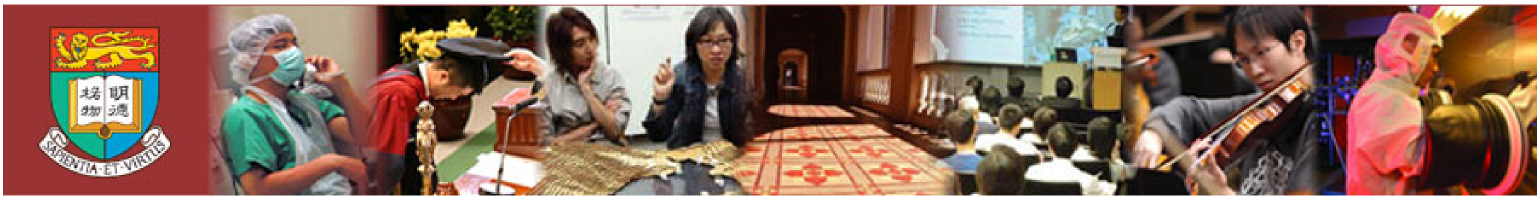

Title	**Energy management system and pervasive service-oriented networks**
Author(s)	**Yang, GH; Li, VOK**
Citation	**The 1st IEEE International Conference on Smart Grid Communications (SmartGridComm 2010), Gaithersburg, MD., 4-6 October 2010. In Proceedings of the 1st SmartGridComm, 2010, p. 1-6**
Issued Date	**2010**
URL	**http://hdl.handle.net/10722/126036**
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Energy Management System and Pervasive Service-Oriented Networks

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***Abstract*—In this work, we study the energy management system (*EMS*) in the customer domain of the Smart Grid. We discuss the desired features and design issues, highlight the characteristics and identify the challenges. To address the challenges, we propose the innovative framework of Pervasive Service-Oriented Networks (*PERSON*). The core idea is to utilize a heterogeneous network as the information infrastructure, abstract the functionalities into services, and deploy context-aware intelligence to address the system dynamics. Furthermore, based on the framework of *PERSON*, we implement a powerful yet cost-effective *EMS*. The effectiveness of the *EMS* is demonstrated by a demand response application.**

I. Introduction

Recently, Smart Grid (SG) has attracted much interest from governments, power companies, and research institutes [1], [2], [3]. Compared to the traditional electrical grids, by employing advanced information technologies, SG can achieve higher efficiency, better reliability, stability and sustainability, lower total infrastructure investment, better exploitation of renewable energies, lower power consumption and lower greenhouse gas emission. An energy management system (EMS) monitors, controls and optimizes the performance of energy generation, transmission, distribution, and consumption. EMS is an important building block of an SG, and plays a key role in achieving the advantages of an SG.

The *Conceptual Reference Model* of SG proposed by NIST [4] divides an SG into seven domains, specifically, customers, markets, service providers, operations, bulk generation, transmission, and distribution. Among the seven domains, EMS for energy generation, transmission, and distribution have been studied for decades. Many models, standards, protocols and systems have been proposed, implemented, and deployed in practical systems [5], [6]. However, EMS in the consumer domain is largely neglected in existing studies.

In this work, we focus on the EMS in the customer domain (for simplicity, we use EMS to denote EMS in the customer domain in the rest of the paper). The main contributions of this work are three-fold.

- In the context of EMS in the customer domain, the desired feature and design issues are discussed, the characteristics are highlighted and the challenges are identified.
- An innovative framework, namely, Pervasive Service-Oriented Networks (PERSON), is proposed to address the major challenges of heterogeneity, distributed system and dynamicity. As far as we know, this is the first framework for the EMS in the customer domain. Moreover, PERSON can be used not only for R&D of EMS, but also to provide insights for the design of other heterogeneous and dynamically changing systems.
- A cost-effective EMS prototype is developed as an implementation of PERSON. The effectiveness of the prototype is demonstrated in Demand Response (DR) [7] application.

This research is supported in part by the HKU Seed Funding Programme for Applied Research (Project code: 201002160022), HKU Strategic Research Theme of Information Technology and the University Development Funding (Initiative on Clean Energy & the Environment).

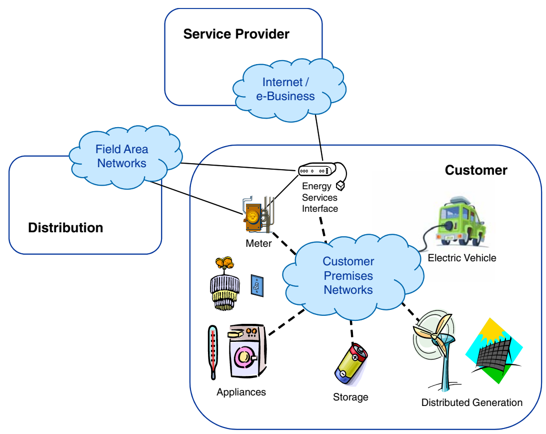

Figure 1. Customer domain and its connections with other domains in a Smart Grid.

The rest of this paper is organized as follows. In Section II, EMS is introduced in details. The desired features, design issues and the major challenges are discussed. In Section III, PERSON is proposed and described in details. In Section IV, an EMS prototype based on PERSON is designed, implemented and demonstrated. Section V concludes the paper and suggests future research.

II. Energy Management System at Customer Domain

According to the *Conceptual Reference Model* of SG [4], the customer domain of an SG is composed of SG actors and applications. Actors include devices, systems, or programs that obtain and exchange information, and make decisions for performing applications. Smart meters, renewable energy generators, and appliances are examples of actors. Applications, on the other hand, are tasks performed by one or more actors. *Energy Management* (*EM*) is an example of applications. In Fig. 1, major actors in the customer domain and major connections between the customer domain and other domains are shown.

Existing EMSs in the customer domain are generally simple monitoring and control systems, which ignore the challenges of an SG and thus only have limited capability and limited intelligence. In this section, we first highlight the features of an EMS. Then we analyze the EMS control flow, discuss the design issues and identify the major challenges. These efforts help us to have a better understanding of an EMS, which is fundamental to an effective design and implementation. An effective EMS brings benefits not only to the end-users but also to the utilities and the whole society.

A. Features of EMS in the customer domain

To support the advantages of SGs, an EMS is required to have some basic features:

- Supports various existing actors as well as emerging actors.
- Continuously monitors the energy consumption at different granularities, such as home level and appliance level.
- Continuously monitors environment parameters, such as temperature and humidity, which can be exploited for context-based intelligent control.
- Supports automatic and manual control of the actors.
- Supports the integration of renewable power sources, such as solar and wind.
- Interacts with actors in other domains to realize advanced features, such as DR.

Besides the basic features, some desired advanced features include but not limited to:

- Intelligence and efficiency: ability to achieve optimized performance under dynamic situations.
- User friendliness: plug-and-play with self-configuration capability.
- High reliability and durability: robustness and self-healing capability after system failures.
- Low cost and low power consumption.

B. EMS control flow

The features listed above are from the perspective of a user. From the perspective of the control processing, EMS can be abstracted as a closed-loop control system as shown in Fig. 2. The control flow is composed of several building blocks.

- Distributed measurement: Measurements include not only power consumption/generation data, but also environmental parameters, users' preferences and behaviors. The measurements are conducted on different actors in a distributed manner.

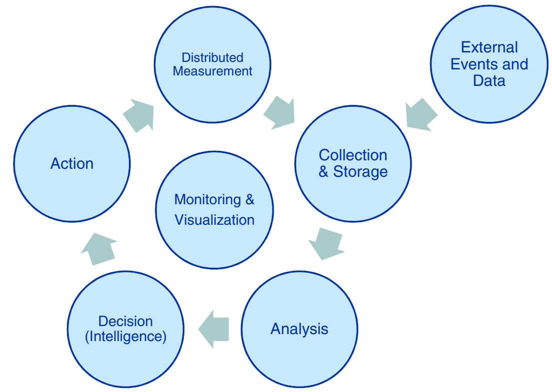

Figure 2. EMS control flow chart.

- Collection & storage: Measurements are exchanged among actors, and stored in some aggregator for further analysis and processing.
- Analysis: The collected and stored data are analyzed to obtain historical and statistical information. In addition, the data is processed to obtain an up-to-date view of the system.
- Decision (intelligence): Based on the results of the analyses, energy management decisions are made via some intelligent algorithms.
- Action: Control decision is delivered to some actuators, such as switches and breakers, for execution.

Besides the main closed-loop control flow, some building blocks are also necessary:

- Monitoring & visualization: It provides an interface and a user-friendly way to monitor and control the system.
- External events and data: This include users' or utilities' control decisions, price of electricity, weather, natural disasters, etc.

C. Energy flow, information flow and challenges

If we take a closer look at the control flow, it is basically energy flow management utilizing information flow.

1) Energy flow: In customer domain, energy is distributed through an electricity network in a tree-like structure. In the structure, generally, the power meter sits at the root, while AC outlets, lights and appliances are at the leaves. The energy flow can be measured by energy monitoring devices, such as meters and power gauges; and can be manipulated by controllers, such as breakers and switches. Although the electricity network is a homogeneous network in terms of the way energy is distributed, monitored and controlled, the energy flow is quite dynamic in terms of quantity and quality. The dynamicity is due to the varying of supplies and demands, dynamic user behaviors, and continuously changing environments. In an SG, increasing usage of renewable energy sources, such as wind turbine and solar panels, makes the problem even more challenging.

2) Information flow: The information utilized in an EMS include the real-time measurements, historical data, external events, control decisions, and etc. The information is

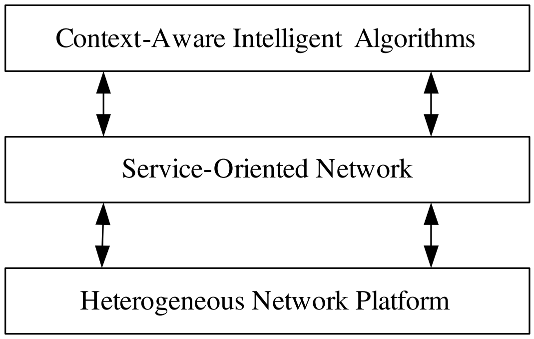

Figure 3. Three-layer structure of PERSON.

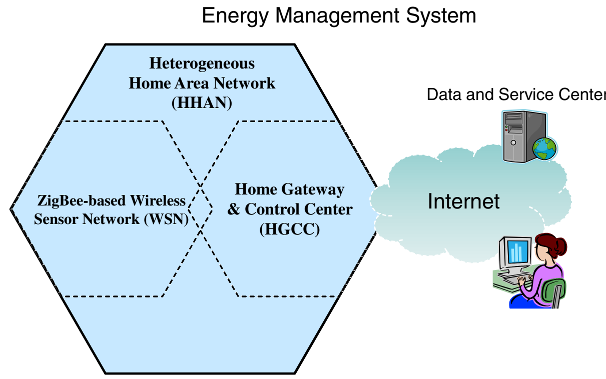

Figure 4. The structure of EMS.

exchanged among distributed actors through some kind of communication channels. The communication channels form a communication network, which is generally a heterogeneous and distributed network. Heterogeneity is unavoidable because different actors may follow different communication protocols, use different media (wire or wireless) and have different communication capabilities. The distributed nature is due to actors being physically spreading throughout the space. The heterogeneity and distributed network impede the formation of a connected and efficient information flow, and thus are considered as another two major challenges of an EMS.

Thus, to effectively realize efficient energy management, the three major challenges are *heterogeneity, distributed system, and dynamicity*.

III. Pervasive Service-Oriented Network Model

A. Overview

In Sec. II, we have identified the three major challenges of an EMS. In this section, we propose a general framework to seamlessly integrate diverse kinds of actors and networks into a unified Pervasive Service-Oriented Network to address the three challenges.

PERSON has a three-layer structure as shown in Fig. 3. The principle is to decompose the complexities into different layers and to have loose coupling among different layers. In the following we will introduce the three layers one by one.

B. Heterogeneous network platform (HNP)

The objective of HNP is to build a homogeneous communication infrastructure for the information flow. HNP provides simple APIs to the upper layer for information exchanging. The Upper layer does not care how the information is delivered. The underlying communication protocols, media and communication capabilities are transparent to the upper layer. An implementation of such HNP can be found in [8], [9].

C. Service-oriented network (SON)

The basic idea of SON is to achieve interoperability, modularity and reusability by abstracting the functions provided by the actors into services [10]. Actors in an SON have different roles:

- Service provider: The service provider creates a service and registers its interface and access information to the service registry. Each provider decides which service to offer, how to balance security and easy accessibility and how to price the service.
- Service consumer: The service consumer discovers the services available in the network, locates services in the service registry and then binds to the service provider to invoke the services. A service consumer can access multiple services from multiple service providers at the same time.

To support SON, mechanisms for service creation, registration, discovery, binding and invoking are required. SON also needs to define a suite of services that can be used for applications, such as EM.

D. Context-aware intelligent algorithm

In this layer, the services provided by SON are exploited for control purpose. The interoperability and service reusability provided by SON bring lots of convenience to develop the proactive and context-aware intelligence to address the challenge of dynamicity. With the context-aware intelligent algorithms, the overall performance of a system is optimized. Better service availability, more convenience, and higher efficiency are achieved.

IV. EMS Implementation

A. Overview

In the last section, to address the major challenges of an EMS, we propose a three-layer PERSON framework. In this section, we implement an EMS to realize PERSON. For the sake of simplicity and without loss of the generality, we develop a *Heterogeneous Home Area Network (HHAN)* as the HNP. On considering the service requirements of an EMS in SG, we define a set of EM services. Moreover, we develop the necessary mechanisms to support SON. Based on the services and the supporting mechanisms, context-aware intelligence is developed to handle the dynamicity. To support the applications which require collaboration between the customer domain and other domains in an SG, we also develop and deploy a *Data and Service Center (DSC)*. We

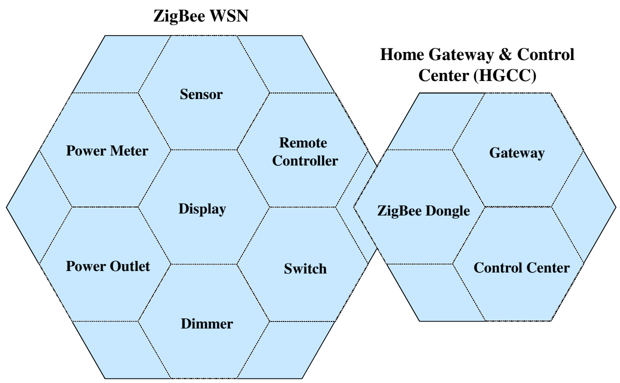

Figure 5. Heterogeneous home area network.

Figure 6. Prototype of ZigBee-enabled EMS actors.

	Measurement	Control	Display	Action
Sensor	√			
Power meter	√			√
Power outlet	√			√
Display			√	
Remote controller		√		
Switch/Dimmer				√
Control center		√	√	

Table I
MAJOR EMS ACTORS AND SERVICES THEY PROVIDED.

then utilize the EMS in a DR application to demonstrate its effectiveness. The architecture of the EMS is shown in Fig. 4. In the following, we will introduce the major building blocks and describe the DR demonstration in details.

B. Heterogeneous home area network

The HHAN realizes the first layer of PERSON. It provides the basic information infrastructure of an EMS. HHAN is composed of a *ZigBee-based Wireless Sensor Network (WSN)* and a *Home Gateway and Control Center (HGCC)*. The structure of HHAN is shown in Fig. 5.

1) ZigBee-based wireless sensor network: ZigBee [11] is selected as the underlying communication protocol of the *Home Area Network (HAN)*. ZigBee is based on IEEE 802.15.4 [12], which is specially designed for low rate, short range wireless communication networks. ZigBee inherits the merits of IEEE 802.15.4, such as low cost and low power consumption, and provides extra supports of ad hoc mesh networking and various application profiles for different kinds of applications. The *Home Automation (HA)* profile [13] and the *Smart Energy (SE)* profiles [14] are employed in the implementation. The major ZigBee-enabled EM actors include:

- Power meter: Measure the power consumption of the whole energy flow tree in a home. It is installed at the root of the home electricity network. The meter is equipped with a clip-like current sensor to realize non-intrusive installation.
- Power outlet: Measure the power consumption of a leaf on the energy flow tree. It can be simply installed between the original outlet and the appliance intended to be measured.
- Sensor: The sensor is capable of measuring temperature, humidity, luminance, motion, etc. An analog and a digital sensor interfaces are also provided for future expansion.
- Display: Visualize the power consumption measurement results.
- Remote controller: Perform manual control of the switches and dimmers in the home.
- Switch and dimmer: Perform ON/OFF control, or dimmer control of a light or other appliances.

Fig. 6 shows the prototypes of the major actors. The different actors may be physically separated and work independently, or combined together to perform an integrated function. For example, a sensor, a remote controller and a display can be integrated to form a thermostat.

2) Home gateway and control center: In a heterogeneous home area network, to support devices not based on ZigBee, a gateway is required for information translation and relaying. Besides the gateway, a control center is also required to host the intelligence and provide interface between users and the EMS. Without loss of generality, we develop an integrated ZigBee-Ethernet/WiFi home gateway and control center, which has the following features:

- Data concentrator and storage: HGCC is also equipped with a ZigBee transceiver to communicate with the ZigBee-based WSN. Collected data is stored on the control center.
- Gateway: HGCC acts as the intermediate point of the ZigBee network and the Ethernet/WiFi network. Through it, information can be exchanged. HGCC is the point where HHAN interacts with the DSC or other actors in the other domains of a SG.
- Monitor and control center at user premises: Through the HGCC, users can monitor and control the ZigBee-based WSN. Both browser/server and client/server modes are supported.
- Host the intelligence and service registry: Based on the collected and stored data, HGCC performs analyses, make control decisions, and places orders. Service registry will be introduced in Sec. IV-C.

C. Services in EMS

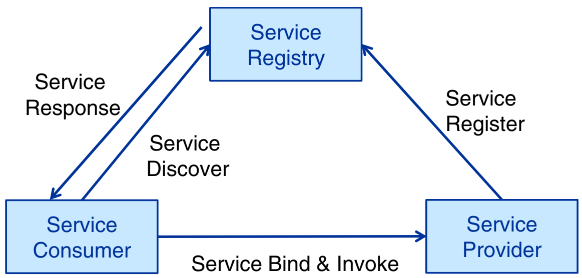

Figure 7. Flow chart of service mechanisms.

1) Services: As introduced in Sec. III, services are the abstractions of functions provided by different actors. In the implementation, four kinds of services, specifically, *Measurement*, *Control*, *Display*, and *Action*, are defined. The major actors and the services provided are listed in Table I. We can find from the table that one actor may provide multiple services; meanwhile, different actors may provide the same service. For example, sensor, power meter and power outlet provide the service of *Measurement*. To differentiate the services of the same kind, characteristics or parameters of the services need to be specified.

2) XML-based service mechanisms: To realize SON and target the best reusability and interoperability, XML-based mechanisms are developed to support the creation, registration, discovery and consumption of a service. In the implementation, HGCC also serves as the service registry of the SON.

The service provider first registers the services it can provide, and publishes their interface and access information to the service registry. When a service consumer wants to use a service, it makes a discovery request to HGCC, specifying the characteristics of the service that it wants to use. HGCC replies with a discovery response, giving descriptions of services that meet the specification. The service consumer can then select one (or more) of the consumable services, bind and invoke. The whole process is shown in Fig. 7.

D. Data and Service Center

DSC is an actor outside the customer domain (generally located at the service provider domain). DSC enables a broader and deeper energy-awareness for a customer and a tighter customer-grid collaboration.

With only the HHAN, customers can obtain a basic understanding of the energy consumption of his home or a certain appliance, which is informative and helpful for energy conservation. However, such basic information can not bring a customer the awareness of the relative energy consumption level compared to his neighbors with similar size of room, or compared to the average level of the whole city, etc.

DSC can serve as the data center of the whole grid and the whole society. With DSC, a customer can obtain more information, such as the average power consumption of his society, which model of air conditioner is the most power-conserving, how much he could save or spend if he turns his thermostat 1-degree up. Such broader and deeper awareness brings much more potential for energy saving.

A more important value of DSC is that it enables a tighter customer-grid collaboration, which not only helps on power saving, but also provides more EM-related capabilities. These capabilities are necessary for realizing the advantages promised by an SG.

In the implementation, a DSC based on LAMP (Linux + Apache + MySQL + PHP) is developed and deployed. A web interface is provided to the customers as well as the utilities for information acquisition and system management. In the next sub-section, we will use *Demand Response* as an example to show the effectiveness of the implemented EMS and the involvements of the DSC.

E. Demand response demonstration

Demand response [7] is one major driving force of an SG. The basic idea of DR is to manage power load in response to power supply constraints. By employing automatic load management, DR can realize peak shaving through reducing power load on peak times, or shifting power load from peak times to times with lower demand. [1]

An effective DR imposes some functional requirements on the underlying EMS, such as capabilities of real-time load monitoring, two-way data communication between the demand side and utilities, data processing and demand side load control. All these functional requirements are satisfied by our EMS. Exploiting the EMS for DR application is a good demonstration of the system capabilities.

DR generally involves management of a large quantity of customer loads. On considering the limited scale of the EMS prototype, in this demonstration, we only test the load management of a single appliance to show the capability of demand side management based on the customer-grid collaboration. Particularly, a dimmable light is employed as the load.

We assume the total power load and the power supply limit are known. We define the load level r as $r = \frac{Total\ power\ load}{Power\ supply\ limit}$. HGCC controls the load of the light as responses to the varying instantaneous load level r_t. The load control target $p\prime$ of the light is calculated as

$$p\prime = \begin{cases} p_{max} & , r_t \leq r_0 \\ p_{max} - p_{max} \times \frac{(r_t - r_0)}{(1 - r_0)} \times \mu & , r_t > r_0 \end{cases} , \quad (1)$$

where p_{max} is the power consumption of the light if no load control is performed, μ is the power conservation parameter $(0 < \mu \leq 1)$ and r_0 is a load level threshold. Lower r_0 and smaller μ indicate a more aggressive power conservation target.

We assume r_t is known at the DSC (DSC obtains r_t from utilities), while μ and r_0 can be configured through DSC's web interface. All the parameters are then distributed to the HGCC. μ and r_0 may be overridden by customers on the HGCC. Based on the parameters, HGCC calculates $p\prime$ and places the load control order.

In the test, we adjust r_t on DSC, and set $r_0 = 0.7$ and $\mu = 1$ at HGCC. We measure the load of the light. In Fig. 8, r_t, $p\prime$

[1] Proper economic incentives, such as variable pricing plans, need to be provided to the customers for shifting or reducing power consumption, which may introduce user inconvenience or uncomfortable.

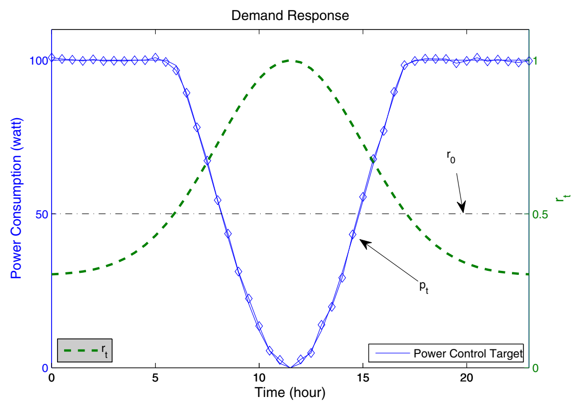

Figure 8. Demand response test results.

and the load measurement results p_t are shown. We find that p_t matches $p\prime$ very well, and p_t and $p\prime$ show a good response to the varying r_t as expected.

This test demonstrates the capabilities of the EMS in the context of DR, and the effectiveness of the PERSON framework for EMS.

V. Conclusions and Future Work

In this paper, we study EMS in the customer domain. The special challenges of heterogeneity, distributed system and dynamicity are identified through thoroughly analyzing the system desired features, characteristics and design issues. We propose PERSON, a novel framework, to address the three challenges. Further, we implement a cost-effective EMS prototype to realize PERSON and show its effectiveness.

As the core contribution of this work, the proposed PERSON framework can not only be employed for energy management in the customer domain, but also utilized in many other applications, such as intelligent transportation, healthcare, entertainment, etc. This is one direction of our future work. Security is a another major concern of EMS in SG. Mechanisms for user authentication, data encryption, privacy control need to be carefully studied and properly implemented in a practical EMS.

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