A consumer-orientated Architecture for distributed Demand-Side-Optimization

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Abstract

Demand-Side-Management (DSM) is one of the key applications in the future smart grid, creating a new degree of control in order to reduce losses and fluctuations caused by volatile distributed energy resources (DERs). To integrate the consumer side, several approaches like flexible tariffs, have been proposed and tested. However, many of these approaches not have been adopted widely yet because of the needed sophisticated (and often expensive) command and control infrastructures or their impact on the user comfort. In this paper an architectural approach for a lightweight demand-side-application will be proposed. Utilizing methods of peer-to-peer (p2p) networks and abstraction patterns the architecture will be enabling consumers to form spontaneous demand-side optimization networks in order to optimize their load and to provide energy services to the Smart Grid of the future. Because of the decentralized characteristic of the architecture, the aggregation instance does not need detailed information of the optimization network, while the approach is scalable.

1. Introduction

Apart from traditional top-down planning of the demand for electricity by electric utility planners, the rising degree of distributed energy resources depending on environmental conditions like wind or sunshine leads to more and more challenging energy-planning [1]. To increase the efficiency and reliability, controlling loads on the consumer-side of the meter with Demand-Side-Management (DSM) has become an additional degree of freedom for planning and controlling the grid [2, 3]. Through the growing dissemination of affordable automation and the spreading Information and Communication Technologies (ICT) infrastructure, the integration of the demand-side becomes achievable. Since then, many projects, like the e-energy projects [4], addressed different exemplary DSM applications, trying to integrate local demand-side entities into the Smart Grid. Due to the availability of household appliances for DSM-activities, a wide-scale concept for the DSM-integration of the appliances into energy related services like control energy is still a matter of concern. The highly distributed and heterogeneous devices require adaptive and scalable solutions for a reliable scheduling and optimization of the loads in order to reach prequalification levels and business-relevant integration and impact.

In this paper, a distributed architectural approach on indirect control without the direct participation of the electric utility or the aggregator of such dynamic loads will be proposed. The generic descriptions and architectural concepts may not be limited to the domestic household domain. The remaining paper is structured as follows: in the next Section an overview on established approaches

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on dynamic load control will be given. In Section 3, the architectural concept will be introduced and the most important components described, followed by an use-case study in Section 4. Section 5 concludes the paper.

2. Approaches on dynamic load management

Regarding the short-term Demand-Side-Management techniques [3], influencing the time-of-use of the loads is one of the most common approaches [5]. Being able to alter the consumers' consumption pattern enables the utility or aggregator of loads to provide energy related services for the grid like control energy, load optimization and other.

In the scope of short-term DSM, two major approaches on dynamic load control can be deviated. The first approach is the classical direct load control (DLC) by the utility or an according entity [6]. Based on the targets of the controlling entity, the loads can be fully or partly controlled via Energy Service Interfaces (ESI), in order to achieve the intended behavior. This top-down oriented approach implies that the controlling entity either maintains all the information about the controlled loads or has statistical models to make a reasonable planning of the resources [2]. Beside this precondition, security and privacy aspects can be problematic. Also, centering the ability to control large numbers of loads in one entity may result in unpredictable security risks for the grid and the end-users as well. The precise scheduling of loads via DLC allows the utility to quick respond on gird or market conditions with a reliable response of the controlled system. An application of direct load control can be found in [7].

The second established approach for DSM is an extension of the classical tariff-model, broadcasting varying tariff-signals to the consumers and thus provoking reactions. Applications implementing varying tariffs were developed and tested in many projects like [8] or [9]. Despite the obligation in § 40 (5) "Energiewirtschaftsgesetz" (Energy Act) by the German government to increase the number of intelligent metering devices capable of dynamic pricing in domestic households, the dissemination and acceptance yet stays relatively low because of the expensive (and often proprietary) hardware and sophisticated software [10]. Legal and privacy concerns of the interfaces not only accessed by the utility are also under discussion currently [11]. Especially interesting business models with substantial financial advantages for the consumer-side are rare. The according ICT-architectures for such business-models must act highly autonomous and automated in order to keep the entrance barriers and time-efforts for the consumers low.

3. Concept of a consumer-oriented Architecture

Demand-Side-Management applications usually consist of large number of highly heterogeneous loads which are represented in an according DSM-application architecture. Regarding DSM potentials and their representation resp. their aggregation potential, three levels of abstraction can be distinguished (see fig. 1). The device-level is the software-representation of the actual physical load, making it available for home automation and managing through ICT. The second level is the domestic household itself, optimizing and planning the own demand for energy and DERs like solar panels and energy storages. The household may also offer numerous services to the grid through the Energy Service Interface (ESI). Aggregating several domestic households and other DSM-capable loads with ESIs, like industrial or commercial entities, to a Virtual Power Plant (VPP) allows entering markets on larger scales as described in [1, 12]. The proposed architecture addresses especially this last DSM optimization-level with regard to the heterogeneity of the loads. One matter of concern in the field of DSM-applications in the domestic household domain is the (statistically) broad availability of the dynamic potentials while the actual loads of the devices are relatively low. The architecture proposes an ICT infrastructure that enables the aggregator or utility to connect different dynamic loads, typically in one control zone, through a virtual network.

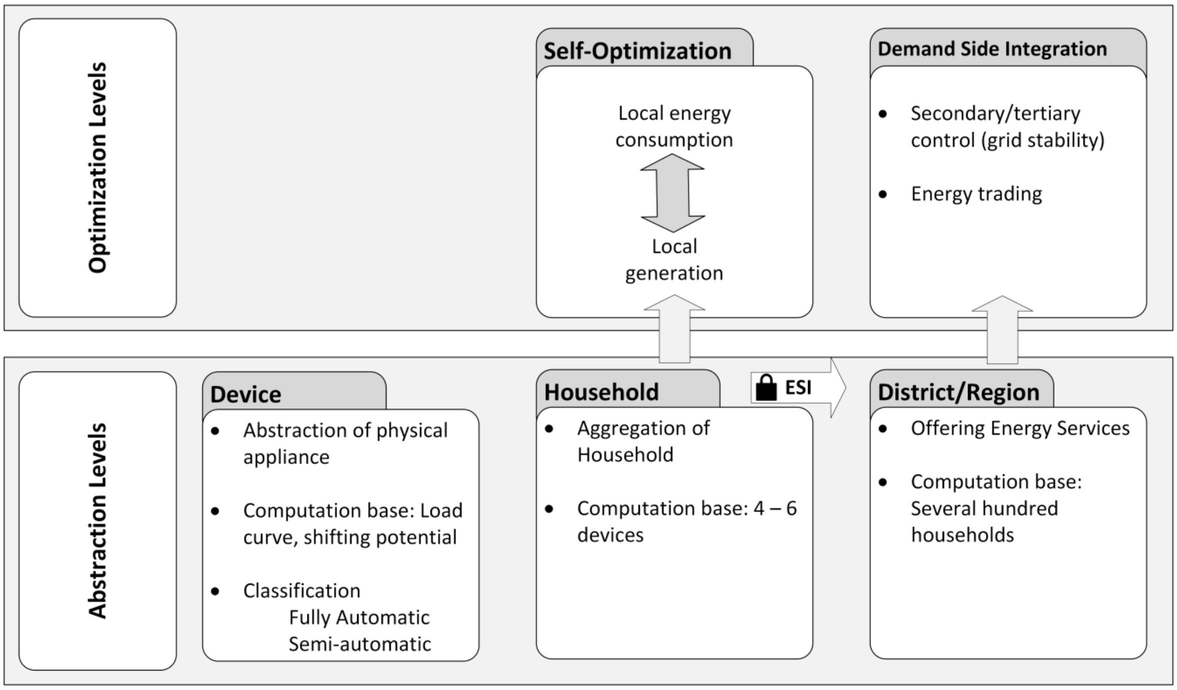

Figure 1: Aggregation and optimization levels.

The overall proposed architectural concept (see fig. 2) will be described according to the NIST Domain Model of the Smart Grid Roadmap [13] and focuses on three for the DSM important components: Energy markets, where the prices and tariffs were made, Energy Management Systems as an interaction and interface platform between markets and the consumer-side, and the consumer-sided Energy Service Interfaces.

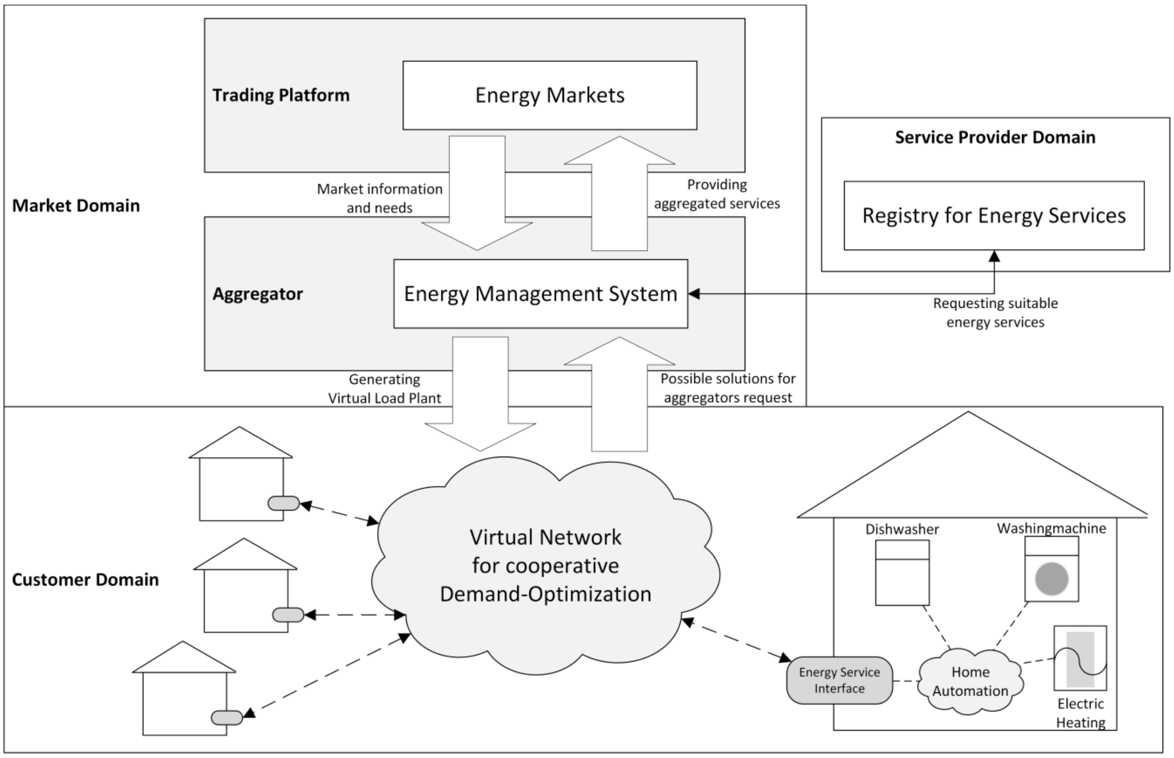

Figure 2: Architecture model with domain-specific components according to the NIST Framework domain model.

3.1. Energy Markets

The architecture of the market model is inspired by stock exchange markets and the actual energy markets in central Europe like the EEX. For each discrete timestep, a trader can place or accept offers, according to the generated or demanded energy. Each offer consists of a certain amount of power and a price per trading unit. With this model, most of the current business cases related to energy market and trading could be represented. Beside the traditional energy market, alternative open markets for energy services may be created e.g. markets for control energy capabilities. Currently most energy markets are not open for DSM efforts because of the high prequalification borders.

3.2. Energy Management System

The Energy Management System (EMS) describes a service platform for the aggregator's role in the domain model. Monitoring the needs of the energy market and offering energy services like volt/var control or other for the smart grid, the aggregator combines smaller entities to enable the DERs to act and trade in these markets.

Managing the signals from the energy market, the aggregator generates tariff-structures for the demand-side, depending on the intended business plan or behavior of the VPP. These tariff-structures can provoke different responses from the demand-side. Consider a classical variable tariffs approach for business-models, where the response of the VPP can be estimated, or commodity-exchange inspired tariff-models, in which certain energy-amounts were offered with different prices for business models where the energy scheduling must be quite accurately. Imperative for efficient DSM activities is the planning horizon for the loads. Real-Time-Pricing (RTP), where the market development is directly forwarded to the demand-side and the consumer must bet on the development of the market-prices, has proven quite inefficient beside some stabilizing effects [2]. To use the full dynamic potential of loads, a certain planning horizon must be provided by the aggregator. In order to achieve these tasks, the EMS needs access to a service where available energy services can be found and booked. This Registry of energy services is part of the service provider domain, and offers search and booking services [14].

An aggregator forms Virtual Networks out of the loads intended to be part of the VPP-structure and broadcasts the tariff-model. To address the issues of direct load control and the indirect tariffs as stated in the Sections before, the Energy Service Interfaces of the households have the abilities to optimize their demand cooperatively and propose a scheduling of the participating loads to the ESM. Thus, the scheduling is not made in the EMS by the utility or the aggregators like in traditional approaches.

3.3. Energy Service Interface

The Energy Service Interface (ESI) is the household's interface to the Smart Grid. It manages the different appliances and devices of the household in order to make their dynamic load-potential available for the utility or aggregators. In Fig. 3 the internal architecture of a basic ESI is stated. It is parted into two components with different functionalities. The user controlled area represents the classical implementation of an ESI as implemented in OGEMA [15] or OpenADR [16]. The communication interfaces can implement a variety of bus systems e.g. I²C, ModBus in order to communicate with a wide variety of household appliances.

The Device Simulation Modules contain important configuration details about the connected devices in the household. As stated by [17] two types of devices are interesting for DSM applications with dynamic loads:

a. **Program-Driven Devices** like washing-machines or dishwashers that need the user to load and start the device and then offer a certain dynamic potential for DSM activities.

b. **Fully-Automatic-Devices** that have sensors and actors to keep a certain state like thermal loads (electric heating/cooling). Under the assumption that the next planning step of a fully automated device might depend on its state, most of these devices could be planned iteratively.

The users' preferences and constraints for the whole energetic behavior as well as for single devices could be entered through the User Control Interface, which could be realized through web-interfaces or apps.

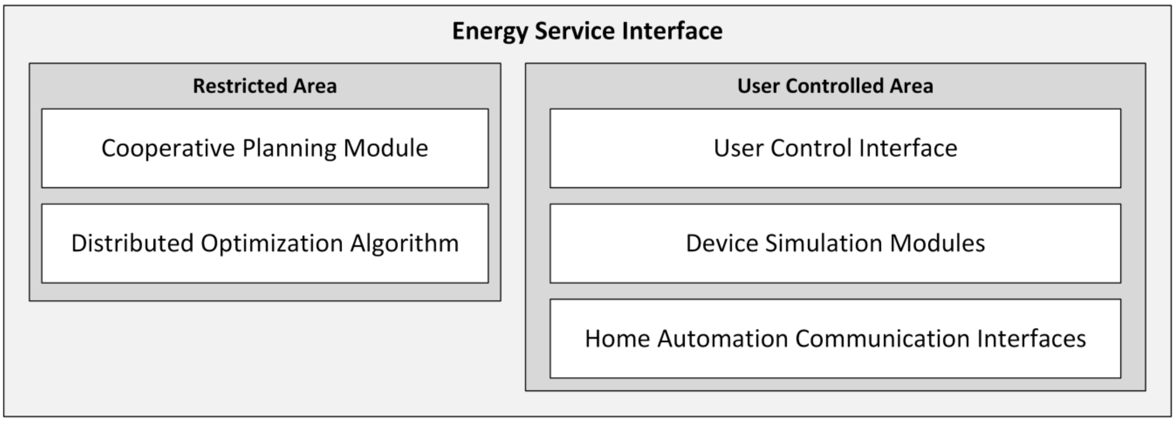

Figure 3: Energy Service Interface

The second part of the ESI contains the access-restricted planning component for the coordinative scheduling. This part communicates with the other ESI planning components about the dynamic potentials of the other loads and thus must be hardened and secured against external access through encryption and user-restrictions. The planning module provides services to request the dynamic potential of the household for optimization purposes based on the Device Simulation Models and the user's restrictions. Running on an embedded device, the computational power may be used to perform a part of a distributed optimization algorithm to solve the scheduling problem.

In the most basic implementation, the planning module of the ESI provides methods to request the possible discrete runtimes of a device, which can be used by an optimizer to schedule the load. Planning a fully-automated device can be done iteratively. For most e.g. thermic loads, the next possible timeframe for operation depends on its condition. Communicating these conditions with the timeframes to the optimizer, the optimizer chooses a runtime and its dependent condition according to the applied optimization algorithm and retransmits it to the ESI where the following timeframe is calculated. The ESI thus remains stateless and can provide its capabilities to many distributed optimization entities.

4. Use-Case Study: Shifting operation

A functional prototype of the above described system, containing several key components, like a basic EMS, was implemented in a simulation tool built with JADEX Active Components [18] in order to demonstrate the capabilities of the approach. In the Smart Grid, shifting operations are an interesting approach on managing the consumption [3], as for example shifting loads from peak hours to off-peak hours or to reduce the peak-to-average-load ratio [19].

The scenario contains of a virtual optimization network, containing 100 domestic households with several dynamic loads like washing machines and electric heating per household. The mean, non-optimized load of the virtual optimization network is shown in Fig.4 as black line. The EMS broadcasts a load-limited shifting signal at time 65 (based on 15-minutes-timeslots). The signal requests a shift of the demand from timeframe $\{66, \dots, 73\}$ to the timeframe $\{74, \dots, 82\}$. Using a distributed Ant Colony Optimization Algorithm described in [20], the households try to optimize their demand and shift their loads according to the request.

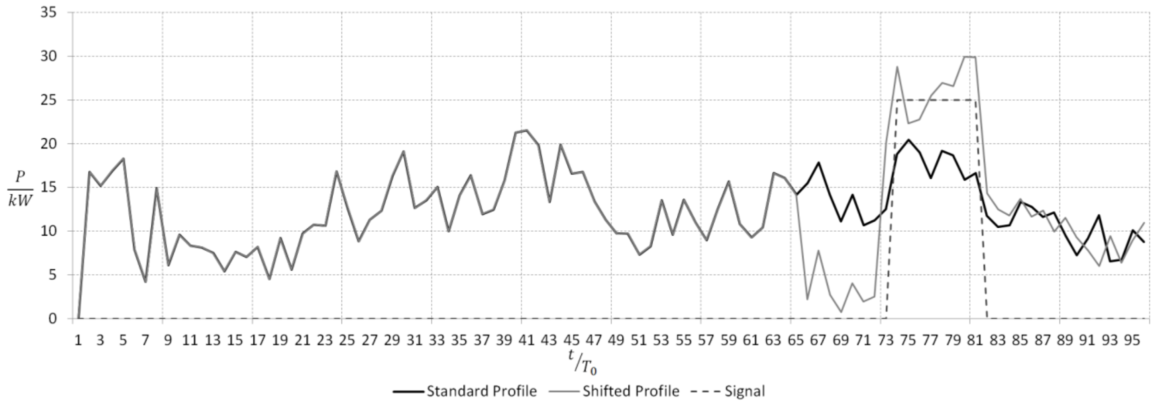

Figure 4: Reaction of 100 households to a load-limited shifting signal

It can be seen in Fig. 4 that the signal requests a limited shift of 25 kW for two hours from timestamp 74 to 82 which can be achieved by the dynamic devices. Due to thermal restrictions and runtime constraints of some devices, the average power of the shifted energy scheduling (grey line in Fig. 4) is slightly higher, because no more shifting potential was available.

5. Conclusion

In this paper a distributed, decentralized and scalable architecture for demand-side-optimization was described. The approach focuses the decentralized integration of the consumer side, using the capabilities of upcoming Energy Service Interfaces for offering energy services without the need of knowing the detailed configuration of the virtual network by the Energy Management System. Generating virtual networks provides a modular and scalable model for Smart Grid applications and energy services. The architecture was described according to the NIST Smart Grid Domain model. A prototypic implementation of the approach was built with JADEX, demonstrating the basic functionality of the approach, i.e. simulating a four hour shifting operation with 100 households. Although those shifting operations may be interesting for peak-clipping and peak-to-average reduction, the demonstration not yet features secondary or tertiary control.

Future work will cover detailed descriptions and reference implementations of the ESI components, as well as further simulations and tests. Field tests and integration of the architecture into common open-source Energy-Management-Systems are also planned.

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