Wireless Communication and Networking Technologies for Smart Grid: Paradigms and Challenges

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Abstract—Smart grid, regarded as the next generation power grid, uses two-way flows of electricity and information to create a widely distributed automated energy delivery network. In this work we present our vision on smart grid from the perspective of wireless communications and networking technologies. We present wireless communication and networking paradigms for four typical scenarios in the future smart grid and also point out the research challenges of the wireless communication and networking technologies used in smart grid.

Index Terms—Smart grid, wireless communications, wireless networking, smart home, microgrid, vehicle-to-grid, paradigm, challenge, vision

I. INTRODUCTION

The term grid is traditionally used for an electricity delivery system that may support all or some of the following four operations: electricity generation, electricity transmission, electricity distribution, and electricity control [1].

By using two-way flows of electricity and information, smart grid, an enhancement of the traditional power grid, attempts to create an automated, distributed, and advanced energy delivery network. This enhanced grid is expected to provide distributed power generation, self-monitoring, self-healing, adaptive and islanding microgrid, pervasive control, and various customer choices.

In order to realize these functions, an advanced information and communication system underlying the smart grid will play a critical role. For example, in the peak period, the electric utility notifies the users the real-time price so as to convince them to reduce their power demands. Therefore, the total demand profile full of peaks can be shaped to a nicely smoothed demand profile. This can help electric utility reduce overall plant and capital cost requirements. In order to realize this, an information communication network, which can guarantee the real-time price notification, is required. Another example is that to realize grid self-healing requires a widely deployed monitoring system. The grid status information obtained by this monitoring system should be sent to the controller in a timely manner. Suppose that a medium voltage transformer failure event occurs in the smart grid. This failure can be detected by the monitoring system and then reported to the controller promptly. Therefore, the smart grid automatically changes the power flow and recovers the power delivery service.

In this article, we focus on the wireless communication and networking technologies, which may be used in the future smart grid. Although Xi et al. [1] did a comprehensive survey on the smart grid, in this work we will refine the exploration of smart grid and present our vision for smart grid from the perspective of wireless communication and networking technologies. We present four wireless communication and networking paradigms for typical scenarios in the future smart grid and also point out the research challenges of the communication and networking technologies used in the smart grid.

The rest of this article is organized as follows. In Section II we overview the basic concept of the smart grid. Then, we vision the wireless communication and networking paradigms for four important scenarios in Section III and describe some research challenges in Section IV. Finally, we conclude this article in Section V.

II. OVERVIEW OF SMART GRID

A traditional power grid is unidirectional in nature. Fig. 1 shows an example of the traditional power grid. Electricity is usually generated at central power plants by electromechanical generators, primarily driven by the force of flowing water or heat engines fueled by chemical combustion or nuclear fission. These power generating plants are often quite large and located away from heavily populated areas. The electric power generated by these plants is stepped up to a higher voltage for transmission on a transmission grid. The transmission grid moves the power over long distances to substations. Upon arrival at the substation, the power is stepped down to a distribution level voltage. As the power exits the substation, it enters the distribution grid. Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s).

Fig. 1. An Example of the Traditional Power Grid
In contrast, the smart grid uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network. In a smart grid, the energy generation and delivery is more flexible. Fig. 2 shows an example of a smart grid. The distribution grid may also be capable of generating electricity by using distributed energy generations, such as wind turbines and solar panels. Note that the transmission grid could also have large-scale distributed generators (e.g., wind farm) connected. Since now power can be generated by users, we can group these distributed energy generators and loads as a microgrid. The microgrid normally operates connected to a traditional power grid (a macrogrid). The single point of common coupling with the macrogrid can be disconnected. The microgrid can then function autonomously without obtaining power from the electric utility in the macrogrid. Thus, the multiple distributed generators and the ability to isolate the microgrid from a larger network in disturbance will provide highly reliable electric power supply. The smart grid also takes advantage of the plug-in hybrid electric vehicles (PHEVs). PHEVs can communicate with the grid and deliver electricity into the grid at peak electricity usage times, if they are parked and connected to the grid. These vehicles can then be recharged during off-peak hours at cheaper rates.

Due to the complicated power delivery pattern being used, the information delivery system should also be updated. Broadly stated, by utilizing modern information technologies, the smart grid could respond to events that occur anywhere in the grid, such as power generation, transmission, distribution, and consumption, and then adopt the corresponding strategies or behaviors.

III. WIRELESS COMMUNICATION AND NETWORKING PARADIGMS IN SMART GRID

In Section II, we briefly overview the smart grid. In this section, we present four scenarios and the communication and networking technologies that may be applicable in these scenarios.

A. Smart Home

Automatic metering infrastructure (AMI) or smart meters in the smart grid enable two-way communications. They have been widely regarded as the most important mechanism in the smart grid for obtaining information from end users’ devices and appliances, while also controlling the behaviors of the devices [1].

A smart meter is usually an electrical meter that records consumption in intervals of an hour or less and sends that information at least daily back to the utility for monitoring and billing purposes. Since based on this infrastructure all the information is available in real time and on demand, both electric utility and users are able to adjust the supply and demand profile to improve the system operations and their own benefits.

In the future smart homes, many applications become possible based on this infrastructure.

First, end users are able to estimate bills and thus manage their energy consumptions to reduce bills. For example, as shown in Fig. 3, the smart meter can collect information and power consumption from the dishwasher, the refrigerator, and the air conditioner. Based on the realtime price information from electric utility, the smart meter can disconnect-reconnect remotely and control these user appliances to reduce electricity cost. In order to realize the wireless communications between the smart meter and the user appliances, ZigBee Smart Energy Profile (SEP) has been selected by a large number of utilities as the communications platform [1]. This wireless communication standard provides a standardized platform for exchanging data between smart metering devices and appliances located on customer premises. The features supported by the SEP include demand response, advanced metering support, realtime pricing, text messaging, and load control [9].

Second, the smart meter should also provide a communication and control mechanism between smart home and remote house owner. Let us consider a simple example pointed out by Xi et al. [1]. In summer, the house owners hope that when they get home, the temperature at home is around 60 – 80°F. Thus, the smart meter connected to the air conditioner can periodically inquire the position of the house owner by attempting to send the inquiry information to the
owner’s smart phone which can obtain the owner’s position via GPS. If the smart meter finds the owner is coming back home, it will decide to turn on the air conditioner in advance so that when the owner gets home, the temperature at home is around $60 - 80\,^{\circ}F$. In this application, the smart meter is able to not only remotely control the air conditioner via, for example, a Zigbee platform, but also exchange information between house owner and itself. For the latter information, the smarter meter may need to contact to the service provider of the owner’s cell phone via a cellular system as shown in Fig.3.

Third, in the future smart home, smart meter should not only be used for an interface between the future smart home and electric utility. Like “Apple’s Application Store”[3], many management applications and services are available online. Users can choose their expected services and download to the local system (e.g. the smart meter) [1]. For example, a user who needs a management program supporting the example about smart control of air conditioner mentioned above, can buy this program from the Smart Grid Store online and download it. This Smart Grid Store provides an integrated platform, which can drive the third party to develop new management programs and meantime help users easily customize their management services.

In addition to Zigbee and cellular systems, WIFI could also be used in a smart home. The most important advantage of WIFI is that it has been widely used and has mature standards. The smart meter can transmit its information to a WIFI access point, and the information then would be routed to the electric utility.

B. Microgrid

Microgrid is seen as one of the cornerstones of the future smart grids [4, 2]. The organic evolution of the smart grid is expected to come through the plug-and-play integration of microgrids. An important operation of microgrid is that distributed energy generations and loads are grouped together, and thus the microgrid can disconnect from the macrogrid and function autonomously. This intentional islanding of generations and loads has the potential to provide a higher local reliability than that provided by the power system as a whole.

The information exchange among the users is needed for operating a microgrid. For example, first, they need to decide when they will operate in an islanding mode, and how to optimize the power usage and resource allocation if the microgrid is working in islanding mode. Second, when the distributed generators (e.g. solar panels) of some users generate more power than these users need, they may sell the electricity to other users in this microgrid. This transaction needs information exchange among these users.

A wireless mesh network is an applicable network architecture to realize the information exchange among the users in a microgrid. Note that a wireless mesh network is a communication network made up of radio nodes organized in a mesh topology. First, a wireless mesh network is a self-organized and self-configured. Considering that the smart grid allows a large number of plug-and-play devices, this feature is very important. Second, since usually multiple paths exist between any two nodes in a mesh network, this provides a high communication reliability. Third, mature research and industry standards have been carried out for a wireless mesh network. Wireless mesh networks can be implemented with various wireless technology including IEEE 802.11, 802.15, 802.16, cellular technologies or combinations of more than one type.

C. Electric Vehicle System

An electric vehicle is a vehicle that uses one or more electric motors for propulsion. As fossil fuels diminish and generally get more expensive, electric vehicles or plug-in hybrid vehicles will rise in popularity. The wide use and deployment of electric vehicles will have a significant impact on future grid.

The first impact is that charging electric vehicles will lead to a significant new load on the existing distribution grids. Recent study has shown that high penetration levels of uncoordinated plug-in hybrid electric vehicles charging will significantly reduce power system performance and efficiency, and even lead to overloading [8]. The second impact is that electric vehicles provide a new way to store and supply electric power. This concept is called as Vehicle-to-Grid (V2G) in the vision of the smart grid [1]. It allows V2G vehicles to provide power to help balance loads by “peak shaving” (sending power back to the grid when demand is high) and “valley filling” (charging when demand is low).

In order to integrate electric vehicle systems into power grid, wireless information technologies will play an important role.
First, in order to mitigate the negative impact of electric vehicle charging, the charging behaviors of electric vehicles should be regulated. For example, it is recommended to do coordinated charging. More specifically, a group of electric vehicles can optimize their charging operations and schedules based on their demands, to guarantee that they will not charge at the same time or when the power demand in the grid is already high. Realizing the coordinated charging requires vehicles, electric utility, and even charging station to exchange a large amount of information, such as location information, battery information, charging service availability information, and grid power supply information. Based on this information, optimizing charging operations and schedules is implementable. Cellular communication systems and mobile adhoc networks (MANETs) are two wireless communication architectures which are applicable in this scenario. Cellular communication system has already been used for vehicle road assistance. For example, “Google Map” on smart phones provides real-time traffic, which helps the users to find the fastest route. Using existing cellular systems and smart phone platform to realize this charging assistant programming has the following benefit. Developing a charging assistant program on smart phone and using the mature cellular system behind it as the information exchange medium, instead of developing a new wireless system, is a cost-effective solution. Every user can benefit from this technology as long as they install this program on their smart phones. In addition, MANET is also a promising platform in this scenario. MANET is a self-configuring infrastructureless network of mobile devices connected by wireless links. Such networks can further be connected to the larger Internet. Based on MANET, vehicles can exchange the information efficiently and thus make effective decisions.

Second, real-time information exchange is also needed for realizing the concept V2G. Suppose an electric vehicle with excess power in a parking lot, which has been connected to the grid. When the electric utility in the smart grid needs electric vehicles to send the power back to the grid in the peak time, they must contact with the owner of this vehicle to get a permission to use the battery of this vehicle. The most effective way to realize this information exchange is using the existing cellular communication system. After the utility gets the permission, it needs to remotely control the vehicle. This can be done via the wireless network, where the vehicle is located in.

D. Monitoring System

Self-monitoring and self-healing are important features in the vision of the smart grid. A large number of sensors are expected to be deployed in order to detect failure events in power grids, such as conductor failures, tower collapses, hot spots, and extreme mechanical conditions. Fig. 6 shows an example of such monitoring system, which uses wireless sensor networks to provide remote system monitoring and diagnosis. A base station reports the grid status to the grid operator periodically via a backbone communication network. This backbone communication network is often built on a fiber optic network. The sensors collect the status and transmit this information to the base station via one-hop or multi-hop wireless networks. Note that a wireless sensor network is probably the most cost-effective way to realize this monitoring system for the following reasons. First, wireless sensors have fairly low installment and deployment costs. Second, if the density of the sensors is high enough, the sensor networks would provide fairly high reliability and survivability. This is because each area may be covered by multiple sensors. Even if some sensors fail, it is highly likely that the important areas are still being monitored. This effectively reduces the maintenance cost.

IV. CHALLENGES FOR THE RESEARCH ON WIRELESS TECHNOLOGIES IN SMART GRID

In Section III, we presented the wireless communication and networking paradigms for four important scenarios in the smart grid. In this section, we describe some issues and challenges existing in the research on the wireless technologies for the smart grid.

A. QoS and Entropy of Information Data

The diversity of the information transmitted within the smart grid makes it necessary to differentiate the quality of service (QoS) of the data. Roughly speaking, we can categorize the data into two types: critical data (e.g. the critical grid status information collected by the monitoring system) and non-critical data (e.g. user energy consumption and billing information exchanged between the smart meter and electric utility). We must pay a particular attention on the QoS of the critical grid status information. In other words, we should guarantee that this type of data is sent to the controller in a timely manner. Otherwise, losing real-time grid monitoring may result in outage or disastrous results, such as cascading blackouts. Therefore, ensuring that the critical monitoring data is delivered on time is a prerequisite to improve the grid reliability and realize self-healing once failure events take place. However, as the wireless environment is usually unreliable, realizing this objective is not easy task.

For the wireless communications in the smart grid, we also need to consider the entropy of the transmitted data. Since
a large number of sensors and smart meters are used in the smart grid, a large amount of data (e.g. sensing data) will be generated. However, this data may have a large amount of redundancy. For example, the smart meter readings must be similar when no activity takes place at home. The monitoring data generated by the sensors in the vicinity may also have information redundancy. It is well-known that the wireless spectrum is a scarce resource. Transmitting a large amount of redundant data significantly reduces the resource usage. Therefore, improving the entropy of the transmitted data in the smart grid would be beneficial.

B. Wireless Communication Network Management and Control

A basic question about the wireless communication network used in the smart grid is: Should this network be organized in a distributed manner or a centralized manner? There is no straightforward answer to this question. On one hand, the traditional electric utility will still play a dominant role in the foreseeable future. A large amount of information should still be controlled and managed by one or multiple large centralized electric utilities. Note that although distributed wireless communication networks (such as ad hoc networks) have been studied for a long time, it is interesting that the centralized control structure is still much more popular, especially for the commercial systems where central utilities are involved. On the other hand, many distributed entities are introduced into the smart grid, which makes distributed communication network be a competitive choice. For example, a microgrid can be organized in a distributed manner. It may prefer a distributed and self-organized communication network structure, because a large number of plug-and-play devices may be used and a microgrid is expected to have the capacity of functioning autonomously. In brief, how to effectively organize the wireless network in the smart grid is still an open question and is worth further investigation.

Another question is how to optimize the complicated heterogenous wireless communication system underlying the smart grid, where multiple wireless communication technologies are used simultaneously. Note that due to the industry standards and utility interests these technologies may overlap in both time and space. For example, a smart meter may exchange data with the user appliances via Zigbee (due to the user appliance industry standard), transmit information to the electric utility via WiMax (because it is cost-effective for the electric utility to set up or lease one base station to cover a large number of users), and keep in touch with the house owner’s phone via a cellular communication system (suppose that the house owner always carries a 3G smart phone). The question is how to jointly optimize these different wireless networks to reduce cost and improve the wireless resource utilization.

C. Security and Privacy

Cyber security is regarded as one of the biggest challenges in the smart grid [5]. The malicious attacks on the wireless communication networks underlying the smart grid can be categorized into three major types based on their goals [7]: network availability, information privacy, and data integrity.

Network Availability: Malicious attacks targeting network availability attempt to delay or block information transmission in order to make system resources unavailable to nodes that need to exchange information in the smart grid. As a result, the real-time monitoring of critical power infrastructures may be lost, which may further lead to a possible global power system disasters. For example, in power grids cascading failure is common when one of the elements fails and shifts its load to nearby elements in the system. Those nearby elements are then pushed beyond their capacity. As a result, they become overloaded and shift their load onto other elements. This failure process cascades through the elements of the system and continues until substantially all of the elements in the system are compromised. In concept, smart grid is expected to handle this case by widely deploying monitoring devices to monitor the grid real-time status. When wireless communication network availability is compromised, the monitoring information cannot be transmitted effectively to the controller. As a result, one element failure may lead to a disastrous cascading failure. Therefore, as pointed out by National Institute of Standards and Technology (NIST) [5], the design of information transmission networks that are robust to attacks targeting network availability is the top priority.

Information privacy: The major benefit provided by the smart grid, i.e. the ability to get richer data to and from customer meters and other electric devices, is also its Achilles’ heel from a privacy viewpoint [5]. The energy use information stored at the meter acts as an information-rich side channel. This opens up a door for a malicious attacker, who is interested in the personal information such as individual’s habits, behaviors, activities, preferences, and even beliefs. Once the wireless transmission security is broken by the attacker, the attacker can retrieve this privacy information by analyzing energy use information.

Data integrity: Data integrity attack attempts to deliberately modify or corrupt information transmitted within the smart grid. This may lead to an extremely damaging result in the smart grid. For example, Liu et al. [6] showed that an attacker can manipulate the state estimate without triggering bad-data alarms in the control center. This attack is called the false-data injection attack or the stealth attack. Consider the cascading failure example above. An attacker can compromise one grid element and prevent the control center from detecting this by using stealth attack. This may result in a disastrous cascading failure.

In summary, the advanced communication infrastructure introduced in the smart grid is a double-edged sword. On one hand, it provides a way for the power grid to realize complicated operations and functions. On the other hand, expanded communication paths can easily result in an increase in vulnerability to cyber attacks and system failures. Security is a never-ending game of wits, pitting attackers versus asset owners. How to guarantee cyber security for the smart grid will be a long-term research topic.
D. Interoperability and Compatibility

Thus far, the smart grid is not a thing but rather a vision. It is regarded as a loose integration of complementary components, functions, subsystems, and services under the pervasive control of highly intelligent management-and-control systems. Therefore, many different wireless communication protocols and technologies probably will be used in the smart grid. As a result, realizing interoperability among them is not an easy task. Although NIST [5] has proposed a draft of framework and roadmap for smart grid interoperability standards, many problems are still left to address.

First, we need to consider how to take advantage of the legacy infrastructure, in order to reduce the deployment and installment cost of the wireless communication system underlying the new smart grid. The cellular communication system and the WIFI network are two widely used wireless infrastructure. It would be beneficial to investigate how to effectively integrate these two systems into the smart grid vision.

Second, we should consider not only how to take advantage of the existing wireless communication systems, but also the system forward compatibility. Since the current concept of the smart grid is just a vision, many new features will be integrated into the new grid in the future. We must consider that the current design for the wireless communication systems underlying the smart grid can also be used or can be easily upgraded to support new features.

Third, from a technical point of view, the classic layer model (e.g. the famous Open Systems Interconnection model) could provide a promising conceptual solution to realize interoperability among different wireless communication technologies. However, it is well-known that this layer model suffers in some modern applications. For instance, the performance of the pure TCP may be very bad in wireless networks, because it cannot differentiate packet loss due to wireless fading from that due to a real congestion in the network. Therefore, in practice some functions or services are not tied to a given layer, but can affect more than one layer, in order to improve the quality of services. This concept often requires cross-layer design and optimization. However, interoperability among different communication technologies, a precursor to cross-layer approaches, is difficult [1].

V. Conclusions

There is no doubt that the smart grid will lead to better power supply services and a more environmentally sound future. However, we still have a long way to go before this vision comes true. Communication system is a nervous system of this new grid and requires a large amount of research effort. In the article, we have visioned the wireless communication and networking paradigms for four typical scenarios in the smart grid and point out the research challenges for wireless communication and networking technologies in the smart grid. We believe that more and more communication paradigms would emerge as the research on the smart grid is extended. Eventually, the information transmission network and energy delivery system will be organically integrated, which will revolutionize our daily life.

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