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ENTICE: Agent-based energy trading with incomplete information in the smart grid

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ABSTRACT

In this paper, energy trading for the distributed smart grid architecture is projected as an *incomplete information game*—a viewpoint that contrasts from all the existing pieces of literature available on the broader issue of energy management in smart grid. The incomplete information is considered as the real-time demand and price to grid and customers, respectively, due to the packet loss in the communication network. Therefore, the paper addresses a realistic scenario, in which real-time information to the destination may not be guaranteed to be received adequately, due to the packet loss. In the proposed scheme, we introduce two types of *intelligent* agents—*customer-agents* and *grid-agent*. The customer-agents are deployed at the customers' end, and are capable of estimating adequately the real-time price decided by the grid. On the contrary, the grid-agent is deployed at the service provider's end, and are also capable of estimating adequate real-time energy demand from the customers. Therefore, one of the key advantage of the proposed agent-based scheme is that the customers and the grid are not involved in complex calculations in order to take real-time decisions for cost-effective energy management, while there is information loss in the communication networks. In the proposed game model, the grid-agent and the customers agents are the players, and estimate real-time demand and price based on the probability of belief to each other. We show the existence of Bayesian Nash Equilibrium in the proposed model, where the utility of the players is maximized. We compare the real-time price with and without packet loss as the price with incomplete and complete information, respectively. We observe that the proposed model is beneficial for the grid, as its utility is maximized. The simulation results show that the utility of the grid increases approximately 40% over that of the existing ones under the scenario of information incompleteness.

1. Introduction

A smart grid is conceptualized as an integration of overlay communication networks with underlay electrical networks. To develop cost-effective energy supply systems, the overlay communication network plays a crucial role for energy management (Meiling et al., 2013; Zhou et al., 2013). Smart meters are implemented at the customers' end in order to communicate with the grid[1] for real-time price (Gungor et al., 2010; Karnouskos et al., 2011). Consequently, the customers optimize their energy consumption profile according to the price information received from the grid. Similarly, the grid receives real-time energy demand from the customers with the help of bi-directional communication facility. Thus, the grid estimates the real-time demand. Accordingly, energy is supplied by the grid (generators) to the customers in order to fulfill their requirements, and so as to maintain supply–demand curve. Therefore, an efficient energy management scheme takes effect in a smart grid architecture. However, this energy management scheme is solely based on the real-time complete information from both ends— grid, and customers.

The deployment of wireless sensor networks (WSNs) in the smart grid is expected to be a promising approach to monitor, predict, and manage real-time energy usage in a cost-effective and efficient manner (Gungor et al., 2010; Asad et al., 2013; Lloret et al., 2011). Erol-Kantarci and Mouftah (2011) proposed the energy management scheme for residential customers based on the real-time information generated from wireless sensor networks. However, the sensor network-based communication septems are prone to increased packet loss due to the harsh environments, resource constraints (such as

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[1] In general, a service provider acts as an intermediary agent between the generators and customers. However, in this work, generator, grid, and service provider are considered as the same entity. Therefore, there is no difference among generator, grid, and service provider.

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energy, memory, and processing), and selfish nodes (Baadache and Belmehdi, 2012; Zare and Rahbar, 2012; Salameh and Badarneh, 2013). Therefore, the implementation of WSN for residential energy management is challenging in the smart grid. Additionally, resource over-run of any of the factors mentioned earlier may lead to packet loss in the smart grid communication networks. The selfish behavior of the sensor nodes may lead to complete information not being sent to the control center as well as to the end-users for taking adequate actions in real-time. Additionally, communication delay is also an important factor that may affect decisions taken in a time period. If the delay is greater than a certain threshold, the control center takes decisions without considering the delayed information (Bolot, 1993). Therefore, the delayed information is treated as lost packets. Therefore, in the communication network, the occurrence of packet loss, and information propagation delay is imminent. Consequently, the grid may not have the adequate real-time information about the customers' energy demands, and the customers may not have adequate real-time price information decided by the grid due to the packet loss in the communication network. According to Niyato et al. (2011), the real-time price increases almost exponentially with an increase in packet loss in the communication networks. Thus, proper estimation of real-time demand from customers in the presence of packet loss in the overlay communication network in the smart grid is a research challenge.

1.1. Motivation

While estimating the real-time demand and price from the customers and the grid, respectively, there is relatively a very few works which addressed the demand prediction in real-time (Rose et al., 2012). Typical approaches for estimating real-time demand and corresponding price are based solely on the received demand and price information to the grid and customers, respectively. Consequently, relying solely on the received information may lead to mismatch between the generation capacity and the customers' requirements, while there is a packet loss in the communication networks. As a result, the grid may have to buy extra energy from the wholesale electricity market[2] at a higher price to fulfill the customers' demands, which in turn increases the real-time price of energy. Hence, the real-time price increases with an increase in the packet loss rate. Therefore, the grid serves the customers in an unreliable and cost-expensive way instead of the reliable and cost-effective ones. Similarly, the customers also fail to optimize their energy consumption cost. To the best of our knowledge, there is no such work which considers the real-time energy management problem with incomplete information, i.e., with the concentration on the packet loss in the communication networks. Therefore, the users (customers and grid) need to perform complex tasks in order to optimize the real-time energy management, while there is packet loss in the communication networks. Consequently, an adequate strategy needs to be designed which can address the issue related to packet loss in the smart grid communication networks, in order to have reliable and efficient energy supply to the customers.

[2] In a smart grid, typically, the micro-grids distribute electricity to the customers as a combination of renewable and non-renewable energy. Additionally, the micro-grids have self-generated energy sources. Therefore, firstly, the micro-grids provide services to their customers with the self-generated energy, and secondly, the rest of the required energy to fulfill the customers' demands, can be bought from the main grid which is known as wholesale electricity market. Therefore, the wholesale electricity market is a common platform for all the service providers from that they are allowed to buy electricity through the bidding process.

1.2. Contribution

In order to address the energy management problem in the presence of packet loss in the communication networks, we introduce two types of agents in the smart grid architecture—*customer-agent*, and *grid-agent*. The customer-agent is deployed at the customer's end, which is autonomously capable of predicting adequate real-time price decided by the grid. On the other hand, the grid agent is deployed at the service provider's end, and predicts the real-time demand from the customers in adequate manner. One of the key advantage of using the agent-based approach is that the customers and grid do not need to bother about the packet loss in the communication networks. The *agents act intelligently* in order to handle the incompleteness of real-time information. Furthermore, the customer-agents have the ability to predict the adequate real-time price information, and take optimal decisions depending on their owners' preferences. Similarly, grid-agent also has the capability to predict the adequate energy demand from the customers, and decides real-time price for maximizing the profit. Therefore, both the agents act autonomously in order to maintain the energy supply–demand curve.

With this, in this paper, we propose a real-time energy management scheme in smart grid with *incomplete* information, named as *ENTICE—Energy Trading with Incomplete Information*—specifically, in the presence of packet loss due to the communication constraints mentioned earlier. We design the real-time energy management scheme with incomplete information as a *Bayesian game*. In such a game model, the grid-agent acts as one player, and the customer-agents act as other players. The customer-agent takes real-time decision on energy consumption depending on the belief strategy for the grid. On the other hand, the grid-agent decides real-time price depending on the belief strategy of the received demand from the customers. We show that *Bayesian Nash Equilibrium* exists in the proposed game model, where the utility of customers and grid is maximized, and the proposed model is well-enough to predict the real-time demand and price to the grid and the customers, respectively. In brief, our contributions in this work are as follows.

- We model energy trading in smart grid as an incomplete information game, due to the presence of packet loss in the associated communication network. In such a game model, two types of agents—customer-agent and grid-agent—are used which can intelligently estimate the real-time price and demand, respectively. The customer-agents are deployed at the customers' end, and the grid-agent is deployed at the service provider's end. Therefore, the customers and grid are not involved in the complex calculations, while there is a packet loss in the communication networks.
- We propose a real-time energy management policy, which is based on the probability of belief strategy for the customers' demands to the grid-agent, to counter the information incompleteness. On the other hand, the customer-agents take optimal decisions for cost-effective energy consumption based on belief strategy of the real-time price decided by the grid.
- Consequently, we present algorithms for the grid-agent and the customer-agents by following Bayesian Nash Equilibrium for maximizing the utility for both ends—grid, and customers.
- We evaluate the proposed scheme and show that the agent-based energy management scheme outperforms than the existing ones, while there is packet loss in the communication networks. The simulation results show that the customers' utility increases on an average of 40% than the existing ones by considering the incompleteness of the real-time information.