Ad Hoc Networks 22 (2014) 43–60

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Quality-of-service differentiation in single-path and multi-path routing for wireless sensor network-based smart grid applications

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ARTICLE INFO

Article history:
Received 28 September 2013
Received in revised form 19 April 2014
Accepted 13 May 2014
Available online 20 May 2014

Keywords:
Wireless sensor networks
Smart grid
QoS differentiation
Single-path routing
Multi-path routing

ABSTRACT

Electrical grid is one of the most important infrastructure of the modern nation. However, power grid has been aged over 100 years and prone to major failures. The imbalance between power demand and supply, the equipment failures and the lack of comprehensive monitoring and control capabilities are other important signs to take incremental steps for switching to a smarter power grid with effective communication, automation and monitoring skills. This new concept is named as *smart grid*, which is a modern power grid system with advanced communication, monitoring, sensing and control capabilities. Wireless sensor network (WSN) concept places an important role in this modernization process of the power grid with its efficient and low-cost deployment characteristics. However, harsh and complex smart grid environmental conditions, dynamic topology changes, connectivity problems, interference and fading may pose some challenges for the communication performance of WSN technology. For this objective, in this paper, the use of multi-path and single-path QoS-aware routing algorithms under harsh SG environmental conditions is investigated in order to evaluate their service differentiation capabilities in reliability and timeliness domains. In this regard, this study is an important step towards developing novel routing protocols specifically designed for smart grid environments.

1. Introduction

Recently, the increasingly growing population and diminishing power resources have threatened the electric utilities in generating and distributing the necessary electricity and forced them finding new ways to generate the electricity with renewable energy resources. The imbalance between power demand and supply is one of the problems of the electric utilities, since generating electricity more than the actual necessity may result in huge electricity lost due to the non-existence of the advanced electricity storage options. In addition to the imbalance between power demand and supply, the equipment failures and the lack of comprehensive monitoring and control capabilities are other important signs to take incremental steps for switching to a smarter power grid with effective communication, automation and monitoring skills. This new concept is conceived as *smart grid* (SG), which is a modern power grid system with advanced communication, monitoring, sensing and control capabilities.

In general, SG is a distributed system that many of its components are spread over a wide range of area. Thus, a reliable communication and coordination between distributed components of such systems is required for the safety

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http://dx.doi.org/10.1016/j.adhoc.2014.05.005
1570-8705/

and reliability of the power delivery system. To this end, effective management and reliable operation of SGs can be achieved with the installation of wireless sensor nodes on the critical power grid equipments. In these systems, collected sensor data can be used to diagnose arising problems quickly, and hence, system breakdowns due to the cascading effect initiated by a single fault in the power grids can be prevented.

Recently, wireless sensor networks (WSNs) have been used in different SG applications, including power fraud detection, wireless automatic metering, overhead transmission line monitoring, load control, fault diagnostics, demand response, outage detection, and distribution automation. All these applications have different quality-of-service (QoS) requirements in terms of reliability, latency, bandwidth, as listed in Table 1. On the other hand, field tests show that SG systems have also harsh and complex environmental conditions, dynamic topology changes, connectivity problems, interference and fading [1,2]. All these effects cause great challenges in the reliability of WSN communications in SG applications. Furthermore, most WSN-based SG applications include a large number of wireless sensor nodes spread over the deployment field. In these applications, the lack of predetermined network infrastructure requires the WSNs to establish multi-hop connections and maintain network connectivity autonomously. Hence, reliable multi-hop routing and QoS differentiation have become an essential issue to design WSN-based SG applications.

Although there has been an increasing interest in SG applications based on WSNs, wireless multi-hop routing in different SG environments still remains unexplored. To the best of our knowledge, there exists no work on performance evaluations of reliable multi-hop routing protocols specifically for harsh SG spectrum environments. To address this need, in this paper, the performance of QoS-aware single-path and multi-path multi-hop routing protocols is investigated for different SG environments. Specifically, we evaluateSPEED and MMSPEED routing protocols in terms of latency, reliability, and overhead to better understand their advantages and disadvantages in different SG spectrum environments. In addition, we also present potential applications of WSNs in SG along with the related research challenges. Consequently, the main contributions of this study can be summarized as follows:

- The research challenges of WSN-based SG applications have been presented.
- A routing approach has been presented to handle the challenges and communication requirements of SG applications.
- Multi-path and single-path QoS-aware routing algorithms which aim service differentiation in reliability and timeliness domains have been explored. The performance evaluations of these routing algorithms, namely SPEED and MMSPEED, under harsh SG environmental conditions have been studied to better develop future routing protocols specifically for SG environments.
- The performance evaluations in this paper are based on the previous work of Gungor et al. [2] which includes field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different SG environments including a 500 kV substation, an industrial power control room, and an underground network transformers vault [2]. Log–normal shadowing channel model has been implemented in J-SIM simulator [4] to realistically model the wireless channel in different SG environments.

Table 1
Smart grid application requirements [3].

Application	Latency requirements	Reliability requirements (%)
Advanced metering infrastructure	2000 ms	99.0–99.99
Distributed generation	300–2000 ms	99.0–99.99
Electric transportation	2 s to 5 min	99.0–99.99
Asset management	2000 ms	99.0
Demand response	2000 ms	99.0
Wide area situation awareness	20–200 ms	99.0–99.99

The remainder of the paper is organized as follows. Section 2 briefly describes various WSN-based SG applications. In Section 3, research challenges for WSN-based SG applications are presented. Related work on reliability-aware and link-quality-aware routing protocols for WSNs is summarized in Section 4. Proposed routing approach and overview of simulation results are presented in Section 5 and in Section 6, respectively. Finally, the paper is concluded in Section 7.

2. WSN-based smart grid applications

The existing power grid has been causing critical problems to the humanity and to the electric utilities due to the structural characteristics of the aging electricity infrastructure. The equipment failures, the lack of comprehensive communication infrastructure and monitoring abilities, and the continues uncertainty to be able to provide demand-response balance are the important signs to take incremental steps for switching to a smarter grid with effective communication, automation and monitoring skills. Hence, WSN-based SG applications are the proper choice to be used in a wide variety of SG environments to provide efficient, low-cost, flexible, expandable communications network for advanced monitoring, analysis and data transmission purposes.

WSN-based SG applications can be grouped into three main categories, e.g., generation side, transmission and distribution side, and consumer side. The consumer side WSN-based SG applications have a focus on home energy management and demands response, while generation side and transmission and distribution side applications have narrowed down their focus on monitoring, controlling the specific equipments of SG. From generation to consumer side, there are tremendous number of WSN-based SG applications, e.g., smart metering, remote power system monitoring and control, electricity fraud detection, fault diagnostics, demand response and dynamic pricing, load control and energy management, and equipment fault