Service-Oriented Middleware for Smart Grid: Principle, Infrastructure, and Application

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ABSTRACT

The current smart grid is undergoing a drastic change in order to deal with increasingly diversified and various service requests from the huge number of users. The next-generation smart grid, characterized by service-oriented middleware, will be upgraded by jointly employing the technologies in the areas of communications, control, and computing. To design a general middleware, an efficient design principle plays a fundamental role, while reliable communication infrastructure and heterogeneous applications lead to sustainability and stability. In this article, we propose an integrated and efficient middleware for heterogeneous services in a smart grid. Specifically, we first develop a mutual application access control principle that keeps users obtaining a satisfying assignment. Next, a collaborative and dynamic information exchange infrastructure is proposed for different smart meters, and a local information collector is designed to implement the communication and computing through power management messages. Finally, we present four steps to design a flexible service-oriented middleware for heterogeneous applications. Numerical simulation results are provided to demonstrate the efficiency of the proposed middleware.

INTRODUCTION

Recent years have witnessed the power industry integrating its distribution system with communication networks and control techniques to form a data-flow-based framework, commonly called a smart grid. Such integration not only moves the traditional power generation and transmission system to an advanced intelligent communication system, but also brings heterogeneous service provision (e.g., multimedia applications) to these data networks. Actually, supporting different kinds of services over smart grids has been one of the hot topics in the network and communication communities. For example, as shown in Fig. 1, a classical intelligent smart grid platform has defined an overlay architecture for providing heterogeneous services [1].

To provide heterogeneous services with quality of service (QoS) guarantee, technologies (i.e., wireless communications and multimedia signal processing) have incorporated into the smart grid. Moreover, the middleware should be developed as a bridge between system and operator. A fundamental part of middleware is the wide-area monitoring system including sensor networks, WiFi, satellite communications, cellular network, the Internet, and so on [2, 3]. Importantly, the information of the system state is the input of the middleware, which enables system operators to dynamically assign power to users according to their requests via the communications networks. Unlike the middleware in traditional wireless/wired networks, in the smart grid, it extends the role of arrangement to users' applications [4].

From the QoS enhancement aspect, application implementations have high efficiency strengths. However, the power consumption of application provision is much higher than that of pure software implementations. The reason is that flexible application provisions yield higher computation complexity, which causes a considerable increase of power consumption [5]. Recently, there is a new trend: the energy assignment problem is transformed to distributed resource allocation or scheduling at the application level [6]. To this end, for an energy-constrained system, at least in theory, we can satisfy different users' requirements using software implementations such as middleware.

As the smart grid becomes a reality, heterogeneous service provisions are also expected to grow exponentially. Users' satisfaction or quality of experience (QoE) will also certainly face substantial user access and huge applications' computation. Therefore, the role of middleware is totally different from the traditional pure software tool from the aspects of both the user and the system [7]. To the best of our knowledge,

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there has been little research on service-oriented middleware design in the context of the smart grid. In this article, we aim to design an integrated middleware for heterogeneous services. First, we develop a mutual application access control principle so that the users in this system can obtain a corresponding satisfying assignment. Next, a collaborative and dynamic information exchange infrastructure is provided between different smart meters. Moreover, a local information collector fulfills efficient communication and computing for power management messages.

The rest of this article is organized as follows. First, we provide the middleware design principle for a general smart grid. We then show heterogeneous service infrastructure and specify the interaction between the different services. We describe the application trend, and evaluate the proposed method. At last, we conclude this article.

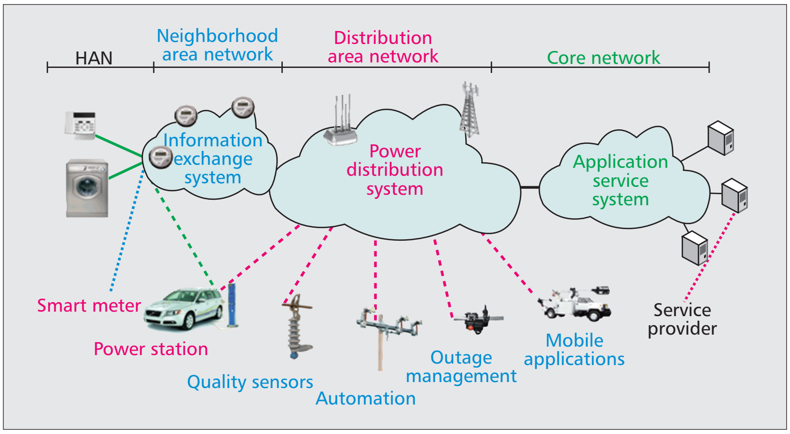

Figure 1. *An overlay architecture for providing heterogeneous services.*

Middleware Design Principle

Service-oriented middleware has recently attracted much attention as an interesting and prospective topic for the smart grid [4, 8]. Service-driven design is an essential feature of the smart grid, because almost all smart grid systems aim at serving well for power allocation and consumption. We adopt Qiu's definition of service as "*any information that can be used to satisfy the users' requests*" [3]. Specifically, the term information includes time, place, and object states that are considered relevant to the interaction between a user and an application, including the user and application themselves.

Essentially, service-oriented middleware characterizes a series of protocol stacks and scheduling schemes to efficiently perform well for different applications by exploiting the characteristics of various users' requests. In this article, we deploy the service-oriented definition of middleware in [9], that is, *the smart grid is the ubiquitous communication network that extends the system monitoring and control to the end-user level*. In particular, end users have the right to request various application services from the aspects of power consumption and price. In general, the middleware design principle focuses on being user-centric, which is realized by service-oriented protocol stacks and scheduling schemes. Figure 2 illustrates the basic parts of the design principles.

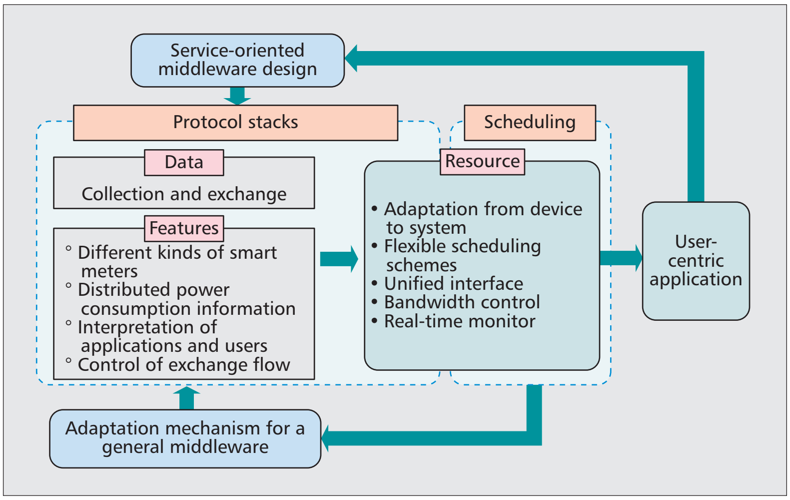

Figure 2. *Design principles for the service-oriented middleware.*

Service-oriented middleware involves performing data acquisition from the end users, and some devices can provide applications when the users' requests can be satisfied. As we know, traditional data collection and information exchange mechanisms make the middleware almost impossible to reuse because of the different service requests. One possible solution to such a problem is to decouple the service-oriented middleware into multiple application-based functionalities, which can be implemented by stochastic optimization. In that case, a service-oriented middleware has to provide a variety of applications with the following characteristics:

- Supporting different kinds of smart meters
- Satisfying the distributed nature of power consumption information
- Providing for transparent interpretation of applications and end users
- Controlling the information exchange flow

In addition, some applications (e.g., multimedia monitor) need extra requirements for large communication and computation. Hence, they need substantial network bandwidth and processing power. In this case, the middleware should have the ability to deal with the following issues:

- Making use of the available bandwidth. The middleware should use all the available connections from the devices to the end users to try its best to fulfill the users' requirements at any time
- Controlling the amount of information exchange

To exploit the limited network resource, the middleware needs to determine which kind of information exchange is necessary based on the known or observed information [7].

Furthermore, the middleware is able to support various devices, such as video cameras, microphones, and so on. To this end, the designed middleware should have multiple open interfaces between different devices and networks to make the system adaptable and flexible. Specifically:

- Triggering of adaptation from the devices to the communications networks

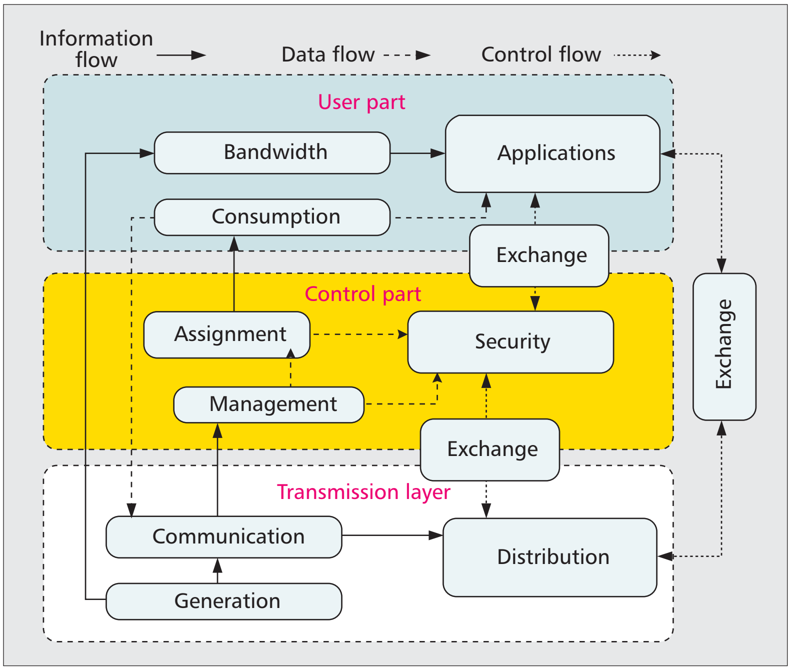

Figure 3. *Heterogeneous service infrastructure.*

- Support for system-wide adaptable and flexible scheduling schemes in both centralized and decentralized manners

Basically, developing an adaptation mechanism suitable for service-oriented middleware for the smart grid is an excessively demanding task. A summary of the fundamental design principles are:

- Clear specification of the relationship between the middleware's functions and the users' requests
- Support for various computational complexities of heterogeneous applications
- Independence from the types of devices for wide use
- Interoperability and portability

Ideally, the middleware can integrate other devices or users in a variety of environments.

Heterogeneous Service Infrastructure

The service infrastructure for smart grid depends on the communications fashions that collect and transmit real-time energy consumption data. In general, the service infrastructure is a mix of hybrid wireless and wired services [5]. To provide heterogeneous services in a general smart grid system, we design a service-oriented middleware which consists of three main parts:

- Transmission part
- Control part
- Presentation part

Figure 3 shows the heterogeneous service infrastructure for a general smart grid middleware.

Transmission Part

The transmission part is the foundation for the basic service framework. From the function perspective, the transmission part can be further divided into three parts: generation, communication, and distribution. Specifically, the main task of the transmission part is to transmit the needed electrical power from generation to distribution through multiple substations [8]. Usually, it is operated through a real-time communication mechanism that monitors the customer need from home, commercial, and industrial sectors.

The core component of the transmission part is the adaptive meter infrastructure (AMI), which is designed to measure energy consumption data to adapt for dynamic electricity pricing [10]. Given that AMI data travels from the appliances to the controller,[1] it is one of the main applications whose data spans over the whole smart grid, such as home area networks (HANs), neighborhood area networks (NANs,) and wide area networks (WANs). With respect to a specific AMI, demand function (DF) is introduced in response to the variations of user demand by adaptively allocating the available power according to the demands. In fact, DF aims at providing users' incentives to reduce their electric consumption corresponding to system overloads. The controller can set the power consumption price by shifting consumption time and lowering the cost. The users, on the other hand, also get net profit incentives from dynamic power consumption. In addition, DF can utilize the AMI to realize the missions in the transmission part. Obviously, the success of AMI and DF is based on a prior agreement between the user and the power generator, and this offers motivation to research the control protocol, which is interpreted in the next subsection.

Control Part

Typically, the control part connects the user and transmission parts. The main function of the control part is how effectivethe proposed control mechanism better manages the complex and diverse devices (in the transmission part) to improve the QoS or QoE (in the user part). We put forward a visual control framework that divides the control part into four functions: fault report, power allocation, user information management, and security guarantee. To give a clear description, we provide multiple examples, such as active distribution (AD), error detection (ED), mobile management (MM), and multimedia surveillance (MS). AD operates on the distribution substation and utilizes an adaptive response strategy to present more effective fault detection, isolation, and restoration. ED is achieved through AD to control and monitor abnormal conditions such as devices that are not working. MM is used for navigating the mobile devices to the location that needs to be served. MS is employed to monitor the critical devices in the smart control in the form of video and voice. The collected data in the above four functions is directly connected to the central control center through a specific communication network from the security perspective.

User Part

Users usually care about QoS (or QoE), which provides certain performance in terms of bandwidth, reliability, delay, jitter, an so on. The applications in the framework of a smart grid

[1] In this work, the controller is the output of the flow from the middleware.

require services to provide high reliability and availability, especially for practical economy-driven applications [8]. Specifically:

- MS for securing critical transmission requires high bandwidth.
- The power consumption data from each user can arrive at the controller with high-probability security (this is also related to the control part).
- Get an appropriate data report frequency to achieve the trade-off between the information accuracy and communication overhead.

In addition to the classical applications, there are many challenges that arise from the underlying protocols to support the above applications. Due to the specific features of the transmission and control parts, different wireless communication and network technologies usually provide diverse QoS, which impacts the performance of resource scheduling [6].

It should be noted that scheduling flexibility to provide satisfying QoS at any condition is very important for the smart grid. A variety of devices, such as smart meters, are connected to a communications network to deliver power usage data from each user to the control center. However, the number of devices connected to the network at a certain location will vary with user density and user preference. Therefore, any proposed scheduling strategy should be able to scale under a variety of users with their distinct operational requirements. Therefore, the user part and control part should be designed jointly in a practical system. In particular, we should pay attention to route discovery, maintenance, and resource allocation with secure routing and scheduling, since thay can grow rapidly with the size of the smart grid.

The Trend of Applications in Smart Grids

For any smart grid applications, it is necessary to collect energy consumption information from the users and deliver the information to the control center through either open or private WANs [11]. In a NAN, a cognitive gateway (NGW) connects smart meters from multiple home wireless networks together. From the application point of view, the NGW can be considered as the cognitive radio access point to provide a single-hop connection in a hybrid access manner [4]. The trend of the application is presented in Fig. 4.

Cognitive Radio-based Application

To improve the spectrum efficiency, a hybrid dynamic spectrum access scheme is employed to satisfy different kinds of service requests. Note that some licensed spectrum bands are leased from a telecommunication operator, in this case, these bands are used as licensed access for the NGW to ensure the QoS of the application. The NGW distributes these licensed bands to different users according to the transmission demand from the users. However, licensed spectrum bands are not enough to meet the large amount of data, especially for multimedia applications.

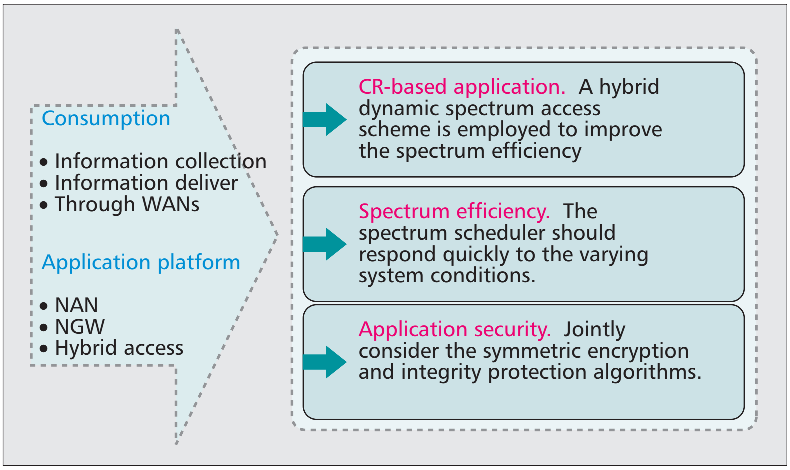

Figure 4. *The trend of the application in smart grids.*

Hence, unlicensed access is also needed for the NGW to improve the throughput and reduce the transmission delay [4]. Similar to traditional cognitive radio, the communication links between the NGW and devices are connected in an opportunistic manner for unlicensed access. Therefore, the data exchanged between device and NAN should employ hybrid access.

Furthermore, each NGW is no longer only an access point in the framework of cognitive radio service, but a cognitive intelligent device with the capability to communicate with the control center. More precisely, the control center is connected with cognitive radio base stations. To accommodate the heterogeneous applications, service-oriented middleware plays an important role in sharing the spectrum resources among different NANs to enable coexistence of heterogeneous applications [7]. The cognitive radio base stations manage the QoS requests of the applications and implement the resource allocation for the spectrum. In a large geographical distribution of NANs, several NGWs may not be within the geographic area covered by base stations. These NGWs should communicate with each other in an opportunistic way to share unoccupied spectrum bands. In this way, a unified cognitive radio application framework can be established by incorporating the service-oriented middleware described in the previous section.

Spectrum Efficiency

To improve the spectrum efficiency for a large number of applications, spectrum access mode should be intelligently scheduled. In fact, the users are not aware of the access mode or method they are using; to this end, the power controller allocates the available power by realizing the spectrum sharing for different users. Taking into account the dynamic variation of the transmitted data in the network, the controller should respond quickly to the varying request conditions and distribute the available spectrum in an efficient manner (to meet the requests regarding transmission delay, throughput, bandwidth, and so on).

Different kinds of devices in the smart grid system are interconnected for information col-

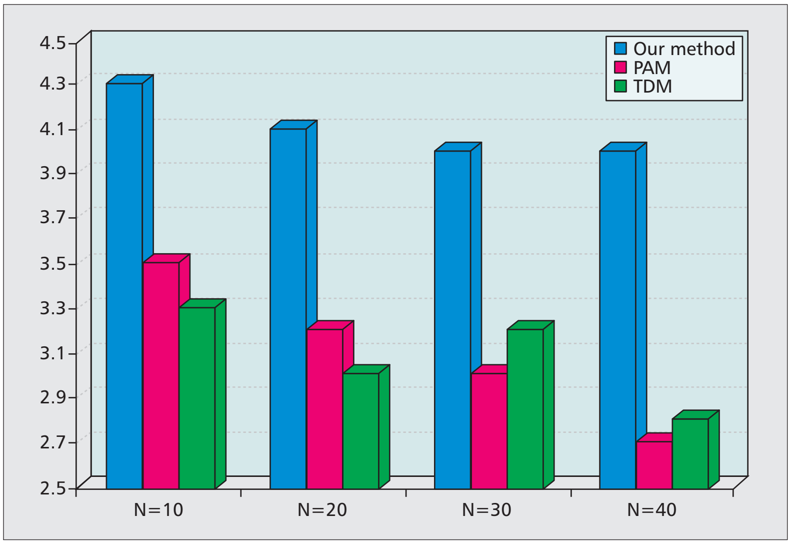

Figure 5. *Comparison results for different methods in various scenarios.*

lection and delivery to construct the information transmission platform (ITP). As mentioned previously, various wireless communication technologies can be adopted by various devices, and hence coexist in an ITP. Note that improving the spectrum efficiency in ITP may cause interference between each device, and hence lead to decreased QoS for all the users. Thus, a spectrum sharing mechanism is essential to coordinate the spectrum access of the heterogeneous applications [8]. Here, we employ a dynamic spectrum access method that consists of two main components, the spectrum access controller and power allocator, which operate at the transmission part and control part, respectively. Each device is allowed to access the spectrum only if it is permitted by the access controller, while the power allocator helps in the realization of cooperative communication among devices to achieve the optimal QoS from the aspect of the users.

The Security of the Applications

Recently, there has been substantial work addressing schemes to defend against the attacks in smart grid systems. Typically, confidentiality can be realized by various encryption algorithms, authenticity can be implemented by digital signature, and integrity can be achieved by employing a universal communication interface [9]. In this framework, we can see that the additional energy cost resulting from security protection largely depends on the complexity of the security algorithm. In order to provide a scalable security application framework for different services, we need to take the symmetric encryption algorithms and integrity protection algorithms into account. There are two important factors:

- Providing protection over all aspects of the security issues
- Setting an appropriate scale factor to achieve the trade-off between security priority and computational overhead

Generally, the devices that interact with the users should be protected by the security scheme with scalable priorities. The corresponding additional energy consumption contains two parts:

- The energy consumption resulting from the operations of the applications
- The extra energy consumption coming from the implementation of the security priority

To be more specific, the first one is dominated by the physical circuits of the devices. Since the computation complexity resulting from security protection is implemented online, the extra energy consumption is determined by the operation of the security algorithms.

Performance Evaluation

In this section, we design a service-oriented middleware in a smart grid based on the above discussions. Basically, there are four steps:

Step 1: Access control: A new user sends an access request to the gateway, and it makes a decision about the user request based on the principles proposed earlier.

Step 2: Message transmission: The access controller transmits the requests of the new user to the power assignment. The request information contains the specific parameters of the users' satisfaction function model. In particular, this model can be implemented in the user part described earlier.

Step 3: Power allocation: The central controller implements an optimization problem (the optimization goal can be set from the spectrum efficiency or security, described earlier) to obtain the optimal power allocation of all users. The resulting power allocation is sent back to the access controller.

Step 4: Service quality: If one or more users' requests cannot be met, the allocated power should be increased only if the total power is available, and the detailed mechanism is interpreted. The access controller informs the new users of the access decision and the corresponding allocated power.

In what follows, we evaluate the performance of the proposed middleware by using ns-2. In the simulations, the collecting node is modeled by a personal computer with each smart meter node modeled with an ARM processor. We deploy IEEE 802.11b for the physical/medium access control (PHY/MAC) protocol [6]. The data flow is generated as a constant-bit-rate UDP session at 2 packets/s with packet size of 100 bytes for each smart meter. The power request of each user is a random variable located in [0, N], where N is the number of the users.

The proposed middleware (noted as our method) is benchmarked against the traditional power-aware middleware (PAM), proposed in [7], and time-driven middleware (TDM), proposed in [4]. In order to provide a clear and fair comparison, we employ the mean opinion score (MOS) as the metric. Specifically, the highest score of the MOS value is 4.5, which denotes the best service quality. Figure 5 presents the comparison results for different methods in various scenarios. From the given results, we can clearly observe that our method substantially outperforms the traditional methods, particularly when the number of users tends to larger. For example, when $N = 10$, the mean opinion score value gap between our method and PAM is 0.8, while it increases to 1.3 when $N = 40$. Therefore, these simulation results are consistent with our theoretical analysis, and again verify the validity of the proposed middleware.

CONCLUSIONS

In this article, we present an efficient, integrated, and general middleware for heterogeneous services in the smart grid. First, we develop a mutual application access control principle that means users can obtain a satisfying power assignment. Next, a collaborative and dynamic information exchange infrastructure is provided between different devices, and a local information exchange mechanism is designed to realize efficient communication and computing for power management messages. Finally, we propose four steps to design a service-oriented middleware, and numerical simulation results are presented to verify the validly of the proposed middleware. For future work, we will focus on applying the proposed middleware to the practical smart grid or Internet of things.

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