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Learning automata-based multi-constrained fault-tolerance approach for effective energy management in smart grid communication network

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ABSTRACT

Smart grid networks aim to overcome the inadequacies of the existing electricity grids infrastructure. These networks may exhibit faults due to over-usage of data on electricity grids. Moreover, they must be configured such that energy utilization can be minimized while dealing with energy delivery networks. In order to optimize the performance of smart grids on these two issues of fault tolerance and energy management, a learning automata (LA)-based data transmission path selection algorithm with multiple constraints such as cost, delay, and energy consumption is proposed in this paper. The proposed algorithm named LAMCR is simulated for a real-time environment using NS-2 and is evaluated for QoS parameters such as packet delivery ratio, end-to-end delay, and energy consumption. LAMCR is tested and compared with the legacy systems such as OMCR (Kuipers et al., 2002) and HWMP (Zhu et al., 2011). The results show that LAMCR performs better, while exhibiting higher packet delivery ratio, lesser delay, and lower energy consumption, which improves the throughput of the system.

1. Introduction

An electric grid (Misra et al., 2014; Lorenz and Orda, 1998; Van Mieghem and Kuipers, 2004; Xue and Makki, 2007), in general, refers to the electrical network of transmission lines, transformers, and anything that is used to deliver electricity from a power plant to the points of consumption. Due to the limitation in traditional electric grids, smart grids have been designed to enable reliable, efficient, and cost-effective power supply to the end users. A smart grid system has an underlay electricity network and an overlay communication network (Misra et al., 2014). A smart grid architecture comprises a network of nodes such as power station, substations, and power appliances. Smart grid concerns communication among these nodes.

The conventional electricity distribution system faces many challenges due to the growth in human population and their increased use of power in various electrical appliances. Currently, power consumption by the end users has increased substantially, while there has not been any substantial increase in the production of power. Smart grids (Misra et al., 2014; Lorenz and Orda, 1998; Van Mieghem and Kuipers, 2004; Xue and Makki, 2007) have been envisioned to solve some of these problems. To solve these issues, either the power production needs to be increased or the power utilization must be controlled. The smart meters in the smart grid system help in various ways such as management of the power utilization by the end users based on the power consumption pattern and the corresponding unit prices, and distribution of power in a cost effective manner.

1.1. Motivation

QoS in smart grids applies to all stages, i.e., power generation, transmission and finally distribution to the end user. QoS in smart grid networks is an important issue because of their real-time nature. The QoS of a system can be ensured by supervising, guarding and improving the operation of the interconnected elements. The interconnected elements of a smart grid are the central generator, distributed generator, industrial users, automation system, energy storage elements, end users, electric components and household devices. Providing QoS in smart grid networks with fault tolerant capability is a challenging task. This serves as the *motivation* behind our work.

The smart grid structure is hierarchical in nature (Li and Zhang, 2010). In the hierarchy, the control room is in the topmost level, power appliances in the last level and the substations in the

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middle level. The number of substations determines the number of middle levels in the hierarchical structure. As there are many levels in the smart grid structure, there is a possibility of multi-hop communication in smart grid. The performance of the smart grid communication system can be improved with the help of efficient routing algorithms.

1.2. Contributions

Many routing protocols (Van Mieghem and Kuipers, 2004; Xue and Makki, 2007; Tuppen, 2011) developed in the literature are tested for wireless based network environments but not for smart grid based communication networks. There are some methods described in Kuipers et al. (2002), Li and Zhang (2010), Tuppen (2011), Misra et al. (2012), Zhu et al. (2011), and Jung et al. (2011) that attempt to develop routing algorithm for smart grid environments, but these algorithms are not deficient in meeting the challenges of complex environment of smart grids. Most of the existing routing algorithms are used to determine the path such that they reduce the delay or power consumption or improve the packet delivery ratio. However, it is known that all these parameters are considered to be equally important. Hence, in this paper, an efficient multi-constrained routing algorithm for smart grid communications, LAMCR, is proposed using the concepts of a Learning Automata (LA). The proposed algorithm, LAMCR, determines the path for communication based on the multiple constraints like cost, delay, transmission energy consumption and power usage. The learning automaton is used to obtain the optimal path.

The following are the *contributions* of this paper which are discussed later in detail:

- A network model is developed, indicating the hierarchy of the power stations or substations and end users. This is used to test the proposed algorithm.
- An LA based model is designed for the nodes of the smart grid network. Each node has an associated LA component, along with LA tables which are exchanged between adjacent nodes.
- An LA based multi-constrained routing algorithm is proposed. This algorithm proposes the computation of an optimal delivery path. We also provide a proof of normalization and a proof of convergence.
- An evaluation of the proposed algorithm is undertaken in terms of packet delivery ratio, delay, energy consumption and throughput.
- Finally, we have compared the results of the proposed algorithm, LAMCR, with OMCR and HWMP. Our analysis reveals that the proposed algorithm performs better in terms of the performance parameters mentioned above.

1.3. Organization

The rest of the paper is organized as follows. Related work in this area is presented in Section 2. Section 3 gives an introduction to LA. The system model, the topology used for simulation, and the LA-based node structure are discussed in Section 4, and the proposed algorithm, LAMCR, is proposed in Section 5. Section 6 presents the results and discussions, and, finally, Section 7 concludes the paper.

2. Related work

In Kuipers et al. (2002), a multi-constrained QoS routing algorithm for smart grids is proposed. In this paper, the authors studied the dynamics of power load and the load-price mapping, and then analyzed the QoS parameters such as delay and cost. The K-approximation algorithm (OMCR) (Kuipers et al., 2002) utilizes cost and delay as constraints. It uses a maximization function to calculate auxiliary edge weight. The shortest routing path is selected based on these auxiliary edge weights.

In Misra et al. (2012), the hierarchical structure of the power grids is discussed and a QoS-based routing algorithm is proposed. A hybrid structure of routing is used to enable the resilience, robustness, and efficiency of the smart grid. The rates of communication are optimized from super data concentrator to control room. Further, the authors presented a thorough analysis of reliability of their approach (Misra et al., 2012).

In Zhu et al. (2011), wireless LAN mesh is used as high speed backbone networks for smart grid. The installation and management costs are reduced by such architecture. It has been shown that high scalability and flexibility can be achieved by using the IEEE 802.11s based mesh networks. The authors proposed two methods which are used for improving reliability in routing. The methods are implemented and evaluated using parameters such as packet delivery ratio, delay, and cumulative distribution function. The method proposed by the authors is the modified version of Hybrid Wireless Mesh Protocol (HWMP) (Zhu et al., 2011).

The routing problem in power line communications is discussed in Jung et al. (2011). The authors considered the network to be static and so it can be observed that the position of nodes is known a priori. In Biagi and Lampe (2010), geographic routing algorithms, which are applied for wireless sensor networks, are used to analyze the performance of static networks. The authors showed that geographic routing (Biagi and Lampe, 2010) resolves the problem of flooding. The analysis of the system is undertaken on energy, packet loss rate, and average delay parameters.

In Sanchez et al. (2009), the authors proposed a novel two-pronged strategy to an agent-based intrusion detection system. The two approaches followed for detecting intrusion in this paper are complementary. An auction scheme is introduced to perform the task by the nodes.

In Ramachandran et al. (2008), the authors proposed a channel allocation scheme based on distributed dynamic mechanism. According to the algorithm proposed in Ramachandran et al. (2008), channels are reserved for handoff calls and the system deals with multiple traffic system. The system is modeled by three dimensional Markov chain and is evaluated in terms of the blocking and dropping.

An ant colony optimization probabilities based routing algorithm named for quality-based distance vector routing (QDV) is proposed in Venkata Krishna et al. (2009). The two parameters, QoS and reputation, are associated with each node. Based on these parameters, malicious nodes are disabled from acquiring the access to the network and thus improving the performance of the system. In Dhurandher et al. (2009), the authors proposed an energy efficient routing protocol to increase the lifetime of the network. The proposed algorithm in this paper is simple, ensures reliability, avoids congestion and is evaluated in terms of throughput, average energy consumption, and average network lifetime.

A routing protocol based on IPv6 is proposed in Misra and Dias Thomasinous (2010) for advanced metering infrastructure in smart grids. A novel directed acyclic graph based rank computation method, which is used to record the reverse path, is used to enable real-time utility and read real-time automated meter. Extensive simulations are carried out by the authors to evaluate the system in terms of average end-to-end delay and packet delivery ratio.

In Misra et al. (2010b), the authors had studied and stated the advantages and disadvantages of various types of multi-hop routing protocols in different smart grid environments. The routing protocols considered for the study are table-driven, on-demand and QoS aware based methods. The packet delivery ratio, energy consumption and end-to-end delay are the parameters