Multiagent Architectures and Algorithms for Coordination of Energy Prosumers

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1. Introduction

According to the US Department of Energy, the creation of a sustainable and energy-efficient society is one of the greatest challenges of this century, as traditional non-renewable sources of energy are depleting and adverse effects of carbon emissions are being felt. Two key issues in creating a sustainable and energy-efficient society are reducing peak energy demands and increasing the penetration of renewable energy sources. In order to achieve a reliable operation of the electricity distribution system, supply and the load have to be balanced within a tight tolerance in real time. One way, which is most commonly used, to achieve the demand supply balance is to supply all the required demand whenever it occurs. However, attempting to achieve demand supply balance by adjusting only the supply side leads to the use of flexible (usually diesel operated) power plants that can be expensive, inefficient, and emit large amount of carbon. An alternative to adjusting the supply side only is to also adjust the demand of the consumers, so that flexible power plants required to operate for meeting peak demands are used as little as possible. Managing the demand side becomes more critical when the uncertainty in the energy supply increases as is the case with increasing penetration of renewable energy in the electricity market.

Recent technological advances in smart meters (that can communicate energy consumption periodically, e.g., hourly), smart appliances (that can communicate with the smart meters) have the potential to reduce energy costs for an individual (as well as produce societal benefits) by enabling direct and real time participation of an individual in the energy market. With advances in small scale renewable generation (e.g., solar panels, fuel cells) and small scale storage technology (e.g., batteries), individuals that were traditionally consumers can also supply electricity (as technologies for enabling next generations of smart electricity grids are realized). Thus individuals have the potential of being both producers and consumers or in short *prosumers*.

The key characteristics of the smart devices/agents infrastructure are that (a) the agents are physically distributed, (b) they have physical constraints, such as battery power, capacity of generation, capacity of carrying current, and (c) they have operating and service constraints that reflect human or organizational use preferences that are private and not shared with other smart devices (d) they can communicate with each other through a distributed communication network. Thus they form a cyberphysical system where the problem of optimizing the overall system performance (like low cost of electricity consumption or low carbon footprint) may not be solvable in a centralized manner. Therefore, a key problem is to *design scalable and decentralized algorithms and control architectures that can guarantee provably good performance, and can realistically model private constraints of the prosumers along with physical and safety constraints of the smart devices and electricity grid*.

2. Multiagent Architectures and Algorithms

In energy systems, the nature of the physical organization of the infrastructure is hierarchical (e.g., the energy distribution system has a hierarchical structure of regional, substation, building, and devices within a building). However, currently, the control of the devices at these levels is done in centralized ways by the electric utilities. Figure 1 shows the current architecture of the multiagent system used in controlling the demand of the consumers. The prosumers interact directly (shown by solid lines) with the utility companies or the *market maker*. However another option is the use of distributed architectures that are judiciously partially centralized (see

Figure 2). Understanding the comparative performance of partially centralized hierarchical control architectures with totally decentralized peer-to-peer and also centralized architectures (with respect to metrics that reflect scalability, robustness, performance optimization etc.) is key to efficiently managing the next generation smart grid from the perspective of the "demand side".

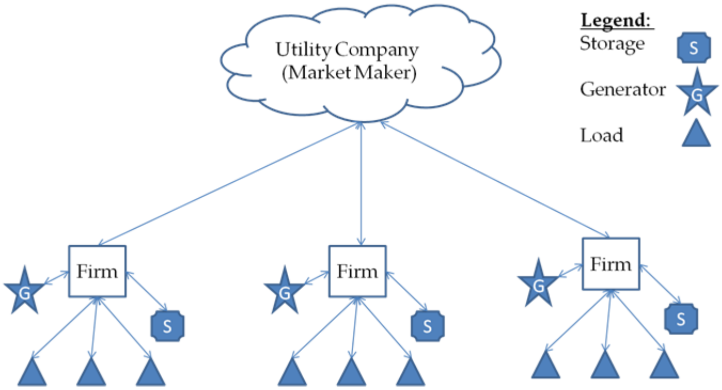

Figure 1: Hierarchical multiagent interaction (solid line) prevalent in current literature.

Several different forms of demand response programs have been developed within the interaction architecture given in Figure 1. The first type of programs are incentive based programs (IBP), where customers receive payments for their participation in the programs. A typical example of an IBP are Direct Load Control (DLC) programs, in which utilities have the ability to remotely control the power consumption of consumers' appliances by switching them on/off. In small scale pilot studies, DLC has been successful in reducing peak energy consumption. However, the biggest drawback of DLC is that consumers may not be comfortable with utility companies having direct control over their appliances.

The second type of programs are price based programs (PBP), which are based on variable pricing rates, so that energy rates follow the real cost of electricity. The objective of this indirect method is to control the overall demand by incentivizing consumers to flatten the demand curve by shifting energy from peak to off-peak times. The basic example of PBP are time of use (TOU) price programs. Smart meters and smart appliances enable direct and real time participation (RTP) of an individual consumer in the energy market through the use of software agents. This allows price based systems with hourly prices depending on the actual cost of generation. A key feature of RTP programs is that each customer participates directly in the market. However, there are two key problems in realizing this potential. First, despite the presence of small pilot programs, the end users are usually not of sufficient size for the utilities to be considered for demand response services. Second, if end users participate in the market directly, without control by the utility companies, the stability of the system may be compromised, due to uncontrolled distributed interactions.

One way to overcome these challenges is to allow *partial centralization* of the consumers to form *consumer cooperatives* that participate in the market through a group coordinator (mediator) agent. Such consumer configurations have the potential to increase energy efficiency via aggregation of demand to reduce peak power consumption, and direct participation in the energy markets. Although this seems to be an attractive model, to our knowledge it has not been formally studied in the literature. Figure 2 shows a partially centralized agent architecture for demand side management. The solid lines show the interaction between the agents across the hierarchy. The dotted lines show interaction among agents at a single level of the hierarchy. The utility company is the market maker from whom the central manager (or coordinator) buys electricity. Note that although it is not shown in the figure, the individual firms can also have storage and generation facilities.

The coordinator is not a market maker or a traditional demand response aggregator since it neither sets energy prices nor aims to incur profits by selling to the market. Rather, its role is akin to a social planner's in that it manages the demand of its associated consumer group for cost effective electricity allocation to the consumers such that their demand goals and constraints are fulfilled, while also helping flatten out peak demands for the group. Real world consumer groups coordinated in the above manner can be formed naturally in many application scenarios, especially when they are geographically co-located, e.g., smart buildings, industrial parks, commercial estates, large residential complexes. The firms espouse the goals of the group, however they are not willing to totally disclose their demand goals and constraints to either other firms or the coordinator. Therefore the coordinator cannot solve the problem in a centralized way. Consequently, the agents autonomously solve their local problems to optimize their cost and decide how to shift their loads in order to help the group flatten peak demands.

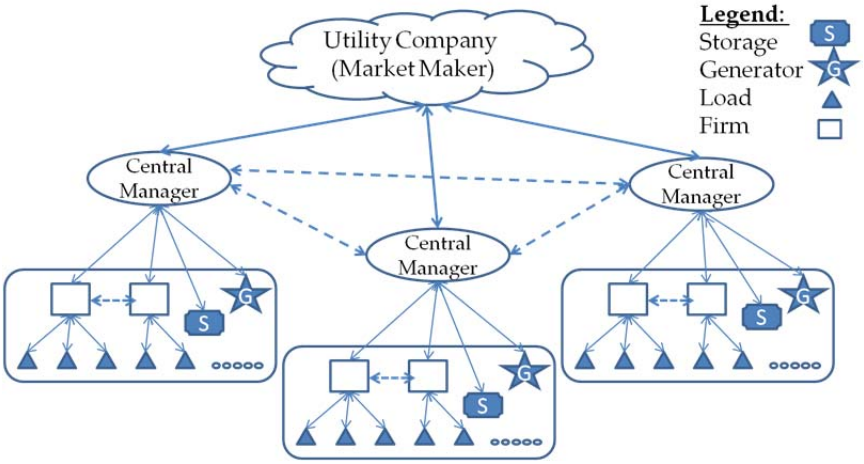

Figure 2: Proposed partially centralized architecture with interaction between two hierarchy levels (shown by solid lines) and interaction among agents at the same level (shown by dashed lines).

The cooperative may have industrial firms or households as members. Cooperatives and households may have different smart devices and machinery that perform various useful operations. One can envision that a coordinator agent can coordinate the underlying devices in a firm, and the firms can be also coordinated by another higher level coordinating agent. For ease of exposition, we will use the terms consumer, agent, firms and household interchangeably. The central coordinator interacts with both the firms, whose energy demands and constraints it aims to satisfy and also with the electricity markets. The coordinator has *uncertain knowledge* about the price of electricity, the electricity markets and the electricity generation amounts available to the consumer cooperative from renewable energy. Furthermore, the coordinator has incomplete knowledge about the demand schedules and constraints of the agents. The decision problems of the agents and the coordinator are different. The decision that an individual agent needs to make is how to schedule her energy consumption so as to minimize her individual energy cost and satisfy her individual electricity usage constraints under assumption of uncertain prices and without complete knowledge of other agents' energy demands. The overall decisions that the central coordinator needs to make are: (1) Determine how to encourage agents to *shift* their consumption so as to ensure that the total cost to the whole group is minimized, (2) Determine *storage and production of the renewable energy* policy of the consumer group so as to reduce the overall cost of the agents.

The partially centralized coordination model offers several practical and computational advantages. From the perspective of the consumers, participation in such energy groups has the advantage that individual consumers can retain the privacy of their own constraints and preferences and in addition obtain electricity at better prices than they would have obtained if they bought individually. The price advantage is due to three reasons. First, the mediated participation of the consumer group in the market allows the group additional flexibility in entering into more flexible contracts. This has the result that the price paid by the consumers reflects more accurately the actual cost of production (which is not the case in current long term fixed contract structures). Second, by buying as a collective, the group can benefit from volume discounts. The situation here is analogous to group insurance programs in companies. Third, in negotiated electricity contracts, the price usually consists of two components, one coming from the actual energy production cost and the other as a premium against volatility in the energy demand and/or supply. Buying as a group helps in reducing the premium against volatility since the coordinated demand management can achieve higher stability of demand and reduce demand peaks.

From the perspective of the utility companies, the consumer cooperatives form large enough groups so that they can be called upon reliably to reduce loads in emergency scenarios. This can help in ensuring stable operation of the overall electricity grid and preventing cascading failures or large scale blackouts.

The partially centralized coordination scheme has also the potential of benefiting the environment by reducing the overall carbon footprint. Recent and expected near-term developments in renewable energy generation technologies have the potential to replace non-renewable energy from fossil fuels. However, the high variability in supply of electricity from renewable energy sources means that high cost non-renewable energy power plants must be available as back-ups to satisfy the technological and physical constraints in demand-supply matching (otherwise, load needs to be shed to match demand and supply, which is undesirable) thus not allowing as much reduction of carbon footprint as would otherwise have been possible. More effective and larger scale control of electricity consumption patterns to reduce demand peaks, which can be achieved through partially centralized coordination, as well as the presence of storage and renewable generation capabilities not only at the supply side but also at the coordinated groups demand side, have the potential for achieving this overall social and environmental goal.

The partially centralized agent organization also offers computational advantages. From the structure of the optimization problem for the cooperative using a partially centralized solution there is a potential for developing computationally efficient coordination schemes that are decentralized, allow private constraints, and result in optimal solutions for the whole group.

Note that the partially centralized organization not only allows interaction across different hierarchies but also allows interaction among agents at the same level of the hierarchy. Thus agents within a cooperative may negotiate with each other to adjust their consumption pattern (e.g., charging times of their electric vehicles, so as to not overload the local grid).

3. Research Challenges

There are several broad architectural as well as algorithmic research challenges that have not been studied adequately in the current literature. From the architectural point of view, the broad challenges are: (a) What are the advantages/disadvantages of a totally centralized architecture (Figure 1) versus a partially centralized architecture (Figure 2)? (b) What are the advantages/disadvantages of designing partially centralized architectures that allow interaction among agents at the same level over architectures that do not allow interaction among agents at same level?

From the algorithmic perspective within the context of the partially centralized architecture key challenges are:

(1) Design scalable, robust, distributed algorithms with formal performance guarantees to coordinate the demand side energy prosumers under (a) realistic modeling of physical and private operating constraint as well as constraints of the energy market, (b) the presence of renewable energy and storage capabilities both at the supply and demand side, (c) safety constraints of operation of the electricity grid and (d) uncertainty of the environment reflected by the stochastic nature of the renewable supply and demands of the prosumers.

(2) Design scalable negotiation protocols among multiple agents that ensure that the agents reach an agreement within a reasonable time, (a) even though an agent may not know other agents’ preferences, (b) ensuring that the negotiated outcome satisfies not only the agents own requirements but also the safety requirements of the overall distribution system.