3 Sensor and Actuator Networks for Smart Grid

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Abstract

As introduced in the previous chapters, compared to traditional power grid, Smart Grid (SG) enjoys various advantages. To realize these advantages, Sensor and Actuator Networks (SANET) play a key role. In this chapter, we focus on SANET for SG. We study the composition and characteristics of SANET, identify the major applications of SANET in SG, highlight the major design issues and implementation challenges, and propose some innovative mechanisms to address these challenges. The effectiveness of the proposed schemes is verified and demonstrated with a case study of Energy Management System (EMS).

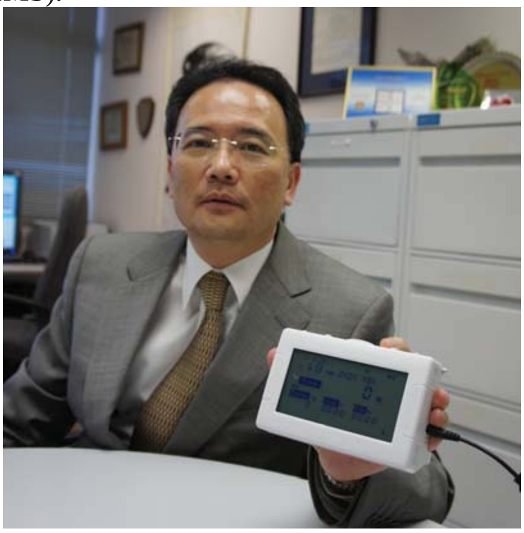

Figure 3-1 Prof. Victor Li and prototype of Energy Management System

3.1 Introduction

In the past few years, Smart Grid (SG) has attracted much interest from governments, power companies, and research institutes. Compared to the traditional power grid, by employing advanced Information Technologies (IT), SG can achieve better reliability and stability, higher penetration of renewable energy (RE), higher energy efficiency and lower greenhouse gas emission.

To realize these advantages, Sensor and Actuator Networks (SANET) play a key role. Compared to its ancestor, Sensor Networks, SANET can not only sense the environment, but also react to it. This characteristic makes SANET an essential enabling technology for various monitoring and control applications. However, to properly design an effective SANET for SG, we must overcome many challenges.

In this chapter, we will introduce the composition and characteristics of SANET, identify the major applications of SANET in SG, highlight the major design and implementation challenges and propose some innovative mechanisms to address these challenges. We also use a case study of Energy Management System (EMS) to demonstrate the effectiveness of the proposed schemes.

The rest of this chapter is organized as follows. In Section II, SANET and SG are introduced. In Section III, the major applications of SANET in SG are identified. The design issues are discussed, and the major design challenges are highlighted. In Section IV, some innovative mechanisms are proposed to address the design challenges. In Section V, an EMS is introduced as a case study. Section VI concludes the chapter.

3.2 SANET and Smart Grid

3.2.1 SANET

A SANET is a network of nodes which sense and react to their environment. Compared to traditional sensor networks, which focus on sensing, SANET can be used for both monitoring and control purposes. With SANET, closed loop control can be achieved to support more powerful applications.

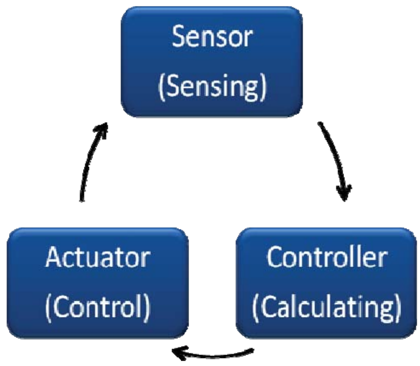

Figure 3-2 SANET actors and closed-control-loop.

Major actors in SANET include sensors, actuators, controllers and communication networks. Sensors are components or devices to measure and convert physical properties into electrical signals and/or data. Controllers perform calculations on the sensed data and make control decisions. Actuators execute the control decisions, convert electrical signals into physical phenomena (e.g. displays) or actions (e.g. switches). Different actors may be physically separated or located in a single device. Actors in a SANET communicate with each other through communication networks, operating diverse kinds of protocols and media, to enable collaboration among nodes and interaction between nodes and the surrounding environment. SANET actors and the closed loop control are shown in Figure 4-2.

3.2.2 SANET Design Considerations

SANET design is application-centric, which means the major design requirements are determined by the specific application. Given the application requirements, the following questions need to be considered and answered:

(i) To realize the application, what are the required functions?

The requirements on physical properties, physical phenomena or actions, control logic and communication networks, need to be determined.

(ii) To realize the function requirements, what are the required actors?

Specifically, which sensors, actuators, controllers and communication media, standards and protocols, need to be determined.

Figure 3-3 shows the simplified design flow, which leads to the determination of the actors for the SANET to achieve the specific application requirements.

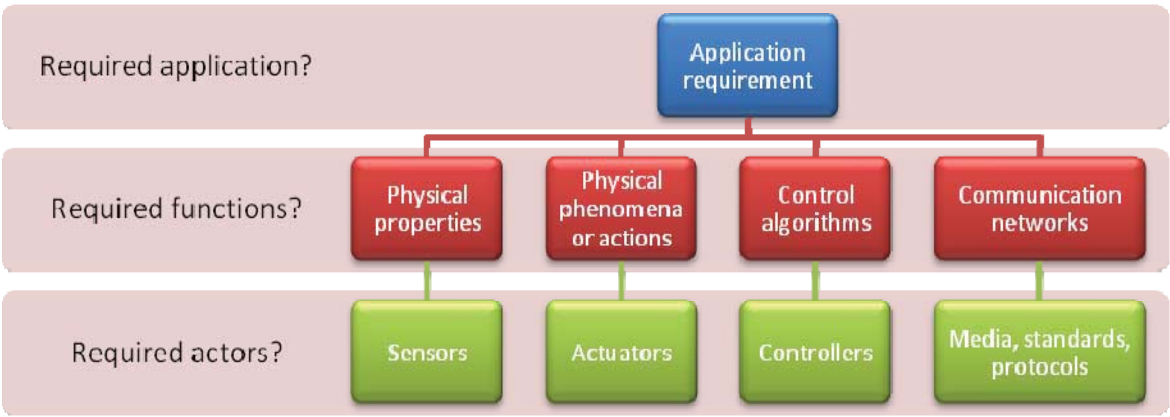

Figure 3-3 SANET design flow.

3.2.3 Smart Grid

As introduced in the previous chapters, compared to traditional power grid, SG enjoys various promising advantages. A comparison of traditional power grid and SG is shown in Table 3-1. There are three major driving forces of SG:

(i) Reducing greenhouse gas emissions to enable sustainability;
(ii) Improving security and reliability;
(iii) Enhancing energy efficiency.

These objectives are achieved by utilizing RE sources and employing modern Power Electronics and advanced Information Technologies.

	Traditional Grid	Smart Grid
System reliability	Low Reactive control, slow response and recovery	High Proactive control, fast and effective response and fast auto-restoration
Power source	Centralized Fossil fuel	Centralized + Distributed Fossil fuel + RE
Energy flow	One way From grid to customer	Two way Grid <-> Customer
Information flow	None or quite limited	Pervasive, two-way, broadband
Greenhouse gas emissions	High	Low Via increasing penetration of RE
Energy efficiency	Low	High Via better balance of supply and demand
Cyber security	No	Resilient against cyber attack
Customer participation	No participation	Better customer awareness and active participation

Table 3-1 A comparison of traditional power grid and smart grid.

3.2.4 Energy flow and information flow

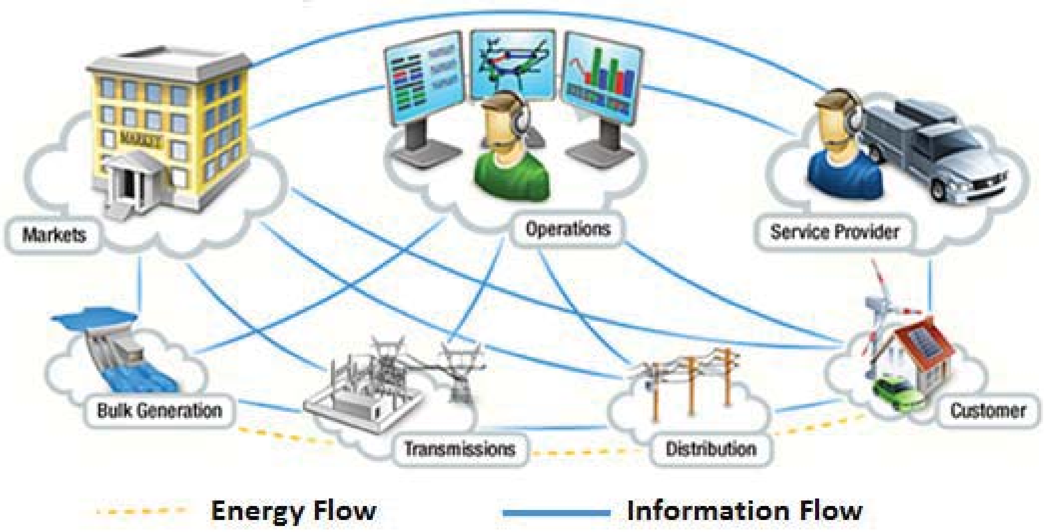

Figure 3-4 Conceptual Reference Model of SG [1].

As shown in Figure 3-4, the Conceptual Reference Model of SG proposed by NIST [1] divides an SG into seven domains, specifically, Customer, Markets, Service Provider, Operations, Bulk Generation, Transmissions, and Distribution. Connections among the different domains support two kinds of flows: Energy Flow and Information Flow.

1) Energy flow

The major energy flow is sourced at the Bulk Generation domain, delivered through the Transmissions and Distribution domain, and consumed at the Customer domain. This flow is similar to what has existed in traditional power grid for decades. Besides the major energy flow, in an SG, there is energy flow in the reverse direction, from the distributed generators in the Customer domain to the distribution networks.

The energy flow can be measured by energy measurement devices, such as power meters and power gauges. Meanwhile, the energy flow can be manipulated by actuators, such as breakers and switches.

Although the power grid 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 variations in supplies and demands, dynamic user behaviours, and continuously changing environments. In an SG, increasing usage of RE sources, such as wind turbine and solar panels, makes the problem even more challenging.

2) Information flow

In the traditional power grid, there is limited information flow. The most significant improvement of SG compared to traditional power grid is the deployment of a full-fledged SANET infrastructure, which carries all the information generated and consumed in an SG, such as real-time measurements, historical data, external events, control decisions, etc.

The information is exchanged among distributed actors within or among domains through diverse kinds of communication channels. The communication channels form a communication network, which is generally a heterogeneous and distributed network. The distributed nature is due to actors being physically distributed throughout the space. While heterogeneity is inevitable because different actors may follow different communication protocols, use different media (wire or wireless) and have different communication capabilities.

3.3 SANET in Smart Grid

From the energy flow and the information flow point of view, SG applications can be viewed as energy flow management and optimization by utilizing the information flow. This processing requires the capability of physical parameter sensing, decision making and physical device control.

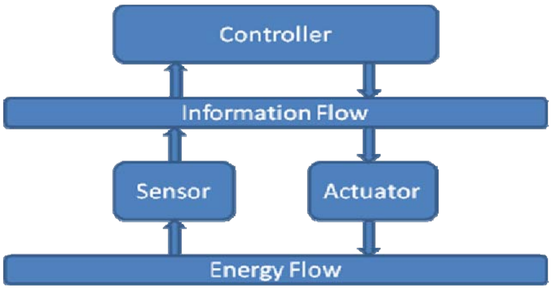

Figure 3-5 Relation of SANET and SG.

A high-level description of SANET in SG is shown in Figure 3-5. By employing SANET in SG, the energy flow and its supporting infrastructures are sensed by distributed sensors. Through information flow, the sensed data is transmitted to controllers for decision making. Controllers make control decisions and issue control commands to the actuators, also through the information flow. On receiving the control commands, actuators execute the control tasks.

3.4 Applications of SANET in SG

As introduced in the previous section, the three major driving forces of SG include reducing greenhouse gas emissions, improving security and reliability, and enhancing energy efficiency. Below, we will elaborate on three major SG applications to show why it is necessary to deploy SANET in SG and how SANET help achieve the three major objectives.

3.4.1 RE Penetration

RE is expected to help to reduce the emissions of greenhouse gases and other pollutants. RE sources include non-variable ones and variable ones. Non-variable RE sources, such as hydro, have already been widely utilized in existing power grids for decades. However, due to their intermittent nature, penetrations of variable RE sources, such as wind and solar, in considerable amount (more than 10%) may cause severe problems in maintaining the stability of the power grid.

With the help of SANET, accurate and up-to-date environmental information, such as wind speed, solar intensity, can be obtained to predict the characteristics of the RE generators. Furthermore, based on the measurements and predictions, compensation mechanisms can be employed to adaptively control the backup generators, advanced storages or even customer power loads to address the fluctuations of the RE supplies.

More information of sensor network for RE can be found in another chapter of this book.

3.4.2 Grid monitoring and control (GMC)

Reliability is critical in the electricity network ever since its birth. However, the big blackout in U.S. in 2003 indicated that the traditional electricity grid is still unreliable. A recent report showed that the U.S. power grid is getting less and less reliable over the years [2].

GMC is essential for reliable, secure, and high-quality electricity services. SANET plays a key role in GMC, as it can continuously monitor and efficiently control the whole system.

The core duties of SANET in GMC include preventive and corrective functions. Specifically, SANET is required to monitor equipment health, predict and detect disturbances, prevent potential failures, respond quickly to energy generation and consumption fluctuations and catastrophic events, and enable fast auto-restoration or self-healing.

Diverse kinds of SANET have been invented and employed for GMC, such as Supervisory Control and Data Acquisition (SCADA), which has been used in power grid for decades, and, most recently, Phasor Measurement Units (PMU) and Wide-Area Measurement System (WAMS), which provide real-time monitoring on power quality and in some cases respond to them automatically on a regional and even national scale.

3.4.3 Generation dispatch (GD) and demand-side management (DSM)

An effective power grid requires a good balance between the power supply and the power demand. GD and DSM are effective mechanisms to maintain the required balance and thus improve the energy efficiency.

GD is a monitor and control mechanism to actively manage electricity generation such that the amount of power generated meets the demands at any time. GD is already deployed and plays an important role in traditional power grid. However, this function in SG must overcome additional challenges, as it has to actively manage significant amount of distributed energy resources, especially RE resources at the Customer domain.

With the help of SANET, Renewable Forecasting (RF) and real-time Grid Frequency Regulation (GFR) are two effective mechanisms to address the RE penetration problem in GD. RF [3] requires real-time Distributed Energy Resources (DER) information to be sensed and gathered at the control centers; and after fast analysis, proper commands issued to generation scheduling and regulation functions. Real-time GFR [4] helps to optimize generation scheduling based on the fast detection on variations of frequency and voltage level, and requires very sensitive and responsive hardware and high speed data transmission.

As the counterpart of GD located in the Generation domain, DSM, which is also known as Demand Response (DR), works primarily in the Customer domain and interacts with the Service Provider, Market, and Operation domains. DSM manages demand side power load in response to power supply constraints. By employing automatic load management, DSM can realize peak shaving through reducing power load on peak times, or shifting power load from peak times to non-peak times.

DSM is an important application of SANET and imposes some special functional requirements on the underlying SANET, such as capabilities of real-time load monitoring, two-way data exchanging between the demand side and utilities, data processing, and demand side load control.

3.5 Actors of SANET in SG

As introduced in the previous sections, SANET is composed of sensors, actuators, controllers and communication networks. Below we highlight the major sensors and actuators commonly used in SG, and highlight the major requirements on controller and communication networks by the different SG applications.

3.5.1 Sensors in SG

Figure 3-6 lists the sensors commonly used in SG. The sensors are classified into three categories based on the type of the physical parameter measurement. Figure 3-7 shows a few sensor examples.

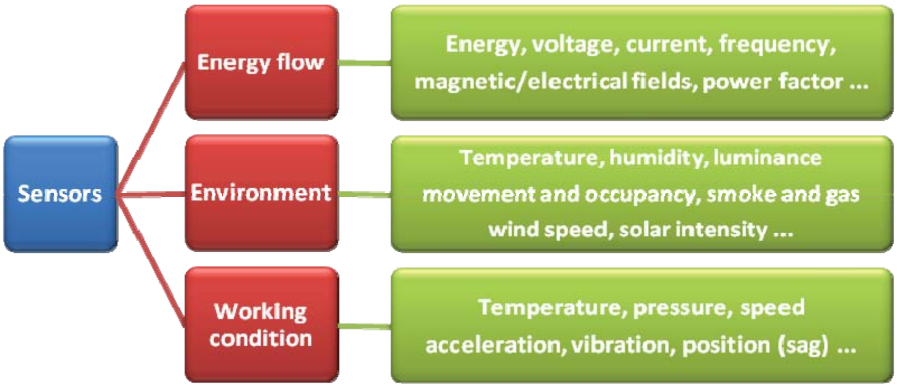

Figure 3-6 Sensors in SG.

Figure 3-7 Sensor examples.

3.5.2 Actuators in SG

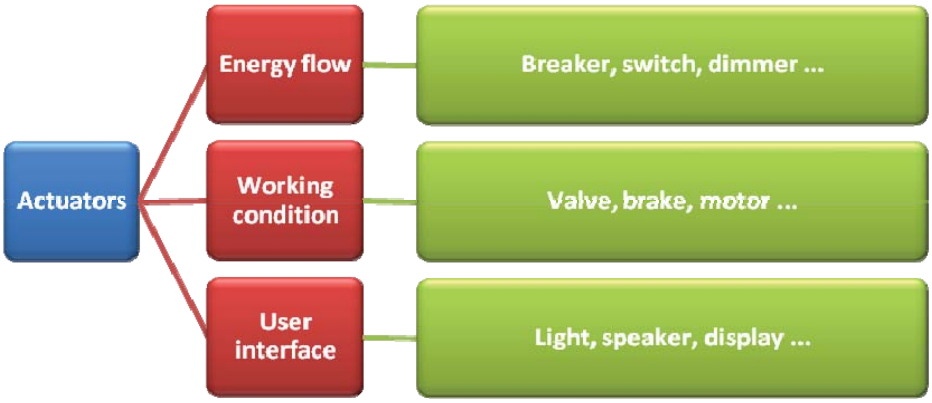

Figure 3-8 Actuators in SG.

Figure 3-8 lists the major actuators commonly used in SG. The actuators are also classified into three categories based on the type of the physical phenomena or actions. Figure 3-9 shows a few actuator examples.

Figure 3-9 Actuator examples.

3.5.3 Controllers and Control Logic in SG

Depending on the application requirements, controllers may be complicated, powerful, centralized control centers, or simple, less powerful, distributed micro-controllers. Normally, these two kinds of controllers work collaboratively to provide the monitor and control function in a single SANET application.

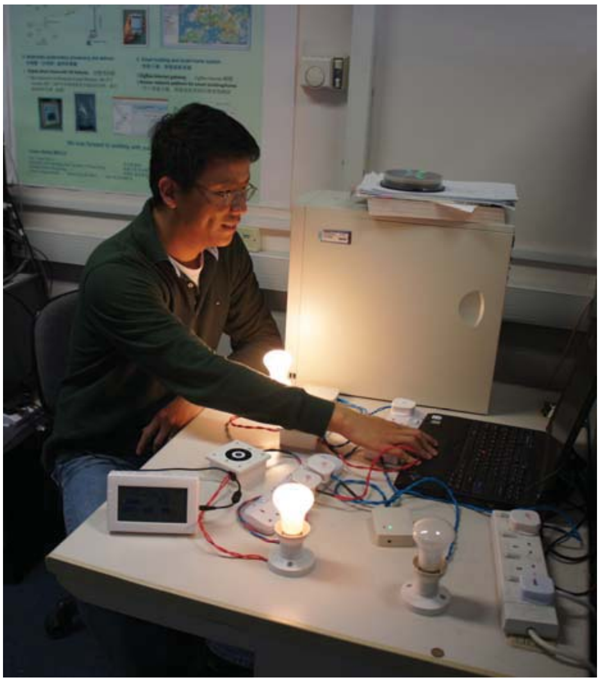

Figure 3-10 Testing the controllers and Control Logic for Smart Grid by Dr. Guanghua Yang

Due to the great fluctuations in energy generation and consumption, SANET applications in SG may require computationally intense control logics, such as fuzzy control and Artificial Intelligence (AI) control, to handle the dynamics, thus requiring more powerful controllers.

In addition, SANET applications in SG may require a large number of controllers to work collaboratively. DSM is such a case, where thousands of user load management units are involved. This requires each controller to be low cost to enable a large-scale deployment.

3.5.4 Communication Network

To support the advanced features of SG, the data volume exchanged among different actors in SANET inevitably increases tremendously compared to traditional power grids. Meanwhile, different SANET applications in SG normally have different communication requirements, in terms of bandwidth, transmission delay, and etc. In Table 3-2, we summarize the characteristics and requirements on different SANET actors for the three major SG applications.

SANET Apps. / SANET Actors	Penetration of RE	GMC	GD & DSM
Sensors	Energy flow Environment	Energy flow Environment Working condition	Energy flow Working condition
Actuators	Energy flow	Energy flow Working condition	Energy flow Working condition User Interface
Controllers	Distributed and centralized Dynamic level: high Cost: medium to high	Distributed and centralized Dynamic level: high Cost: medium to high	Distributed and centralized Dynamic level: high Cost: Low to medium
Communication networks	Bandwidth: medium Delay: medium	Bandwidth: high Delay: stringent	Bandwidth: low Delay: medium

Table 3-2 Requirements of SANET actors for different SG applications.

3.6 Challenges of SANET in SG

Next we study the major design challenges of SANET in SG.

3.6.1 Heterogeneity and distributed operation

As pointed out in Sec. II, heterogeneity and distributed operation and two major characteristics of the information flow in SG. Since SANET relies on the information flow, the heterogeneity and distributed operation, which render the formation of a connected and efficient information flow, become the two major challenges of SANET in SG.

3.6.2 Dynamics

The dynamicity is due to the variation of supplies and demands, dynamic user behaviors, continuously changing environments and other random events. In an SG, increasing usage of RE sources, such as wind and solar, makes the problem even more challenging.

3.6.3 Scalability

A typical SANET application in SG may cover hundreds of kilometers, and involves monitoring and control of thousands of pieces of equipment and devices. Scalability is a major challenge. It is necessary to employ protocols with low overhead and algorithms with linear complexity.

3.6.4 Flexibility

Smart grid is still evolving [5]. New technologies, policies, and user demands keep emerging, and SANET is required to provide the flexibility to accommodate all the diversities and evolving factors.

3.6.5 Energy-efficiency and cost-efficiency

One of the driving forces of SG is to improve the efficiency of the power grid, and SANET itself must be energy-efficient. In addition, to lower the deployment barrier, it must be cost effective.

Mechanisms / Challenges	Pervasive Service-Oriented Network	Context-aware Intelligent Control	Compressive Sensing	Device Technology
Heterogeneity and distributed operation	X			
Dynamics		X		
Scalability			X	X
Flexibility	X	X		X
Energy-efficiency and cost-efficiency			X	X

Table 3-3. Mechanisms to address the major challenges.

3.7 Proposed Mechanisms

In Section 3.3, we identify the major challenges of SANET in SG. In this section, we propose some effective mechanisms to address these challenges. The proposed mechanisms and corresponding challenges addressed are shown in Table 3-3

3.7.1 Pervasive Service-Oriented Network (PERSON)

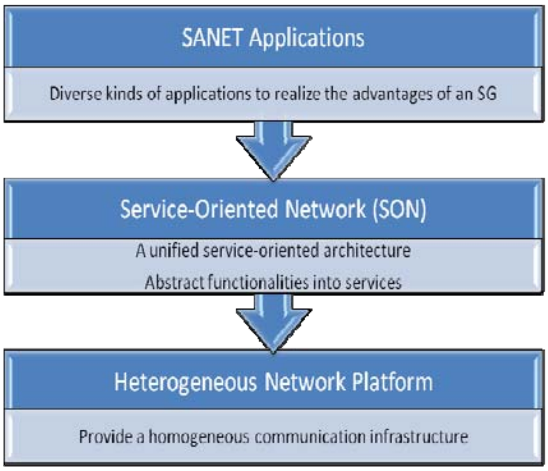

Figure 3-11 Three-layer structure of PERSON.

PERSON is a general framework to seamlessly integrate diverse kinds of actors and networks into a unified Pervasive Service-Oriented Network to address the challenges of heterogeneity and distributed operation, and bring lots of flexibility to develop diverse kinds of SANET applications.

PERSON has a three-layer structure as shown in Figure 3-11. 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.

3.7.2 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 need to care about 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 [6].

3.7.3 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. 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 SANET applications.

3.7.4 SANET applications

On this layer, the services provided by SON are exploited for specific SANET applications. The interoperability and service reusability provided by SON bring much flexibility to develop diverse kinds of applications, such as the applications introduced in the previous sections.

3.8 Context-Aware Intelligent Control

Context-aware intelligent control is proposed to address the challenges of dynamics. The basic idea is to develop proactive and context-aware control logics to optimize the system performance under dynamic environment. Here the contexts have a very broad meaning, including but not limited to

(i) Environment parameters, such as temperature and humidity;
(ii) Energy flow readings, such as power supply and demand level;
(iii) Human behaviors, such as movement, preference on environment;
(iv) Economic incentives, such as tiered electricity rates;
(v) Regulation schemes, such as DSM, and RE penetration.

A simple example of context-awareness is occupancy-based light control, where the context is whether the room is occupied or not, and light is turned on or off based on it.

The context-aware intelligent algorithms exploit the contexts, obtained by exploiting the services of PERSON, to optimize the overall performance of a SANET application. More details of PERSON and context-aware intelligent control can be found in [7].

3.9 Compressive sensing (CS)

CS is proposed to address the challenges of scalability, energy efficiency and cost efficiency. The basic idea of CS is to exploit data correlation in the time and space domains to reduce the hardware cost and the communication cost.

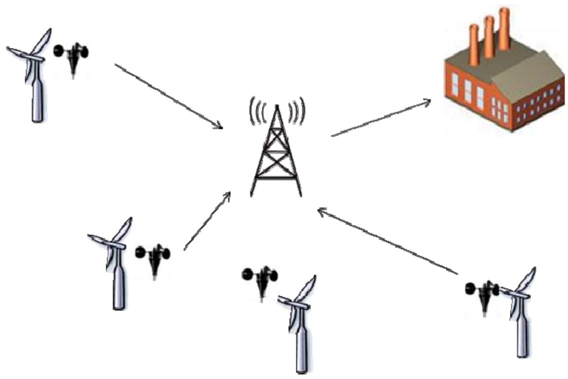

Figure 3-12 Compressive sensing in wind power generator management.

Consider a distributed wind power generator management system as shown in Figure 4-12 in which a number of micro wind power generators are located closely in the Customer domain. The amount of power generated by each wind turbine highly depends on the experienced wind speed. In order to get the accurate information of DER for a better GD, the wind speed need to be measured in real-time and the measurement results should be transmitted to the control center. One option is to install wind speed meters at all the wind turbines, which is costly not only on hardware but also on data transmission. Since wind conditions in adjacent areas are similar, we can exploit such correlation in spatial domain and deploy fewer sensors with less cost on hardware and data communication.

The methodologies employed in CS include:

(i) Complete continuous sampling to ensure reliability and complete understanding of the correlations;

(ii) Selective transmissions to ensure short delay and cost-effectiveness;

(iii) Complete reconstruction based on sparse data

More details of CS can be found in [8].

3.10 Device Technologies

Advanced device technologies can help improve energy-efficiency and cost-efficiency, and make a SANET more scalable and flexible to be employed for SG applications.

3.10.1 Low power consumption design and power-harvesting technologies

The SANET itself inevitably consumes power. To reduce the total power consumption, low power consumption design is required. In addition, mechanisms for power-harvesting are preferred.

Actor	Power conserving mechanisms
Sensing	Compressive sensing to exploit correlations in time and space domains Sensing on demand to avoid continuous and unnecessary sensing
Control	Event-based control
Calculating	Low complexity algorithm
Data transmission	Compressive sensing Distributed data processing and control instead of centralized control Data compression and data aggregation Low power data transmission technologies

Table 3-4 Power conserving mechanisms

In a SANET, all the major functions, such as sensing, control, calculating and data transmission, consume power. In Table 3-4, we list the potential mechanisms to reduce power consumption. The employment of a mechanism on one actor may have impact on others. For example, data compression and data aggregation may reduce the power consumption for data transmission, but increase the power consumption for regenerating the data. So power optimization needs to be considered from a system point of view.

Power harvesting is a process by which energy is derived from external sources, captured and stored. The major power harvesting mechanisms applicable to SANET in SG are listed in Table 3-5.

Energy type	Power harvesting device (energy source)
Ambient-radiation	Solar panel (solar energy) Antenna and transducer (RF energy)
Kinetic	Piezoelectric devices (mechanical strain, motion, vibration, noise) Micro-wind turbine (wind power)
Thermal	Thermoelectric generator (thermal gradient)

Table 3-5. Power harvesting mechanisms.

3.10.2 Modular and Compact design

Modular design can enhance the reusability of the modules to reduce the hardware design cost and development cost. Compact design can lower the development cost of the SANET actors, and improve the flexibility of employing the actors in diverse kinds of SANET applications. Figure 3-13 shows a compact wireless environment sensor applicable to many SANET applications.

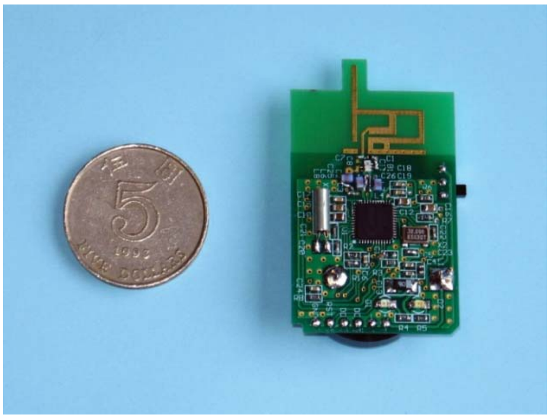

Figure 3-13 Compact wireless environment sensor.

3.11 Energy Management System at Customer Domain

Case Study of SANET in SG

In this section, we introduce an Energy Management System at the Customer domain as a case study to demonstrate the effectiveness of the proposed PERSON framework and other mechanisms.

An 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.

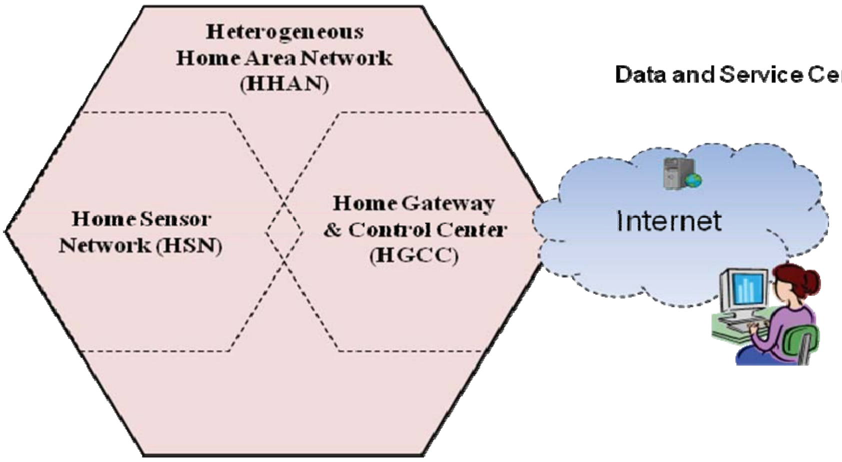

Figure 3-14 EMS architecture.

The structure of the developed EMS is shown in Figure 3-14. The EMS is composed of a Heterogeneous Home Area Network (HHAN) located in the Customer domain, and a Data and Service Center (DSC) located in the Service Provider domain

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Figure 3-15 EMS prototypes.

As an implementation of PERSON framework and demonstration of the advanced device technologies, a ZigBee-based Home Sensor Network (HSN) and a ZigBee-Internet Home Gateway and Control Center (HGCC) are developed to form the HHAN. Figure 3-15 shows the relevant device prototypes. The Context-Aware Intelligent Control algorithm and the CS mechanism are implemented on the HGCC. The effectiveness of the whole system has been demonstrated in a DSM application. More details can be found in [7].

3.12 Conclusion

In this chapter, we study the SANET in SG. Through analysis and discussions, we show why SANET is important to SG and how SANET contributes to SG. We highlight the design challenges and propose some innovative mechanisms to address these challenges. These proposed ideas are representatives of our contributions in promoting the research and development of SG.

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