creating interference with the licensed-user by adapting its radio parameters. In unlicensed spectrum bands, all users have the same right to access the unlicensed spectrum bands by avoiding noisy channels [5]. Hence, CRSNs can enhance the spectrum utilization efficiency to address communication challenges of WSN-based smart grid applications, which are time and location dependent link-quality variations, harsh environmental conditions, resource, energy, and memory limitations of sensor nodes.

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Table 1
QoS requirements of WSN-based smart grid applications [1,5].

Applications	Bandwidth	Reliability	Latency
Price signalling	9.6–56 kbit/s	99%	2000 ms
Substation Automation (SA)	9.6–56k kbit/s	99.0–99.99%	15–200ms
Overhead Transmission Line Monitoring	9.6–56 kbit/s	99.0–99.99%	15–200ms
Automated feeder switching	9.6–56 kbit/s	99%	1000–2000ms
Home energy management	9.6–56 kbit/s	99.0–99.99%	300–2000ms
Distribution Automation (DA)	9.6–56 kbit/s	99.0–99.99%	20–200ms
Distribution Management (DM)	9.6–100 kbit/s	99.0–99.99%	100 ms-2 second
Wide-Area Situational Awareness	600–1500 kbit/s	99.0–99.99%	15–200ms
Advanced metering infrastructure	10–100 kbit/s per node, 500 kbit/s for backhaul	99.0–99.99%	2000ms
Demand Response	14–100 kbit/s per node	99%	500-ms several minutes
Outage Management	56 kbit/s	99.0%	2000ms
Residual energy management	9.6–56 kbit/s	99%	1000ms
Asset Management	56 kbit/s	99.0%	2000ms
Vehicle to Grid (VG)	9.6–56 kbit/s	99.0–99.99%	2sc-5 min

To address these challenges, in this paper, a honey bee mating optimization-based routing and cooperative channel assignment algorithms for WSN-based smart grid applications is proposed. The proposed communication framework deals with the channel impairments by opportunistically switching among different spectrum bands and employs clustering-based routing for organizing CRSN into a connected hierarchy for load balancing and prolonging lifetime of CRSNs in the smart grid. To this end, the dynamic spectrum access capabilities of the proposed system are benefited to mitigate the noisy and congested spectrum bands, yielding reliable and high capacity links for low-power wireless communications in smart grid. The developed approach significantly decreases the probability of packet loss and preserves high link quality among sensor nodes in various smart grid applications. Overall, the main contribution of this paper is the design of spectrum-aware and bio-inspired routing algorithm maximizing spectrum usage efficiency in harsh smart grid spectrum environments. Comparative performance evaluations demonstrate that the proposed approach is efficient in terms of packet delivery ratio, delay and energy consumption.

The rest of this paper is organized as follows. Section 2 discusses the related work. Section 3 explains the proposed clustering, channel assignment and routing algorithms. Section 4 presents the network model, channel model and simulation parameters. Section 5 shows comparative performance results. Finally, Section 6 concludes the paper.

2. Related work

Due to late recognition of smart grid applications, the research on smart grid communications protocols design is found to be limited [2]. Although some QoS-aware routing protocols [5–13] for smart grid exist, but their scope is limited to certain smart grid applications, such as price signaling, automated metering, and emergency handling. The majority of these existing solutions have been designed to meet application-specific design objectives and requirements in a particular scenario. Though these studies guide design decisions for WSN-based smart grid applications, most of the existing routing schemes achieve one or two of these design objectives at the expense of others. For example, energy saving during data collection introduces excessive delay in the network. Moreover, they generally ignore the impact of external interference and noise on transmission reliability in harsh smart grid (SG) environments [2]. Furthermore, they do not have the ability of channel adaptation to alleviate the interference induced at a certain channel due to the power grid equipment.

Recently, cognitive radio sensor networks (CRSNs) have been proposed to serve as a reliable, robust and efficient data aware communications infrastructure that can address both the existing and future energy management requirements of the SG [5]. The study in [5] proposes a QoS-aware communication framework in CRSNs for smart grid applications. The designed framework provides energy efficient data delivery with low end-to-end delay in the network. However, it faces the problem of data redundancy and node memory overflow during routing, which leads to high data packet collisions in the network. In addition, it does not consider the issue of unnecessary multi-hop data packet transmission and data path looping in the network.

Furthermore, in [15] a spectrum-aware cluster based routing scheme for CRSNs is proposed. However, it consumes a significant amount of energy while finding an appropriate next hope relay node in the network. Therefore, the routing in CRSNs in the context of collision free cooperative spectrum sensing is still an important problem for SG applications, yielding bursty traffic depending on the event characteristics. Recent field tests show that the time varying nature of the smart grid environment due to the variations of spectrum availabilities needs frequent re-channel assignment [1,4]. However, the existing network solutions due to their fixed or inefficient channel allocation strategies fail to handle dynamic spectrum access challenges and thus, they are not resilient or efficient enough to provide desired reliable data delivery for WSN-based smart grid applications [2].

Although these studies [5–15] provide valuable insights for WSN-based smart grid applications, they generally ignore the impact of fading, external interference and noise on transmission reliability in smart grid. Moreover, they do not incorporate dynamic channel adaptation to mitigate the interference induced at a certain channel due to the power grid equipment, and hence, the delay and energy efficiency performance is substantially hampered for the sake of achieving communication reliability. Therefore, in this study particular importance is given to design an energy-efficient bio-inspired routing scheme improving spectrum usage efficiency in harsh smart grid environments. The comparison table showing the differences between the proposed approach and the existing studies is presented in Table 2. In this table, the reliability is a metric of how reliable a communication system can perform data transfers. Some of the SG applications, such as substation automation, overhead transmission line monitoring, automated feeder switching, expect highly reliable data communication, and some of them can tolerate some packet losses in communications. In addition, throughput is the rate of successful message delivery over a communication channel for SG applications presented in Table 1. The energy efficiency is the usage of less energy to provide the same services for long time for various SG applications. Generally, the design and implementation of WSNs is mainly constrained by limited battery energy supply. For this reason, communication protocols for WSNs-based SG applications are mainly tailored to provide high energy efficiency.