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Communication costs versus smart grid system performance for energy prosumers' participation in liberalized electricity markets: A trade-off analysis

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Abstract

In the smart grid era, various actors and S/W agents need to exchange vast amounts of data towards meeting the communication requirements of the emerging smart energy network infrastructures and the efficient operation of the smart grid system. In this paper, we consider a hierarchical smart grid architecture, in which a novel aggregator market entity is introduced, which acts as an intermediary between the various market/grid operators and the small-scale energy prosumers. A trade-off analysis is undertaken to study the problem of minimizing the utilized network bandwidth without compromising the efficient smart grid system performance.

1. Introduction

The concept of distributed data aggregation was initially proposed in the area of wireless sensor networks [1], although recently has been applied in smart energy networks area, too. In this paper, we consider an energy aggregator, which manages virtual associations of small and distributed renewable energy source (RES) prosumers (i.e. both RES producers and consumers), created for the purpose of participating in liberalized electricity markets [2]. The aggregator is responsible for participating in various smart grid markets on behalf of its registered prosumers, to buy and sell energy, depending on the their production capabilities and of course consumption requirements [3]. After a buy or sell bid has been accepted in the energy market, RES prosumers are scheduled to consume or deliver the amount of the promised energy based on the outcome of the decision making algorithms that run at the aggregator's side. In any other case, penalties may be charged based on the amount of imbalance that is caused [4]. As a result, efficient market participation requires an accurate prediction of the amount of energy that the aggregator will need to consume and the amount of RES energy that will be capable to contribute to the system at each time interval. The more accurate these forecasts are, the better decisions the aggregator may ensure, resulting in imbalance minimization, and consequently profit maximization.

However, the accuracy of the energy prosumption forecasts depends on the amount of time between the forecast calculation and the real delivery time of the promised energy. As the time of delivery comes closer, new production, consumption and weather data is made available, resulting to more accurate forecasts. On the other hand, the communication costs of exchanging related data too frequently may be too large especially if the wireless interface is used. Prosumers connected through 3G/4G connections are interested in reducing the amount of data transmitted to the aggregator, as their data plan may have strict monthly limits, or even a pay-as-you-go model, where charges are proportional to the data they exchange, usually at high rates. Therefore, there is a trade-off between the amount of data that each wireless prosumer transmits and receives, and the penalties that he will be charged due to inaccurate forecasts.

Based on related work found in the international literature, aggregated data is collected frequently by centralized control centers in order to support intelligent energy distribution and management services. The key role is executed by an advanced metering infrastructure (AMI), which serves as an important component at the prosumer's side. In each AMI, energy gateways (GWs) equipped with computing and communication capabilities are responsible for collecting, monitoring and finally communicating energy-related data in real time. To reduce computation and communication overhead, each energy gateway can perform "en-route" data aggregation instead of having each individual gateway establish a peer-to-peer connection with the collector devices. In [5], a survey on related works about context-aware data exchange in mobile and wireless networking systems is provided emphasizing on system performance analysis in the presence of missing or outdated datasets and data compression, aggregation and filtering mechanisms to cope with communication versus system performance cost. In [6], the deployment of data aggregation points for residential consumers is exploited. Given a wireless mesh network among metering gateways, data aggregation nodes could gather all the required data at periodic time intervals and forward it over to utilities/centralized control centers through fixed line communications. Authors in [7] propose a lossless data aggregation, which is able to reduce unnecessary overhead transmission by concatenating several packets from multiple gateways into a single packet, maximizing in that way the link usage and minimizing the utilized bandwidth. Authors in [8] elaborate on this idea by introducing a trade-off analysis for finding the optimal number and placement of data aggregation nodes without experiencing unacceptable QoS degradation from packet delays and losses. In our proposed approach, different protocols and real-business scenarios are studied, in order to investigate the relationship between data communication cost and a typical smart energy grid system performance.

2. Overview of the smart grid communication architecture

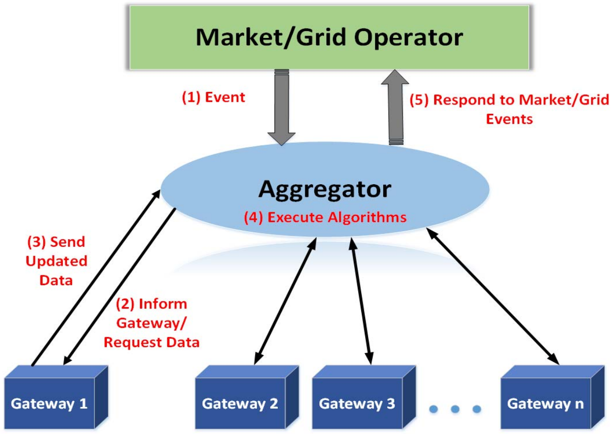

Figure 1. Typical data exchange framework for participating in smart grid market events

A typical data exchange framework of the proposed system is presented in Figure 1. The aggregator collects the necessary data from all RES prosumers (i.e. gateways - GWs) in order to participate in the energy market. The execution of a market participation algorithm is triggered through external market events (step 1). Such events could be for participation in day-ahead, intra-day near-real time congestion management and balancing markets, etc. Examples of these events that may trigger the execution of a decision making algorithm at the aggregator's side may include pricing signals, e.g. a very low or very high-energy price in the balancing market, or a direct trigger that the TSO may publish to the aggregator in case a demand response (DR) event is required for maintaining grid stability. DSO may also publish a DR target pattern to aggregator for a specific network substation in order for short-term congestion management problem at the network feeder level to be confronted.

In case that additional/updated data is required from the prosumers, the aggregator sends the corresponding request messages to the appropriate set of prosumers (step 2). By the term "appropriate", we mean that depending on the type of the event, the aggregator is able to dynamically select only a subset of the prosumers that will send the required datasets in order to lower the communication costs. Gateways respond to the aggregator by intelligently sending the requested data (step 3). We apply the word "intelligently" in the sense that the gateway may decide whether the data needs not to be sent (e.g. too close to the forecast or too late to make a difference in the algorithm). In addition, the gateways may aggregate the data prior to transmitting it to the VMGA, in order to save bandwidth and computational resources at the aggregator's side. Subsequently, the decision-making algorithm execution is performed by the aggregator (step 4). During the final step, after the algorithms' execution, the aggregator's decision is implemented and announced to operators (step 5).

In this paper, we investigate data compression techniques for limiting the communication burden between gateways and the aggregator. In particular, we investigate three simulation scenarios as follows:

- Scenario 1: Seamless distributed data aggregation
- Scenario 2: Threshold-based updates of real-time data
- Scenario 3: Performance analysis in the presence of missing/outdated data

In scenario 1, the aggregator exploits any correlation among various prosumers' profiles aiming to reduce the amount of data required for the proper algorithms' execution. In scenario 2, we examine the case where bandwidth utilization can be considerably reduced, based on a certain threshold policy that dictates the gateways to send updated data only when a specific threshold value (i.e. forecast value minus real measurement value) has been surpassed. Finally, in scenario 3, we study the impact that missing and/or outdated data may have on the proper smart grid system operation. As a result, the aggregator is able to decide not to participate in a specific short-term event, if no adequate and reliable datasets are available from the gateways. Communication between the GW and the aggregator is required for the following types of events:

- Day-ahead market participation: in this market, aggregated prosumption forecast data is required, for each time unit (e.g. hourly block) of the next day. Data should be available to the aggregator before the closing time of the market.
- Intra-day market participation: in this market, aggregated prosumption forecast data is required, for each tradable time unit. Depending on the specific market, as well as the Service level Agreement (SLA) that have already been accepted in previous market auctions (day-ahead or previous intra-day markets).
- Near-real-time balancing market: in this market, aggregated flexibility data, from the entire aggregator's portfolio, is required. Flexibility may be either excess capacity that has not been traded yet, or capacity through the consumption scaling back. In addition, participation to balancing market may occur after the aggregator receives a suitable pricing/capacity signal. Aggregator's participation requires the relevant real-time information from registered prosumers' prior to submitting any bids in the balancing market.
- Demand Response ancillary services market: Participate in the near real-time congestion management market usually occurs after receiving a relevant signal from the TSO or DSO. In order to respond to this event, the aggregator needs short-term forecasts about prosumption, as well as real-time data about flexibility that is available for demand reduction.

3. Simulation Scenarios and Performance Evaluation

In scenario 1, we examine the amount of prosumption data that is necessary for the aggregator to make a decision for efficiently participating in the electricity market. The premise is that some prosumers are wireless, so there is a cost in transmitting their data. However, certain types of generation pattern exhibit strong correlation among closely located prosumers. For example, in a scenario where Photovoltaic (PV) panels are placed on lampposts, we have both wireless data transmission, and also high levels of correlation on the production and consumption.

In the experiment evaluation below, we tested a set of 40 real PV energy prosumers, with maximum output of 20kW each [9]. We assume that only a set of prosumers, which ranges from 1 to 40 transmit their prosumption data to the aggregator, which tries to estimate the total prosumption. We mainly examine two cases: a) random selection of the transmitting prosumers and b) “intelligent” selection using a clustering method based on the prosumption correlations. For the second case, we first calculate a correlation matrix, after we create clusters of prosumers using the k-means algorithm [10] on the correlation matrix. The prosumer that is closest to the cluster centroid is selected as the “representative” prosumer of the cluster, and the total prosumption is calculated by a weighted average of the prosumption values of the representative prosumers. In figure 2, we observe that as the number of prosumers sending data decreases, the mean absolute percentile error (MAPE) increases. As a result, for even a limited number of transmitting prosumers, the total prosumption may be estimated relatively accurately.

In Figure 3, the total value of penalties paid is presented for the case of 40 prosumers. The computations cover one-year worth duration and are related to the errors in estimating the total prosumption accurately. Penalty values were calculated using a constant penalty factor of 0.3 for positive imbalance, a penalty factor of 0.2 for negative imbalance, over a constant price equal to 0.04 euro/kWh. In this case, the performance of clustering algorithm is significant better than the random selection case.

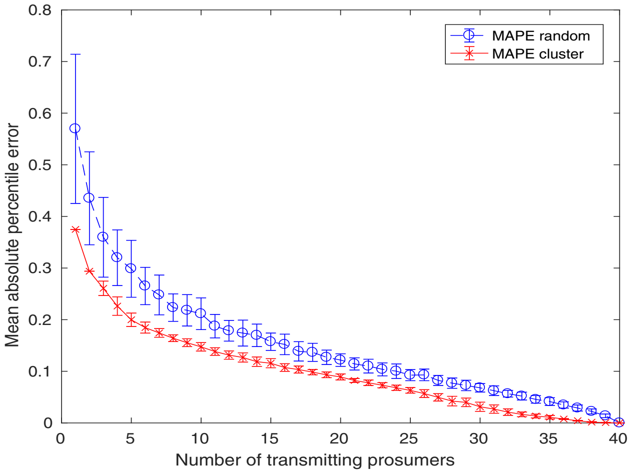

Figure 2. The mean absolute percentile error (MAPE) for random and clustering algorithm

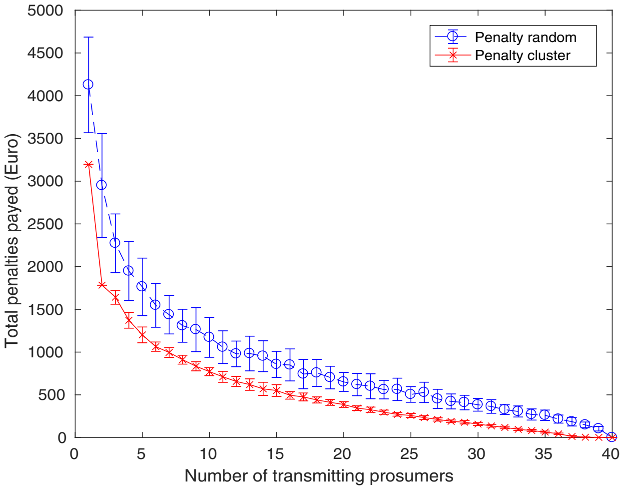

Figure 3. The total penalties paid due to inaccurate estimation

In scenario 2, we investigate a second method of reducing the communication burden between the GWs and the aggregator. The idea is to reduce the number of transmitted messages, by discarding updated forecasts, when the difference between the old and new estimates is below a predefined threshold value. As a result, we examined the dependence of the packets sent or discarded on the selected threshold value. For illustration purposes, we use two forecast values: a day-ahead forecast (calculated the day previous to the day of delivery), and a near-real-time forecast (15-minutes prior to the time of delivery). The GW sends the near-real-time forecast, only if the difference between the day-ahead forecast and the real-time forecast exceeds a threshold. In Figure 4, we can see the total number of the messages sent and not sent, based on a threshold value ranging from 10^{-3} to 5 kWh, for the 40 prosumers. When the threshold is at its highest value, no real-time forecast messages are sent, and the day-ahead forecast is used. As the threshold decreases, the number of packets that are transmitted increases, and the not-sent packet number decreases. This continues until a point where the threshold is so low, that the values stabilize. Even at a threshold value of zero (two forecast values are the same), some packets are not transmitted.

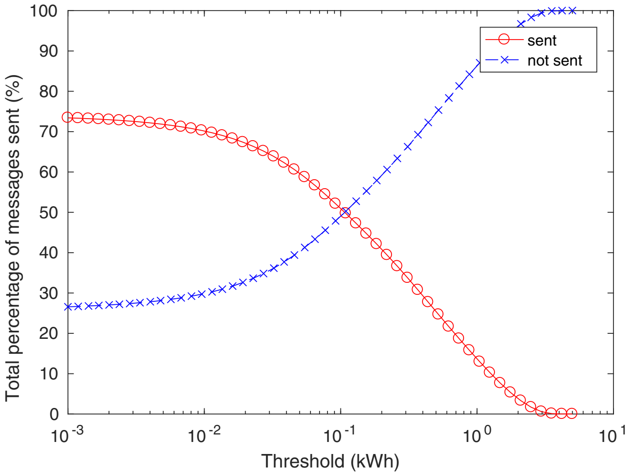

Figure 4. Total numbers of packets sent or discarded for different threshold values

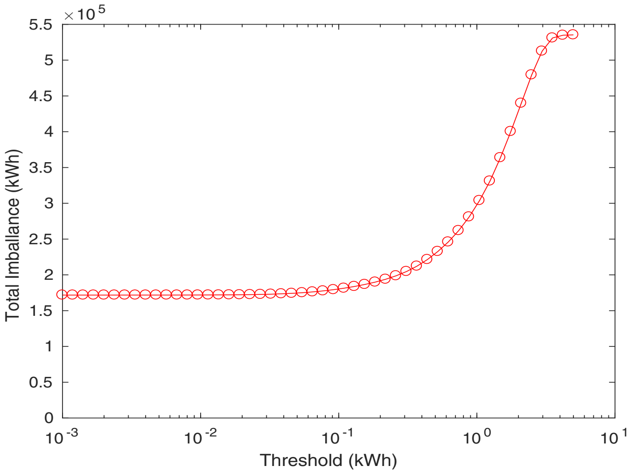

Figure 5. The imbalance as a function of the threshold

In scenario 3, we investigate how a varying threshold value affects the performance of the system in terms of the imbalance (caused due to inaccurate forecasts). In this case, the aggregator participates in the day-ahead market on behalf of its registered prosumers. The aggregator is responsible for any inaccuracies in the energy contribution versus the energy bid on the market. As a result, the main goal is to balance its portfolio by participating in the real-time balancing market, using real-time forecasts (when available). In order to be more accurate, we assume that the day-ahead market closed at noon of the previous day, and the real-time market 15 minutes before the actual delivery of energy.

As presented in figure 5, imbalance value is affected by the threshold for transmitting the real-time forecasts. For low threshold values, the imbalance is minimized, as the real-time forecasts are much more accurate than the day-ahead forecasts. As the threshold value increases, imbalance increases, since the system falls back to the more inaccurate day-ahead forecast estimations. In Figure 6, the relationship between the number of messages transmitted (i.e. bandwidth utilization) and the imbalance incurred is presented. The above graph representation proves that we are able to reduce the number of transmitted messages (by almost a third), without affecting the system imbalance.

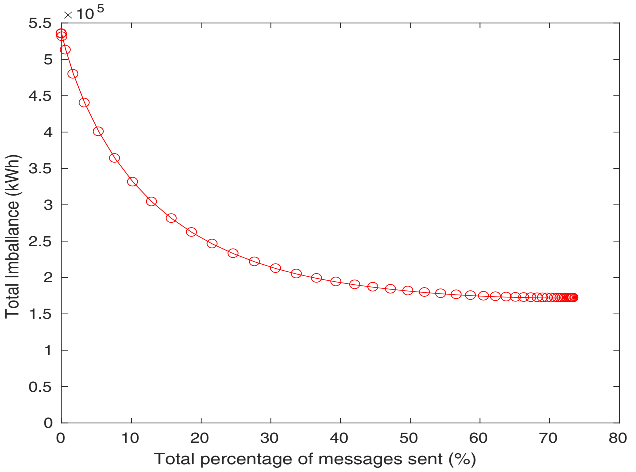

Figure 6. The total imbalance versus the number of sent packets

However, as the number of transmitted messages decreases due to the increased threshold, a rapidly increasing imbalance is observed.

4. Concluding remark

In this paper, we studied the trade-off problem between data communication cost and smart grid system performance for energy prosumers' participation in liberalized electricity markets. Results show that: a) bandwidth utilization can be considerably decreased at the expense of negligible system performance degradation, and b) there is an optimal point at which the bandwidth utilization can be minimized given a predefined quality of service level of the smart grid system performance that should be respected.

5. Acknowledgements

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