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Smart pricing scheme: A multi-layered scoring rule application

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ABSTRACT

Defining appropriate pricing strategy for smart environment is important and complex task at the same time. It holds the primal fraction in Demand Response (DR) program. In our work, we devise an incentive based smart dynamic pricing scheme for consumers facilitating a multi-layered *scoring rule*. The proposed strategy characterizes both incentive based DR and price based DR programs facilities. This mechanism is applied between consumer agents (CA) to electricity provider agent (EP) and EP to Generation Company (GENCO). Based on the Continuous Ranked Probability Score (CRPS), a hierarchical scoring system is formed among these entities, CA–EP–GENCO. As CA receives the dynamic day-ahead pricing signal from EP, it will schedule the household appliances to lower price period and report the prediction in a form of a probability distribution function to EP. EP, in similar way reports the aggregated demand prediction to GENCO. Finally, GENCO computes the base discount after running a cost-optimization problem. GENCO will reward EP with a fraction of discount based on their prediction accuracy. EP will do the same to CA based on how truthful they were reporting their intentions on device scheduling. The method is tested on real data provided by Ontario Power Company and we show that this scheme is capable to reduce energy consumption and consumers' payment.

1. Introduction

With the growing needs of environmental sustainability and continuing changes in electric power deregulation, smart grid becomes an inevitable choice for the society. As one of the important features of smart grid, Demand Response (DR) is gaining importance in designing grid functionalities specially in the end user level. Formally speaking, DR is a mechanism that influences the end users (consumers) to modify their energy usages from the normal consumption patterns in response to the changes in the price of electricity over time (Albadi & El-Saadany, 2008). The DR strategies can be grouped into two general categories, one is incentive based DR and another is price based DR. In the incentive based DR, the consumers are given incentives in payment to down their consumption in response to the system reliability. As an example, Chen, Li, Low, and Doyle (2010) devised an algorithm to match the supply when the energy supply is deficit based on supply function bidding. And for price based DR, the consumers are going to dynamically adjust their consumption according to the time varying pricing while maximizing their payoffs. For instance, Samadi, Mohsenian-Rad, Schober, Wong, and Jatskevich (2010) proposed a real time pricing mechanism by maximizing the aggregated utility of all consumers.

In order to fully utilize the DR capability, smart houses already started to adopt devices which can be controlled, maintained, monitored and even scheduled as the necessity calls. Smart house technologies make all electronic devices around a house acting "smart" and becoming more autonomous. Most of the important appliances in the future will take advantage of this technology through home networks and the Internet. Such feature of smart grid is a way for ordinary electronics and appliances to communicate with each other, consumers and even higher entities such as Energy Provider and GENCO. Now to talk about price based DR, smart pricing has attracted much attention as one of the most important demand-side management (DSM) strategies to encourage users towards consume electricity more wisely and efficiently (Samadi et al., 2010). Moreover, intelligent operations on smart grid is equally important to mitigate various challenges ranging from renewables integration (Alonso, Amaris, & Alvarez-Ortega, 2012) to micro-grid controlling (Ramachandran, Srivastava, & Cartes, 2013).

On different note, in order to numerically measure up the actual realization of a probabilistic event which was forecasted ahead, *scoring rule* was defined (Boutilier, 2012; Gneiting & Raftery, 2007). Moreover, it binds the assessor to make a careful prediction and hence truthfully elicit his/her private preferences. Which is why, *scoring rule* has been applied successfully while designing truthful incentive mechanism in diverse applications such as voting rules (Ianovski, Yu, Elkind, & Wilson, 2011; Xia & Conitzer,

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2009). Strictly proper scoring rules can be employed by a mechanism designer to ascertain that agents accurately declare their privately calculated distributions, reflecting their confidence in their own forecast. The applicability of scoring rule is being investigated in field of smart-grid. For instance, Harry, Rogers, and Gerding (2012) presented a methodology for predicting aggregated demand in smart-grid.

Household devices such as Roomba vacuum cleaners, LG Thinq smart oven (LG) are some commercially available smart devices that can be controlled and monitored via smart-meter. Using such devices, consumers (actually a consumer agent, refereed as CA hereafter, will be responsible to take such decision in conjunction with smart-meter) can respond to day-ahead dynamic pricing signal by effectively and intelligently managing and scheduling devices, thereby flattening out peak demand and achieving better resource utilization.

This paper presents a hierarchical multi-layered scoring rule based payment mechanism for CA provided by the EP and GENCO in response to the dynamic day-ahead time dependent pricing. The proposed method can be viewed as a bridge between incentive based DR and pricing based DR. We can treat such pricing scheme as "Incentive based smart pricing". The brief ideas of this scheme is follows: The consumers will be rewarded a discount on the price to measure up how well they predict the shifting the devices/loads towards the lower demand (lower price as well) periods. These rewards are again a fraction of the discount which were provided by GENCO to the corresponding EP depending on EPs prediction of required energy demand. The reward mechanism is based on a strictly proper scoring rule. The scoring rule is chosen to reflect to work with continuous variable (the normal distribution, as in the proposed method) and measure up how accurate the prediction could be. The Continuous Ranked Probability Score (Matheson & Winkler, 1976) possess such characteristics. EP will formulate an optimization problem total energy demand for its consumers and reports to GENCO. GENCO then run an optimization algorithm that will minimize the cost of providing rewards to EPs while satisfying EPs energy demand. Therefore, the reward is actually dependent on both the consumers prediction and EPs optimization problem. The rest of the paper is organized as follows. Section 2 introduces the system model architecture while Section 3 describes the applied scoring rule function and associated key points. The cost optimization formulation and discount distributions are detailed in Section 4. Section 5 shows the steps of the processes for each entity with brief proofs of *optimality* and *truthfulness* of the proposed scheme. Agent simulation based on Ontario Power System data (Ontario, 2011) are presented in Section 6. Related works are pointed out in Section 7. Finally, Section 8 concludes the paper with follow-up research goals.

2. Incentive based dynamic pricing: system model

GENCOs and EPs are responsible to determine electricity pricing. GENCOs make revenue by selling energy to the distributers (in our context, EP) based on their demand while distributers provide that energy to consumers.[1] A supply–demand chain is thus formed among these entities. Fig. 1 shows the model outline architecture depicting the major components. However, for that model in hand, it is critically important to have a sophisticated smart pricing scheme that will take advantage of the DSM technique as well as incentivize the CAs to schedule smart devices in order to reduce the total demand.

[1] Since, the scenario takes place in smart-grid infrastructure, we assume that all the consumers participating are equipped with smart devices.

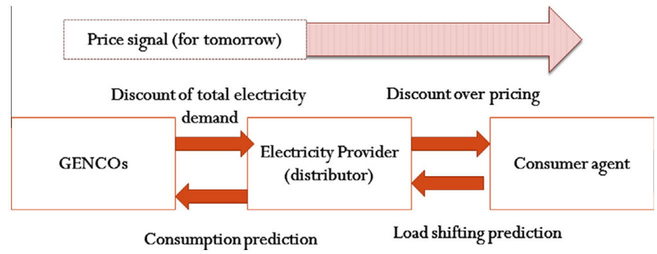

Fig. 1. GPC model architecture.

As a mechanism deign to incentivize agents (both the CAs and EPs) for providing private probabilistic information accurately (truthfully) and to the best of their forecasting ability, scoring rule is being applied in this model. Interestingly, this scenario in particular coincides with DSM strategy where consumer responses to demand by shifting their device to lower price periods. Therefore, EP incentivizes consumers not only based on their prediction accuracy but also on the question of whether they shifted such loads to lower priced periods. Strictly proper scoring rules can be employed by a mechanism designer to ascertain that agents accurately declare their privately calculated distributions, reflecting their confidence in their own forecast. The details flow of information and task assignments are pointed in Fig. 2. As we can see, GENCO will send the price information as a signal to EP. The price signal is typically determined based on the generation costs of electricity.[2] Although this model does not include the price determination mechanism, we assume that in dynamic pricing environment, the signal follows the demand. Which is, the price is higher when the demand is higher and its lower when demand is lower. The price signals are then conveyed to CAs via EPs. One thing can be noted that, one EP can provide energy to one or more consumers while one GENCO can also serve one or more EPs.

Since, this model assumes a dynamic 'day-head' pricing signal, CAs receive their prices one day in advance. So, CAs can schedule their device usages for the upcoming day into the lower price periods. Lets say, the demand in each period i is D_i. The demand D_i in each period is assumed to be roughly the same each day due to repeated daily patterns in electricity demands (e.g., period 1 has the same demand on Monday, Tuesday, etc.). So, the aggregate demand over each day is usually constant. This assumption is verified using real traces from an Ontario operator of hourly demand data over seven years (Ontario, 2011).

2.1. Reporting strategy of CA to EP

CA located in consumer's household integrated with ECC. Therefore, it can access the local information and data of that particular consumer. This information includes device usage schedule, duration, energy consumption, etc. CA also keeps track of the previous schedule prediction. Using such information plus the day-ahead dynamic pricing, CA makes a pre-schedule plan of different devices based on its forecasting accuracy and consumer's preferences. However, it will report EP the prediction confidence in a form of Gaussian distribution and tentative schedule of the assigned devices. For each device, CA calculates its uncertainty over the error it expects to make using a statistical model of random errors. So, CA makes its prediction through a Gaussian distribution. This assumption is based on the sampling of higher number of devices, since eventually an EP must handle a wide range of devices. Central Limit Theorem (CLT) tells us in a case of wide range of events, the

[2] In our model, we assume that GENCOs operate on multiple plants of different types, such as coal, hydro and nuclear. Therefore, pricing signal could be a function of statistical forecast of historical price and the payment of EPs to purchase energy from generation companies.