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Infrastructure based on supernodes and software agents for the implementation of energy markets in demand-response programs

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HIGHLIGHTS

- Lessons from P2P are used to develop a new type of Smart Grid node, called ASPEM.
- It is demonstrated that ASPEMs facilitates the implementation of energy markets.
- It is demonstrated that ASPEM nodes are compatible with the OASIS EI standard.
- Realistic simulations using GRIDLAB-D and OpenADR programs are presented.
- Markets based on parallel auctions are described and simulated.

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ABSTRACT

The most successful peer-to-peer networks are based on the concept of supernode, which is an operating point of the network that provides services and advanced functionalities to other nodes. Inspired by this idea, this paper proposes to integrate nodes that provide intelligent advanced services in the future architecture of the electrical grid. Besides facilitating the access to data services such as demand estimations and weather forecasts, these nodes are especially meant to hold virtual environments in which software agents, after being contracted, negotiate on behalf of users in energy markets. This architecture is designed to be compatible with the Energy Interoperation OASIS standard. The capabilities and feasibility of the proposal is demonstrated through realistic experiments based on OpenADR programs, in which users exchange energy by using parallel auction markets. In addition, in order to have the roles of buyer and seller in demand-response programs, thus allowing the creation of markets, a conceptual model based on negative loads and critical loads is provided. The experiments have proven that the proposed architecture facilitates the implementation of advanced distributed management systems in order that smart metering infrastructures, in contrast with traditional agent-based solutions, are released to perform negotiation tasks and access data services, while users gain both autonomy and decision-making capacity.

1. Introduction

Peer-to-peer (P2P) networks have been a successful technology for over 15 years. The experience during this time can provide valuable lessons for other distributed contexts such as energy networks or grid computing. A particularly important conclusion drawn by file-sharing networks community is that hybrid architectures have proven to be the most effective approach. This type of architecture is characterized by the concept of *supernode*: a node with advanced capabilities that performs demanding functionalities and provides ancillary services to other nodes. In particular, the role of supernode is primarily intended to work as an entry point for limited sections of the network to which it provides a global index of all network content, and facilitates the search for resources.

On the other hand, software agents is one of the most promising technologies to achieve widespread implementation of energy markets in which users are expected to play a more prominent role. However, the inherent complexity of agent-based solutions, along with the lack of knowledge about artificial intelligence, has meant that in many cases the solutions of this subject are understood as unreliable, thus discarding its great potential. In the

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context of the electrical grid, these obstacles are greater, since works project solutions in which local agents, installed in AMIs (Advanced Metering Infrastructure), must be able to negotiate in markets, access external data services, process the data obtained therefrom, and provide user interfaces. All these tasks are too demanding for devices that are intended to be installed on a mass scale, and therefore should be affordable and easy to maintain. As a matter of fact, main Smart Grid standards are being developed with more classical and practical technologies in mind.

In order to overcome the above barriers and thus facilitate the reliable and realistic application of agent-based solutions, this paper proposes to use the Agency Services model, which was explicitly designed to achieve the easy adoption of software agents in large distributed environments while retaining all their virtues. The core idea of the Agency Services model is that software agents are offered as services by certified providers, so that customers contract brokering agents in order to participate in large virtual environments such as electronic markets. By combining the concept of supernode with the core idea of the Agency Services model, this paper designs a novel third-party service provider that, in the role of supernode that offers advanced functionalities, deploys virtual environments in which brokering agents (contracted and configured by users) negotiate energy exchanges for specific sections of the electrical grid. This paper also addresses the need to tailor the concept of supernode to the particularities of the electrical grid, such as the presence of local resources that need to be managed through standard interfaces, and the need for solutions that do not jeopardize the security and reliability of the network. Our work shows that the installation of this new role in the spectrum of services providers of the electrical grid will enable the adoption of agent-based solutions, and therefore the application of market-based management systems in enclosed areas of the electrical grid. The work also shows that this novel approach frees the local AMIs to address most of the tasks related to intelligent agents, and also facilitates integration with external data services such as weather forecasts and demand estimations.

To demonstrate the benefits and feasibility of this novel approach, we present realistic experiments in which demand-response (DR) events are successfully handled through solutions based on users' preferences and parallel auction markets. Despite being a restricted environment to perform management tasks, DR programs are chosen as test environment because they are one the most immediate and realistic milestones in the road to a more efficient electrical grid [1]. In this regard, in order that users can behave as consumers and producers in these contexts, thus enabling the creation of markets, this paper also describes a conceptual model using the notions of negative load and critical load that leads to the roles of producer and consumer. Moreover, with the aim of achieving a standard solution, the proposal is designed to be fully compliant with the OpenADR standard and the Energy Interoperation model defined by OASIS. At the same time, the simulation infrastructure is based on GridLAB-D, which is used to simulate the electrical grid; and Jade, which is a framework for the creation of standard agent-based solutions.

The remainder of this article is organized as follows. Section 2 provides insight into the Smart Grid standards, focusing on those related to the DR programs. Section 3 describes the architectonic solutions that have been successful in P2P networks. Section 4 describes the Agency Services Model and, guided by the architectonic principles that have been successful in the P2P networks, studies its application to the electrical grid. Section 5 defines and simulates two advanced management systems for DR programs. Section 6 discusses aspects of the solution, including additional advantages that will be possible if standards are adapted to the concept of supernode. Section 7 is the conclusion.

2. Smart Grid standards

The goal of the Energy Interoperation (EI) standard from OASIS is to define messages to communicating prices, reliability and emergency conditions between any two parties, such as energy suppliers and customers, markets and service providers [2]. In the architecture defined in the EI standard: (i) interactions are always possible between any pair of actors; and (ii) an actor can participate in many interactions at the same time. The standard adopts a services-oriented approach and is agnostic in relation to the technology used to carry the messages. As for the local devices, facilities must be provided with communication interfaces such as that described in [3]. Specifically, the point of communication whereby nodes offer and consume services is the so-called *Energy Services Interface* (ESI).

For interactions typical of DR programs, the EI model is principally based on the definition of two roles: Virtual Top Node (VTN) and Virtual End Node (VEN). A VTN can interact simultaneously with many VENs, while VENs are not allowed to interact directly among themselves. As in any interaction of the EI standard, parties may participate in many interactions concurrently. In this case, a node may implement both interfaces, playing the role of VTN in some interactions, and the role of VEN in others. In the common use case, VTNs are intended to be authoritative nodes, such as the Distribution System Operator; while VENs are intended to represent generation and curtailment resources. Thus, VTN nodes usually send DR signals and requests for information to VENs. The nodes that implement both interfaces are usually *aggregators*, which are entities that are in charge of the management and representation of multiple loads (e.g. user facilities).

Fig. 1 illustrates how the combination of pairwise interactions of VTNs and VENs enables the implementation of complex structures. The graph could model a DR event initiated by the system operator, which in this case is represented by the node *A*. Initially, the event is sent to the first-level nodes *B* and *C*, which work as aggregators. In a real case, they could represent the controller of a micro-grid [4], a factory, a smart building or a floor of a building. In turn, the second-level node *E* wrappers the nodes *F*, *G* and *H*, while the node *C* wrappers the node *H*. These are all end-nodes. They could represent devices of micro-grids, HVAC units, machines or floors of smart buildings. Note that aggregators are not required to re-send the same signal they receive. Actually, they can process it and generate a new set of signals which, from the point of view of the higher level, are usually expected to yield the same result.

As for DR programs, OpenADR is the most widespread standard, whose version 2.0 has been developed on the EI model. In specific, in the OpenADR networks the nodes are divided in two groups: (i) nodes that publish and transmit information about events to other nodes (e.g. utilities); and (ii) nodes that receive and respond to that information (e.g. end-users). Following the terminology of the EI standard, the nodes belonging to the former type are VTN nodes, while the latter are VEN nodes. With the aim of accommodating all kinds of devices and thus expanding the adoption of the standard, OpenADR 2.0 defines three levels of support: (i) 2.0a, minimal support; (ii) 2.0c, full support; and (iii) 2.0b, intermediate level support. The simplest level (2.0a) is intended to accommodate devices with limited computational resources, such as end-use units or even users facilities. On the other hand, the profiles 2.0b and 2.0c are targeted to more complex devices, such as aggregators and scheduling nodes, which are supposed to include capabilities typical of information and communication systems.

An important characteristic of the profile 2.0a (thereafter *Profile-A*) is that it only supports signals of type *simple*, which are basically defined by using one of the following values: *normal*, *moderate*, *high* and *critical*. The value *normal* means that no