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The impact of scalable routing on lifetime of smart grid communication networks

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ABSTRACT

The paradigm of sensors organized in a multi-hop wireless network has been recognized as a cost effective way to satisfy the real-time sensing and communication needs of a smart grid. For wireless sensor networks, one of the most important design goals is the maximization of network lifetime. Scalability, on the other hand, is also of utmost importance for any given network design problem and especially in a wide area smart grid deployment scenario. Improving scalability requires the network flows to be more localized, however, localizing network operations works against the utilization of some optimal paths required for load balancing and lifetime prolonging. Therefore, lifetime maximization and scalability are two design criteria acting against each other. In this study, a characterization of achievable network lifetime as a function of level of localization of the routing operations under optimal conditions is performed using three localized routing approaches. We build a novel Mixed Integer Programming (MIP) framework with a special emphasis on the details of energy dissipation terms in sensor nodes to model the network behavior correctly. Numerical analysis performed using the developed MIP framework enables us to quantify the impact of different levels of route localization on network lifetime.

1. Introduction

The condition of traditional power grids has been started to be questioned after major blackout events affected around 60 million people in Northeast of the United States and Canada on 14th August 2003 and in Italy and Switzerland on 28th September 2003 [1,2]. These incidents unveiled the deficiency in communication, automation, monitoring, and diagnostic tools which failed in determining and evaluating the condition of the power system and had delay in recovery even after a single outage [3–5]. After discovering the need to improve the traditional power systems, institutes such as U.S. Department of Energy (DoE), European Technology Platform (ETP), and Electric Power Research Institute (EPRI) established their smart grid programs for the years 2020 and beyond [6–8]. The vision of smart grid programs is resilience and energy efficiency, future system adaptation, self-healing and automation, and reduction of carbon emissions in power grids. To achieve these goals, the next generation power grids have to incorporate various smart grid applications such as distributed renewable energy generation, distributed storage, sophisticated energy management in consumer side, and intelligent and interactive consumer applications which need improved monitoring, analysis, and control functions [3,4,9,10].

The heart of the smart grid revolution is the ability to monitor the status of the electric grid in a more accurate and fine-grained way. Hence, the real-time communication

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system is the main part of the smart grid vision. This system could be implemented using various communication technologies including wired, wireless, and power line communication. In the traditional power grid, monitoring and diagnostic systems are realized through wired communications. However, wireline communication systems require high cabling costs in installation and maintenance especially due to the wide geographical spread of the utility assets [11]. For instance, to monitor a typical utility comprised of 25,000 km of power lines and thousands of transformers, capacitors and breakers spread over an 80,000 km^2 area requires over 100,000 distributed sensors and sources of data [12]. Thus, a wireless ad hoc networking approach could be a preferable solution due to low installment and operation costs. It was stated that most utility and billing companies have also recognized that wireless communication becomes one of the most cost-efficient way to collect utility meter data with the invention of low-cost low-power radio sensors [11].

Cost may not be the only differentiator. Available wireless sensor technologies (such as Mica2 motes from Crossbow [12]) could play a significant role in smart grid [13,14] also due to other advantages such as high fault-tolerance, scalability, high sensing fidelity, improved accuracy and larger coverage. As a matter of fact, applications based on Wireless Sensor Networks (WSNs) such as wireless smart meter, deployment of ultra low-power wireless sensor nodes to measure power consumption of residential consumers, remote monitoring and wireless automated meter reading have been started to be implemented by various utility industries in USA and Japan. In addition, numerous WSN applications have increasingly been implemented in transmission and distribution side (T&D) and generation side of smart grids. In Table 1, a categorization of WSN based applications in smart grids is presented [14]. A study by DoE indicates that deployment of WSNs in the industry could improve the production efficiency by 11–18% while reducing the industrial emissions by more than 25% [15].

Table 1
WSNs based smart grid applications [14].

Smart grid side	Application
Consumer side	Wireless automatic meter reading Residential energy reading Automated panels management Building automation Demand-side load management Process control monitoring Properties control monitoring Equipment management and control monitoring
T&D side	Equipment fault diagnostics Overhead transmission line monitoring Outage detection Underground cable system monitoring Conductor temperature rating systems Overhead and underground fault circuit indicators Cable, conductor and lattice theft Conductor temperature and low-hanging conductors Insulators Fault detection and location Animals and vegetation control
Generation side	Real-time generation monitoring Remote monitoring of wind farms Remote monitoring of solar farms Power quality monitoring Distributed generation

For implementing wide-area smart grid systems, a multi-hop network architecture is essential. The sensors collect the data such as meter readings or failure information and send it to a base station possibly via other sensor nodes acting as relays. The base station has a gateway functionality and is controlled by the grid operator.

There are multiple challenges for a successful deployment of wireless sensor networks in smart grids. Power management, interoperability, security, scalability, resource constraints, reliability and latency requirements, and harsh environmental conditions are just some of these challenges [11,14]. These challenges are either due to the nature of WSNs or arise from the harsh environment of smart grids. We note that in some of the applications mentioned in Table 1 (*e.g.*, the monitoring of transmission lines via sensors) the network is not restricted with energy since the energy can be fed from the transmission lines easily. On the other hand, in other applications, due to physical limitations, feeding energy from transmission lines is not an option and it is difficult to charge or replace the battery of a wireless sensor node (for instance when the node is deployed on a monitored device such as solar panel, wind tribune or substation). Hence, energy-efficient networking protocols must be utilized for maximization of the network lifetime.

In multi-hop wireless networks, one important design issue is routing; how to select the path to send the data to the destination. In the literature, there are many routing protocols designed for Wireless Sensor Networks (WSNs). These protocols could be analyzed and compared using various performance metrics. In our vision, we consider scalability as one of the most important metrics for evaluating routing protocols in WSNs deployed in large-scale smart grid applications. In this context, scalability could be defined with respect to network size (*i.e.*, the ability to accommodate the growth in the number of nodes deployed in the network).

When we look at traditional large networks (*e.g.*, Internet), we see that scalability of routing is mainly achieved by dividing a routing domain into several routing areas (autonomous systems) [16]. Different routing protocols are used within and between autonomous systems, complementing each other for end-to-end packet delivery. To put it in more precise terms, an intra-autonomous system routing protocol is used first to bring the data packets to a special gateway router which then runs an inter-autonomous protocol. Finally, another – possibly different – intra-autonomous routing protocol is used to reach the ultimate destination. With this hierarchy, routers need to keep only partial information about the Internet topology (with less memory and processing overhead). Consequently, a more scalable and efficient operation could be achieved.

One distinguishing feature of WSNs is the many-to-one traffic pattern (*i.e.*, rather than a peer-to-peer communication paradigm, the base station is the sink of all data traffic). Hence, a good option to apply the idea of autonomous systems is to make the base station a member