A Cyber-Physical System Framework for Smart Grid Wireless Communications

Yibo Pi*, Yuhang Zhang*, Xudong Wang*, and Hua Huang†
*UM-SJTU Joint Institute, Shanghai Jiao Tong University
Email: {piyibo, zhangyuhang, wxudong}@sjtu.edu.cn
†Shanghai Electric Power Research Institute, State Grid Corporation of China
Email: huahuang@sina.com

***Abstract*—Wireless communications have been widely deployed to collect and disseminate data for industrial applications. However, to date the mostly accepted technologies for information collection and dissemination in power grid are still based on wired communications instead of wireless. To leverage the advantages of wireless communications for smart grid, proper wireless networks need to be designed to satisfy the specific service requirements of power grid. Considering the diverse service requirements in different applications of power grid, the design of a wireless network is usually application-specific. So far no systematic approach is available to guide the design of smart grid wireless networks. To this end, a systematic approach is developed in this paper to provide guidelines for smart grid wireless communications. It is based on the framework of cyber-physical system (CPS). Under this framework, a smart grid wireless communication system is categorized into either a loosely-coupled or closely-coupled CPS, considering different mechanisms of interaction between a wireless network and power grid. For either CPS, general procedures of wireless network design are proposed by considering the service requirements and unique features of such a CPS. To illustrate how these design procedures are applied in reality, two application scenarios are presented to demonstrate smart grid wireless communications based on loosely-coupled CPS and closely-coupled CPS, respectively.**

I. INTRODUCTION

Communication system has been a critical part of power grid. With the support of communication technologies, power grid can be monitored, controlled, and managed to ensure proper operation under different conditions. To meet the ever-increasing energy demand, robustness and intelligence of power grid need to be significantly improved, which is the ultimate goal of smart grid. Communication technologies will continue to play a critical role to reach the goal of smart grid.

The current accepted technologies for smart grid are mostly wired communications. For example, large-scale automatic meter reading and remote terminal unit control are supported by power line communications (PLCs) [**?**] and the secure and high rate data transmission for substation automation is provided by optical communications [**?**].

The advantages of wireless communications over wired ones, like low cost, easy installation, mobility, etc., makes wireless communications important for industrial applications. However, in smart grid regime, the potentials of wireless communications have not been fully exploited. A typical application of wireless communications in smart grid is the energy management system (EMS) in smart home, where a local controller manages the power consumption of appliances via a Zigbee network [1]. The Zigbee network is a cheap and mature technology, which is competitive compared to the broadband PLCs proposed in home area network. Similar to Zigbee network, wireless LAN and cellular networks are competitive in neighboring and wide area network, respectively.

Till now, wireless communications have been proposed for smart grid communications in the literature. However, there is no systematic way to guide the design of a wireless network for smart grid. Wireless networks are designed to satisfy the service requirements of applications and the service requirements vary with applications. Thus, the design of a wireless network is usually application-specific. In this paper, the concept of CPS is leveraged to study the interaction between a communication network and power grid. Depending on different features of such an interaction, the communication network needs to be designed accordingly.

In the framework of CPS, the CPSs are categorized into loosely coupled CPS (LC-CPS) and tightly coupled CPS (CC-CPS). In a CPS view, all applications with CPSs in smart grid can be classified into two types. The applications that monitor and manage the power grid belong to the LC-CPS regime, while the applications that control the power grid belong to the CC-CPS regime. General design procedures are developed for both LC-CPS and CC-CPS to provide a guideline for the design of wireless network in smart grid. The network design procedures are further demonstrated by two applications in smart grid. The application of smart substation monitoring aims to detect the impending problems in substation and the application of the integration of photovoltaic system focuses on the fairness among users under power grid constraints.

The rest of the paper is organized as follows. The framework of CPS is first introduced in Section II. Based on the framework, applications of wireless communications in smart grid are categorized in Section III. In Section IV, a design procedure for wireless network is discussed. The design procedure is demonstrated in Section V, and the paper is concluded in VI.

II. THE CPS FRAMEWORK

The concept of CPS emphasizes the integration of systems of computing and communication capabilities with physical systems. The computing and communication systems are in

978-1-4799-0698-7/13/$31.00 ©2013 IEEE

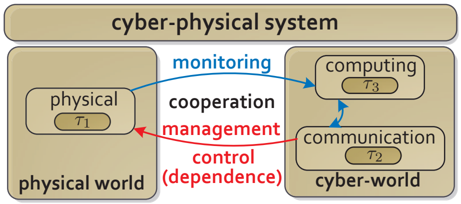


Fig. 1. The interactions between cyber and physical worlds

cyber world, while the physical system is in physical world as in Figure 1. Systems in cyber world can provide monitoring, management and control services for physical systems in physical world. In these services, the mechanisms of the interactions between physical and cyber worlds are different. The CPS framework is built based on the differences in interaction mechanisms, which can be leveraged to classify all CPSs in a systematic way and guide the design of a CPS.

A. Differences in Interaction Mechanisms

The definition for CPS has been mentioned in many papers. Almost all the definitions state that the computing, communication and physical systems should cooperate closely. In [2], the physical system is supposed to have a feedback loop to affect the computing system. The feedback loop is interpreted as a tight coupling of physical and computing systems in [3]. The feedback loop and the tight coupling relation reflect the data flow among systems in cyber and physical worlds. However, the data flow cannot distinguish different mechanisms between cyber and physical worlds. The management and control services in Figure 1 have the same directions of data flow, but differing in mechanisms of interaction.

In monitoring service, physical data is measured by sensors and sent to control center for analysis, while in management service, a management command needs to be sent back from cyber world to physical world as in Figure 1. Even though monitoring and management services differ in data flow, the aim of both monitoring and management services is to provide a fast and convenient way to manage the physical system. Without the monitoring and management services, the physical system can still operate normally.

Unlike the monitoring and management services, the normal operation of physical system depends on the control schemes provided by control service. Physical system malfunctions without control service. Therefore, the mechanisms of interaction between cyber and physical worlds differ with services.

B. Classification for CPS

Based on the differences in interaction mechanisms, the CPSs can be classified as follows. In a CPS, if *the physical system in physical world can operate normally only under the services provided by communication and computing systems in cyber world*, the system is a *tightly coupled CPS*; otherwise, the system is a *loosely coupled CPS*. The physical system in LC-CPS can function separately independent of the systems in cyber world.

C. CPS Design

The first thing for CPS design is to figure out the service requirements from various aspects and the priority levels of these requirements. Delay requirement is of high priority in CPS design, which relates to the design of systems in both cyber and physical worlds.

1) Service requirements: Classification for CPS implies that LC-CPS and CC-CPS have different service requirements. In general, the service requirements for a LC-CPS are mainly from the customers, while the service requirements for CC-CPS have to include the requirements from physical systems. Further, the requirements for CC-CPS are more strict than those for LC-CPS. The violation of requirements for CC-CPS results in the malfunction of physical system.

2) Delay in CPS: Delay is irrelevant to the classification for CPS, but it is an important factor for CPS design. Whenever a system, no matter it is computing, communication or physical system, receives an input, the system needs to react to the input, which causes some delay. If delay in one system is comparatively large than delay in the others, the system with large delay becomes the bottleneck. Improvement for other two systems contributes little to the entire system performance.

III. SMART GRID WIRELESS COMMUNICATIONS: A CPS VIEW

Smart grid is a typical complex CPS, which can be analyzed in the framework of CPS. In a CPS view, wireless communication systems can be categorized into either in LC-CPS regime or in CC-CPS regime. Data exchanges between controller and power grid in smart grid are illustrated in Figure 2, where the physical system in CPS is replaced with power grid and the computing system is replaced with a controller.

A. Wireless Communications in LC-CPS Regime

Applications implemented with LC-CPS mainly include power grid monitoring and management. The data flow in monitoring is unidirectional from power grid to controller and the data flow in management is bidirectional. The examples of the applications with wireless networks in smart grid include: 1) Power line monitoring via wireless mesh networks and cellular networks; 2) Smart meter reading via wireless sensor networks and wireless mesh networks; 3) Real-time pricing of electricity and video surveillance via wireless mesh networks.

In power line monitoring and smart meter reading, communication networks transmit data to control center for analysis. The data flow is unidirectional, as no message is involved to affect power grid in monitoring. In contrast, the electricity pricing and video surveillance need the bidirectional data flow. The message from controller to power grid in electricity pricing shifts the user loads to non-peak time to reduce overall power grid costs and the message in video surveillance can dynamically change the angle of a video.

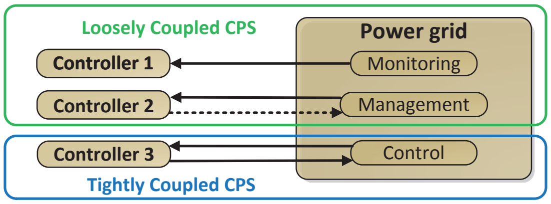


Fig. 2. A simple model for loosely coupled CPS in smart grid

B. *Wireless Communications in CC-CPS Regime*

Data exchanges between power grid and controller in CC-CPS are always bidirectional. To emphasize the differences of bidirectional data flow in both LC-CPS and CC-CPS, the channels from controller to power grid are respectively represented by solid and dashed lines in Figure 2. Compared to the channel in LC-CPS, the channel in CC-CPS is necessary to ensure the normal operation of power grid.

With the increasing need of renewable energy, many distributed renewable resources are installed into distribution grid. However, the existing power grid cannot support the integration of large volume renewable resource energy without any control. Delivery of control message needs the support of wireless networks. Another application is the electric vehicle charging in distribution grid. Solutions that wireless communications provide for these applications can be a wireless mesh network, which can provide real-time services in neighbor area network. The wireless mesh network has to respond to the variations of power grid responsively.

IV. WIRELESS NETWORK DESIGN FOR LC-CPSS

A general design procedure is developed for both LC-CPSs and CC-CPSs, respectively. As the design of computing system in cyber world is not the concern of this paper, only the design of wireless network is discussed below.

A. *Requirements and Constraints on Network Design*

1) Customer Requirement: Customers requirements in smart grid are from both DNO and household customers. For a single application, not all the listed requirements are necessarily included.

- Throughput: The required throughput for a wireless network depends on the application. Video and image are common data for monitoring, which require large throughput, but the size of management packet in management application is small and the throughput is not the bottleneck.
- Data integrity: The data taken by cameras should be transmitted to destination node without any data loss, especially for image transmission.
- Delay: The video and image data for smart grid monitoring is not sensitive to delay, where the delay can be on the time scale of seconds. Nonetheless, the delay requirement can be strict, which depends on the need of customers.
- Cost: If cost is a concern, the cost of network is expected to be as low as possible.

2) Network Constraints: Unlike wired communication, wireless communications due to the broadcast nature have more problems. The network constraints only include the internal issues, like the link quality and security, incurred by the nature of wireless network. The link quality between two nodes in wireless network varies with the surrounding environment, which is strong affected by deep fading from time to time and interference from other nodes. Besides link failure, other problems may include security and node failure.

3) System Constraints: The system requirement in LC-CPS is concerned with the interfaces of sensors and actuators in power grid. In order to build connections, nodes in wireless network should use the same communication protocol. However, in some cases, sensors and actuators only have limited communication protocols available. The limited options on communication protocols are taken as a system constraint. Other system constraints can be brought by the legacy devices, which are not programmable.

B. *Design Complexities Incurred by Constraints*

The network and system constraints are concerned with the very practical aspects of designing a network, which may complicate the network design. The link failure in network constraints is a common problem of wireless network, which may happen unexpectedly and affect the data integrity in customer requirements. The nonprogrammable sensors in power grid may be required to accomplish a task that is well supported by the communication protocols that the sensors do not have. In this case, the wireless network should be delicately design to help the sensors accomplish a task, which increases the design complexity.

C. *Wireless Technology Selection*

The differences among the wireless technologies can be basically categorized into two aspects, transmission rate and coverage range. A review on the transmission rate and coverage range of various wireless technologies can be found in [4]. For applications with large data volume, a network that can provide high throughput is needed, while for applications that need long distance communication, a communication network with large coverage range is needed. The wireless LAN has a high transmission rate, but the coverage range is short. The microwave and cellular communications have high transmission rate and large coverage, but the cost is high. There is no wireless technology that is better than others in all aspects. In general, Zigbee and bluebooth are suitable for home area network; wireless LAN are suitable for neighbor area network; cellular and microwave communications are suitable for wide area network.

D. *Protocol Design*

In each layer of the protocol stack, there are various protocols and techniques, which all have their own features. The selection and design of a protocol depend on the specific services required in applications. A unified method for protocol design may not exist.

E. Storage as Backup

Many methods have been proposed to improve the reliability for wireless communication networks. However, as the link quality is affected by external environment, the link failure is inevitable. For applications that need high throughput, if the link failure lasts for a long time, packets may be congested in the network and be lost during transmission, which contradicts with the data integrity requirement of customer. Since in monitoring application, delays on the time scale of seconds can be tolerated by customers, the data generated by sensors can be first stored locally. The stored data is eliminated only after the data is transmitted to the destination safely.

F. A Combined Use with Wired Communications

The devices in power grid are all connected by power lines. The power line communication (PLC) that utilizes the existing power line as transmission medium becomes very attractive. There is a tradeoff between the coverage range and transmission rate of PLC. At low transmission rate, ultra narrow band (UNB) PLC has a coverage of several hundred kilometers; at high transmission rate, broadband PLC only has a transmission range within several hundred meters. Besides the PLC, Internet is another promising alternative for smart grid communication because the infrastructure of Internet already exists. A combined use with wired communications can utilize both the advantages of wired and wireless communications.

V. WIRELESS NETWORK DESIGN FOR CC-CPSS

A. Requirements and Constraints on Network Design

1) Requirements and Constraints for LC-CPS: The requirements on network design in CC-CPS should be more strict than that in LC-CPS. Besides the requirements and constraints for LC-CPS, the network design for CC-CPS has to satisfy the requirements from physical system, which, if not satisfied, may damage the physical system.

2) Physical System Requirement: With the integrations of renewable energy and electric vehicles into power grid, the energy profile of household customers changes significantly and the existing power grid is not sufficient to satisfy the energy need. The risk-dispatching of renewable resource energy is discussed in [5], where the dynamic behaviors of renewable energy are assumed to be stochastic. Since the power grid operates at the margin of operation limits, uncontrolled load variances may easily cause the operation limits of power grid to be violated and results in a bad power quality for household customers. In order to control the loads of customers, a wireless network connecting with all controllable loads is needed to transmit control command. The delay requirement on the network depends on the dynamics of power grid.

B. Requirement Differences from LC-CPS

1) Strict delay requirement: The delay requirement on network design in loosely and closely coupled CPS can reflect the basic difference between loosely and tightly coupled CPSs. In LC-CPS, if the delay requirement is not satisfied, no damage happens to power grid. On the contrary, the time constraint in CC-CPS cannot be violated. If the constraint is not satisfied, the operation limits for power grid are violated and the power grid becomes unstable.

2) Data volume: The control message that contains control command for power grid is of small size, which greatly mitigates the stress of wireless networks.

C. Wireless Communications Selection and Protocol Design

The selection of wireless communications for CC-CPS obeys the same rule as LC-CPS, but the differences in requirements should be taken into account. The wireless communications for CC-CPS do not need to have a high throughput, but a high reliability. The similar rule applies to protocol design.

D. Local Controller Design as Backup

When wireless communication is used, a reliable transmission cannot be ensured in bad conditions. Then, a local scheme should be designed as backup when the delay requirement is failed to be satisfied by communication networks; otherwise, the operation limits of power grid are to be violated.

Since the local controller does not have global information, the scheme for local controller cannot ensure the performance of the entire system. Conservative measures are usually taken by local controllers so that the power grid operates within the normal range.

E. Relaxing the Delay Requirement

Strict delay requirement in CC-CPS makes network design difficult, which results in that the operation limits of power grid are easy to be violated. The situation can be improved if the delay requirement on network design can be relaxed.

The method proposed here can be generally applied to applications in smart grid. The key idea is to divide the problem into prioritized subproblems and try to solve the subproblems of highest priority locally. Since the response time of local controller is short, the most dangerous subproblems can be solved quickly so that the operation limits of power grid is controlled within normal range. The left subproblems are of low priority and the delay requirements on these subproblems are less strict than high prioritized subproblems. In this way, delay requirement on network design is relaxed.

VI. SMART SUBSTATION MONITORING: AN EXAMPLE OF LOOSELY COUPLED CPS

A. Problem Formulation

The equipment in the substation experiences both the external harsh environment and internal issues, such as load imbalance and overloading. The reliability of power delivery is deteriorated with the aging of the equipment. As a sign of system failure, high temperature of the equipment is considered as a warning and needs to be detected in time. Infrared camera now has become an important tool to detect the impending problems.

Since the camera is expensive and the equipment in substation spreads in a large area, installing on-site controlled cameras would be costly and thus the handheld cameras are

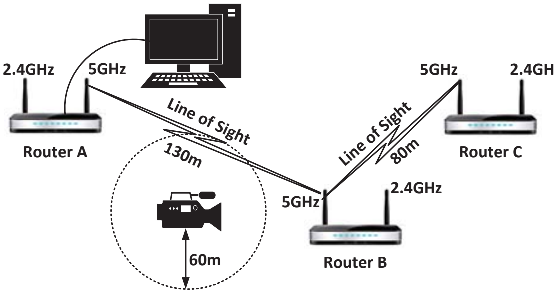
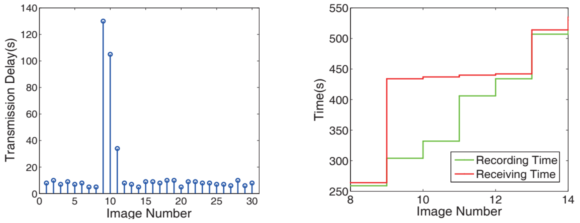


Fig. 3. The system setup and network topology for experiment



(a)

(b)

Fig. 4. (a) The transmission delay for all 30 images. (b) The received time and sending time for images from 8th to 14th.

still necessary. Due to the absence of communication networks in the substation field, the images taken by infrared camera can not be transmitted to control center for analysis immediately, which degrades the effectiveness of detection. Thus, a wireless network needs to be designed to provide reliable real-time image delivery.

B. Requirements and Constraints for Network Design

1) Customer Requirement:

- Data integrity: No image loss is allowed, since the lost images may contain the information of impending problems.
- Network stability: The wireless network can function normally for a long time under the external harsh environment. The failure of one node does not influence the performance of the entire system.
- Delay: The delay requirement is on the time scale of seconds for most images.

2) Camera Constraints:

- Hardware interface: Only a universal serial bus (USB) interface is available.
- Software interface: The operating system on the camera is nonprogrammable, but it provides the function of configuring the operation mode, IP address, network service set identifier (SSID) and gateway. In application layer, only ftp service is available. There are no other functions, like routing and roaming between two routers.

C. Experimental Results

1) System setup: The system is set up as shown in Figure 3. Router A is far apart from router C and thus have no direct connection with router C, but router A can communicate with router C through router B. An Ethernet cable is used to connect router A and the server. Due to limited transmit power, infrared camera has a coverage of 60m, which results in a ”blind zone” between router A and router B. In the blind zone, camera cannot communicate with both router A and B.

2) Results analysis: The number of images taken by the camera is 30 in total. Transmission delay for each image is illustrated in Figure 4(a) and the received time and sending time for images from 8th to 14th are illustrated in Figure 4(b). All the 30 images are received by the server in the end. Most of the transmission delays of the images are between 4 to 10 seconds, while the delays of 9th, 10th and 11th images are 137, 102 and 36 seconds respectively. The three images are taken in the blind zone, where the images cannot be sent to any routers. They are first stored in the camera and sent to a neighboring router immediately after the camera enters into the coverage of the router. In Figure 4(b), the red and green lines respectively represent the received and sending time for these images, where the 9th to 11th images are received within 4 seconds. The large delay for images taken in blind zone does not satisfy the delay requirement, but the blind zone can be easily eliminated by using more routers.

VII. INTEGRATION OF PHOTOVOLTAIC SYSTEMS INTO POWER GRID: AN EXAMPLE OF CLOSELY COUPLED CPS

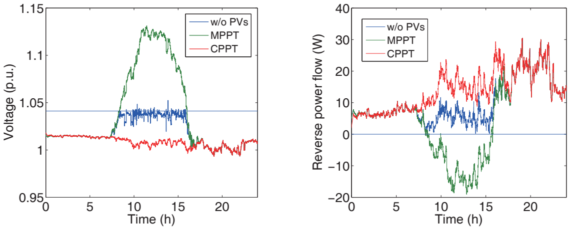
A. Problem Formulation

The increasing efficiency and decreasing price of photovoltaic (PV) cells greatly thrust the installation of distributed PV resources into the distribution grid to generate electricity for daily use. As the power generated by PV systems varies with the light intensity and temperature, the PV system is considered as an intermittent renewable source. The power generated by individual PV systems is first consumed by user loads. If the output power of PV system exceeds the power of user loads, the excessive power is injected into the power grid. Since individual users can benefit from the injection of power into power grid, all users want to inject as much as power into the power grid.

However, there are three problems associated with the excessive power injection into grid. The *overvoltage problem* is the rise of voltage at users' site. In the worst cases, the voltage of users should be controlled in emergency range. The level of voltage rise depends on users' position on the feeder, which implies unfair chances for users to inject surplus power into grid, i.e., *fairness problem*. The *reverse power flow problem* happens when power flows reversely from end users to upstream substation through distribution transformer.

B. Requirements on Network Design

The requirements on network design vary with the applications, but the network and system constraints apply to network design in all applications. The requirements from DNO and physical system are listed below.



(a) (b)

Fig. 5. (a) The profile of the maximum voltage at users' side in a typical day. (b) The profile of reverse power flow at transformer side in a typical day.

- DNO requirement: The DNO as a coordinated controller needs to ensure the fairness between individual users and the maximum benefits for all customers. Moreover, no reverse power flow is allowed at the transformer side.
- System requirement: In order for the power grid to operate normally, all the physical parameters should be controlled within allowable limits. The physical parameters include voltage, current and power flow.

C. Simulation Results

PV systems are controlled via a wireless mesh network. Detailed settings for simulation due to space limitation are omitted here. The aim of the results is to demonstrate the relation between wireless network and power grid, and the relation between delay and system performance.

The profiles of the maximum voltage of all users under three different control schemes are illustrated in Figure 5(a). If the maximum voltage in the power grid is less than the operation limit, the power quality of household customers can be ensured. The red line is the profile when no PV systems are connected into grid. The maximum voltage remains within the upper bound. When the PV systems are connected into grid without control, the voltage exceeds the upper bound as represented by green line. If the coordination control among PV systems is applied, the voltage is controlled within upper bound as represented by blue line. The voltage profile in three cases fully demonstrates the dependence relation between power grid and the communication network in CC-CPS. If there is no communication network, the voltage exceeds the upper bound as the green line. Similarly, the dependence relation can be demonstrated by the profile of reverse power flow in Figure 5(b). The reverse power at the transformer side can be prevented only after the coordination control is applied.

The data in Figure 5 is obtained under the zero end-to-end delay assumption. The next step is to find out the effects of end-to-end delay on system performance. Under different time scales of delay, three metrics for performance analysis are listed in Table I. The unfair ratio is the percentage of time that the power outputs of all PV systems are fair. The energy deviation is the deviated energy under nonzero delays from the zero delay case and the reverse power time length records the total time that the power flow at transformer side is reverse. It is easy to see that a larger delay means a worse fairness among household customers. However, the effects of delay on energy and time length of reverse power are not significant. To obtain a better performance, a end-to-end delay requirement on the time scale of 0.1 seconds is enough. The network can be designed based on the exact end-to-end delay requirement.

TABLE I
EFFECTS OF DELAY ON SYSTEM PERFORMANCE

Time scale (s)	Unfair ratio (%)	Energy deviation (Kwh)	Reverse power time length (s)
10^{-4}	0.07	8.6×10^{-4}	0.02
10^{-3}	0.10	1.8×10^{-4}	0.02
10^{-2}	0.36	0.04	0.03
10^{-1}	3	0.14	1.04
1	24	0.15	1.08

VIII. CONCLUSION

Wireless communications will play a key role in smart grid communications. However, so far no systematic approach is available for wireless protocol design to support various applications and their diverse service requirements in smart grid. In this paper, a systematic framework was developed based on the concept of CPS. Under the framework, the wireless communication systems in smart grid were categorized into loosely and closely coupled CPSs. Network design procedures for both loosely and closely coupled CPSs were proposed based on the service requirements and unique features of the CPSs. The design procedures were further demonstrated by two applications in smart grid. In the future research, the CPS framework developed in this paper will be applied to various scenarios of wireless communications in smart grid.

ACKNOWLEDGEMENT

The authors would like to thank the National Natural Science Foundation of China (NSFC) (No. 61172066), Pujiang Scholar Program (No. 10PJ1406100), and Oriental Scholar Program of Shanghai Municipal Education Commission, for their generous support.

REFERENCES

[1] J. Han, H. Lee, and K.-R. Park, "Remote-controllable and energy-saving room architecture based on zigbee communication," *Consumer Electronics, IEEE Transactions on*, vol. 55, no. 1, pp. 264–268, 2009.
[2] E. A. Lee, "Cyber physical systems: Design challenges," in *Object Oriented Real-Time Distributed Computing (ISORC), 2008 11th IEEE International Symposium on*. IEEE, 2008, pp. 363–369.
[3] Y. P. Fallah, C. Huang, R. Sengupta, and H. Krishnan, "Design of cooperative vehicle safety systems based on tight coupling of communication, computing and physical vehicle dynamics," in *Proceedings of the 1st ACM/IEEE International Conference on Cyber-Physical Systems*. ACM, 2010, pp. 159–167.
[4] P. P. Parikh, M. G. Kanabar, and T. S. Sidhu, "Opportunities and challenges of wireless communication technologies for smart grid applications," in *Power and Energy Society General Meeting, 2010 IEEE*. IEEE, 2010, pp. 1–7.
[5] P. P. Varaiya, F. F. Wu, and J. W. Bialek, "Smart operation of smart grid: Risk-limiting dispatch," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 40–57, 2011.