Smart Grid Communication: Its Challenges and Opportunities

Ruofei Ma, Hsiao-Hwa Chen, *Fellow, IEEE*, Yu-Ren Huang, and Weixiao Meng, *Senior Member, IEEE*

***Abstract*—The necessity to promote smart grid (SG) has been recognized with a strong consensus. The SG integrates electrical grids and communication infrastructures and forms an intelligent electricity network working with all connected components to deliver sustainable electricity supplies. Many advanced communication technologies have been identified for SG applications with a potential to significantly enhance the overall efficiency of power grids. In this paper, the challenges and applications of communication technologies in SG are discussed. In particular, we identify three major challenges to implement SG communication systems, including standards interoperability, cognitive access to unlicensed radio spectra, and cyber security. The issues to implement SG communications on an evolutional path and its future trends are also addressed. The aim of this paper is to offer a comprehensive review of state-of-the-art researches on SG communications.**

***Index Terms*—Cognitive radio, smart grid communication, smart utility network, wireless sensor network.**

I. Introduction

TODAY'S electricity grid was designed and constructed to meet the requirements set up in the last century. The grid is primarily radial, built for centralized power generation, and is dependent on manual restoration. Besides, reliability of traditional electric grid is ensured mainly by having excessive power capacity in the whole system, with one-way power flow from power plants to consumers. Although lots of newly-developed information and communication technologies have dramatically affected the other industry sectors, the electric systems generally remain to operate in the same way for decades.

Most of the electrical energy we consume today comes from fossil-fuel power stations. Electricity generation in fossil-fuel power stations is low in efficiency and causes pollution to the environment. In other words, there is a tremendous amount of energy left behind in the process of electricity generation [1]. In this sense, the power generation presents a substantial waste of limited natural resources and emits lots of carbon dioxide (CO_2) into the air. Renewable energy resources, characterized by their carbon-free and environmental friendly electricity generation processes, have become more and more popular. However, these resources are mostly intermittent in nature and distributed over electrical grid. Combination of distributed energy storage systems and distributed energy resources (DER) is an attractive way to address the environmental problems with existing grid [2]. The distributed storage nodes can be used to supply energy during peak loads and save the surplus energy when demand is low. SG communication technologies are anticipated to enable electric distribution systems to incorporate large amounts of distributed energy resources into the grid and to deal with the intermittent nature of renewable energy [3]. Table I makes a comparison between SG and the existing grid.

TABLE I
Comparison of the Existing Grid and Smart Grid

	Existing Grid	Smart Grid
Information flow	Unidirectional	Bidirectional
Electricity generation	Centralized generation	Distributed generation
Grid topology	Radial	Network
Integrating DERs	Seldom	Often
Sensors	Few sensors	Lots of sensors
Monitoring ability	Usually blind	Self-monitoring
Outage recovery	Manual restoration	Self-reconfiguration
Testing	Manual check	Remote check
Control ability	Limited control	Pervasive control
Control type	Passive control	Active control
Overall efficiency	Low	High
Environmental pollution	High	Low

Energy waste in traditional power transmission and distribution (T&D) systems, which includes everything between power plants and customer side, is also a motivation for us to implement SG using communication technologies. The other waste is due to inefficient routing and dispensation of electricity. T&D losses are considered normal in a traditional grid, and these losses can result in huge revenue losses for utilities [1]. As a result, SG helps to lower the T&D losses with its monitoring ability with the help of communication technologies to distribute electric power in a more effective way. Another important issue is that most of generated electrical energy in the grid can not be stored, and even if it can, lots of electricity will be lost in energy conversion processes. Therefore, SG is needed to make generated electricity closely match to the demand.

If we focus on the end of grid, customers' non-smart appliances are the main cause for ineffective use of electricity. SG will help those appliances to use electricity in a more efficient manner by its communications capabilities. Smart appliances in the future should be able to manage power to take advantages of real-time billing function. This is often referred to as demand response (DR), which is a mechanism to adjust customer electricity consumption in response to supply-side conditions, for instance, reducing electricity consumption in reaction to market prices, etc. [4]. DR can also be regarded as a semi-emergency application triggered during peak loading

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The authors are with the Communications Research Center, Harbin Institute of Technology, Harbin 150001, China (e-mail: maruofei@hit.edu.cn; hshwchen@ieee.org; n96984171@mail.ncku.edu.tw; wxmeng@hit.edu.cn).

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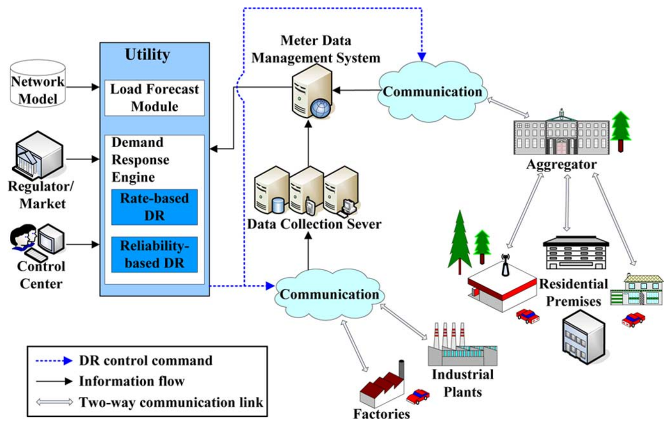

Fig. 1. A conceptual diagram to implement DR in a SG communication network.

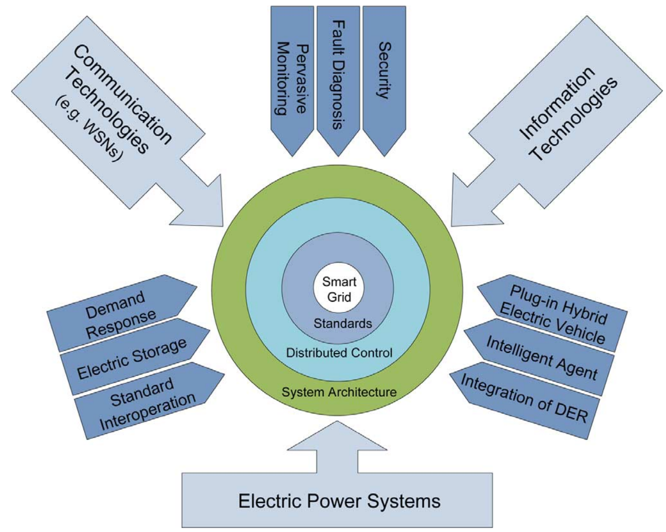

Fig. 2. Basic components in smart grid.

times to reduce the total demand at distribution systems for a certain duration of time. Fig. 1 shows a conceptual diagram on how to implement DR in a SG communication network. Using different communication technologies, meter data management system (MDMS) receives data from aggregators or individual customers, and then the received data are delivered to a DR engine which promotes DR activities by sending DR control commands to optimize resource allocation in an energy network. The DR engine can also forecast the future demand through a load forecast module.

Wireless communication plays an extremely important role in realizing all aforementioned goals of SG. Advancements in wireless communication technologies have made it possible to implement a SG with its capability to convey various vital information from and to electricity consumers, to achieve a very high utility efficiency. While we say in general telecommunication infrastructure is important to implement a SG, wireless communications in particular can offer SG a much greater degree of freedoms for information collection, dissemination, and processing than wired communication infrastructure. For instance, wireless sensor network (WSN) forms an essential part in realizing a SG, since it has the ability to construct a highly reliable and self-healing power grid that can quickly react to the events with appropriate actions. Also, the use of pervasive control systems will improve efficiency and stability of the networks, to avoid overwhelming load on the grid and hence reduce possible blackouts which might cause a massive economic impact. The recent advances in WSNs have made it attainable to realize embedded electric utility monitoring systems [5]. The potential applications of WSNs on SG might include remote system monitoring, equipment fault sensing, wireless automatic meter reading (WAMR), network distributed resource optimization, and so forth [5], [6]. It is noted that WSNs can be utilized and implemented throughout the entire SG network due to its many advantages such as rapid development, flexibility, and low-cost.

From Table I and the above descriptions, it is understood that SG is built to solve the problems and drawbacks of the existing grids, such as the lack of two-way communications, limited control capabilities, and inefficient use of electricity [1]. Basically, a SG needs to provide the utilities with pervasive measuring and control over their assets and services. Given those salient features, underlined communication and information infrastructures definitely play important roles in SG applications. The basic components in SG are depicted in Fig. 2, which conceptually shows the major functional blocks of a SG, built on communication and information technologies, and electric power systems, supported by new approaches and applications such as DR, distributed energy resources, and pervasive monitoring, etc.

The aim of this paper is to offer a comprehensive review on the recent works on the applications of wireless communication technologies in SG, based on which we want to show an evolutional path of SG development. The possible research trends for SG communications are also discussed in this paper. It is observed from our survey that the current SG communication research focuses very much on smart monitoring technologies, applications of DR, implementing SG communications in licensed-exempt bands, security technologies, pervasive sensing using WSNs, and interoperability in different SG communication standards.

The remainder of this paper is outlined as follows. Section II elaborates the wireless communication technologies related to SG. In the same section, suitable wireless communication technologies for distribution grid are also discussed. Section III reviews the applications of wireless sensor networks in SG. The challenges and trends of SG communications are discussed in Section IV, followed by the conclusions drawn in Section V.

II. Communications Networks in Smart Grid

Recently, diverse communication and information technologies have been identified to realize SG. In this section, first we will introduce a general SG architecture, and then we will discuss those recently developed technologies according to their functionalities in electricity delivering processes, including electricity transmission and distribution systems. A transmission system is often regarded as the section in an electricity grid that moves a great amount of power over very long distances, and thus it is distinguishable from a distribution system, which is usually considered as the section that delivers electric energy from a high voltage transmission grid to user-end premises

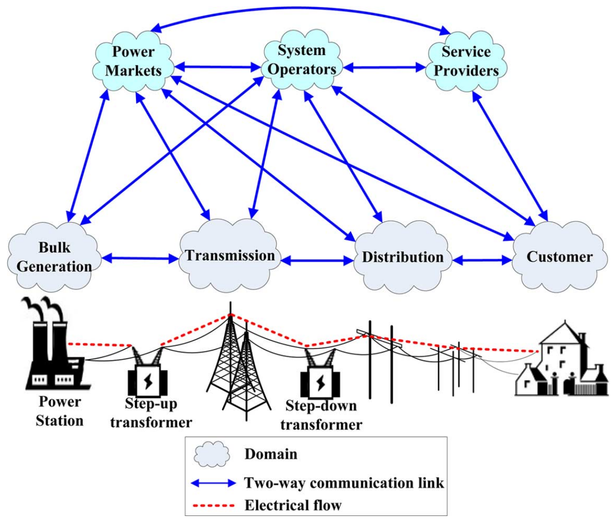

Fig. 3. Interactions among different smart grid domains.

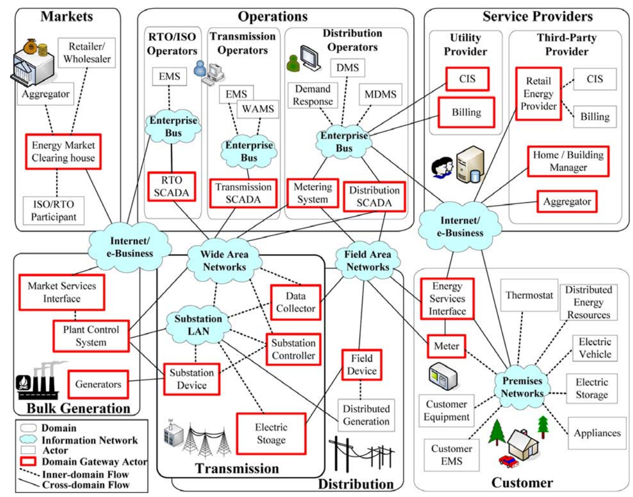

Fig. 4. Conceptual model for smart grid information networks.

such as a residential district or commercial center. At the end of this section, we will discuss the issues related to SG security.

A. SG Framework

As reported in [7], Energy Independence and Security Act (EISA) assigned National Institute of Standards and Technology (NIST) the responsibility to coordinate the development of an interoperability SG framework including model standards and protocols. There are lists of standards presented in [7] based upon the comments received from workshops, stakeholders, and public reviews. There are two major principles that NIST used to select the standards. First, whether they support interoperability of SG as it evolves from the existing grid with new utility deployment to SG equipment and appliances. Second, whether they have a demonstrably high level of consensus to support. According to the document [7], SG infrastructure is most likely to be built based on 75 standards. For example, IEC 61850 Suite is for communications within transmission and distribution sectors, ANSI C12.20 is for revenue metering accuracy specification, and IEEE 1588 is for time management and clock synchronization of equipments across the SG, etc. These identified standards will definitely have great influences on how SG will be implemented in the future.

According to a conceptual model of SG proposed in [7], a SG framework of information exchange among the seven domains (denoted as clouds) is illustrated in Fig. 3. The four domains in the lower layer related to electrical power system are generation domain, transmission domain, distribution domain, and customer domain. The physical configuration of a power system is constructed mainly on these domains. The higher regulatory layer domains include regional system operators, energy service providers, and power markets. In Fig. 3, the blue arrow-lines show bidirectional communication links among these domains, and the red dotted lines represent electricity flows in power grid. In this SG paradigm, each domain encompasses several actors and applications. Actors include devices or systems that make decisions and exchange information necessary for implementing SG applications. On the other hand, applications are the tasks performed by one or more actors within a domain. For example, smart meters, solar power plants, and control centers are the actors in this model. In this case, the corresponding applications may be home automation, solar energy generation, and energy management.

In Fig. 3, whenever energy demand occurs, the customer has to exchange information with power markets, system operators, service providers, and distribution domains. The power market involves energy buying and selling, and it exchanges information with all domains to balance supply and demand. Service providers offer the services to support business activities of power producers, distributors and customers. System operators exchange information with all domains to provide smooth operation of the whole system. With market and operation information, the generation domain, transmission domain, and distribution domain work jointly to deliver power to the customer domain.

A specific conceptual diagram [7] for SG information network is depicted in Fig. 4, which shows information flows in those seven domains as depicted in Fig. 3. Communications in this conceptual model can be illustrated by six basic components, i.e., domains, information networks, actors, domain gateway actors, inner-domain and cross-domain information flows. Each of the seven SG domains is a high-level group of organizations, systems, devices or other actors that have similar objectives and participate in similar types of applications. Domains may contain subdomains or have overlapping functionalities, as in the case of transmission and distribution domains. An information network is a combination of interconnected computers, communication devices, and other information and communication technologies, all of which can exchange information and share resources with each other. The information networks in this diagram include enterprise buses, substation local area networks, wide area networks, field area networks, and premises networks. Actors are systems or devices capable to make decisions and to exchange information with the other actors. Communications among actors in the same domain may have similar characteristics and requirements. Organizations might have actors in more than one domain. On the other hand, a gateway actor is an actor in one domain

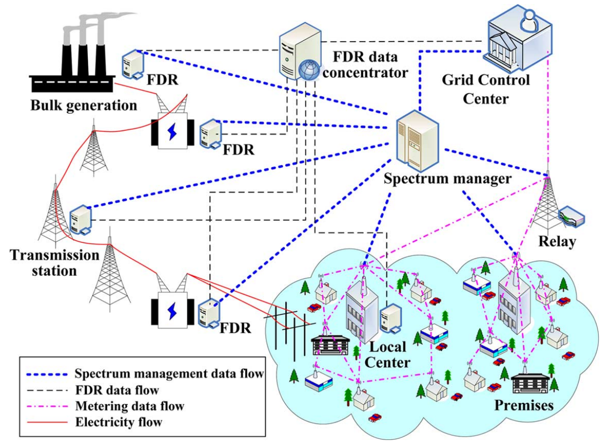

Fig. 5. FNET and cognitive radio in smart grid information networks.

that interfaces with the actors in the other domains. Generally speaking, a variety of communication protocols are adopted by gateway actors in the real world; therefore, the gateway actors should use interoperable protocols if seamless interconnectivity is required. Finally, inner-domain and cross-domain flows show data communications between actors or between actors and information networks.

B. Communications in SG Transmission Systems

1) Wide-Area Frequency Monitoring Network: [8] presented some latest implementations of frequency monitoring networks (FNETs), which facilitate wide-area monitoring networks for observing various statuses in an electrical grid. In FNET systems, frequency disturbance recorders (FDRs) are implemented as sensors to measure phase angle, amplitude, and frequency of a voltage source. Phasor measurements of a power grid are transmitted via the Internet or other wireless WAN technologies to a local client or a remote data center. A conceptual model of FNET in SG is depicted in Fig. 5. FDRs can be installed in many locations in the grid, such as power plants, substations, office buildings, and premises. Measured data from FDRs are processed in a data center by multilayer agents in a multilayer fashion. The top layer is a FNET data concentrator, which is responsible to receive data from FDRs, create GPS time-aligned records, share data with real-time application agents, and forward data records to data storage agents as well as subscribed clients. The real-time application agents and data storage agents are located in the second layer of the data center hierarchy. The third layer is a non-real-time analysis agent, in which applications implemented on this layer are operated on the saved data from the data storage server.

FNET applications can be classified into two categories, one is real-time applications and the other is non-real-time applications. Real-time applications require immediate response after receiving data, while non-real-time applications have more flexible timing requirements. Real-time applications operate on data in a memory cache. The real-time applications include frequency monitoring interface, event trigger and inter-area oscillation trigger. The frequency monitoring interface can display unit name, IP information, connection status, and dynamic frequency curve of one certain FDR. FNET event trigger module can detect frequency variations, which always reflect a mismatch between generation and demand in a power system. In addition to generation losses, a system-wide frequency disturbance caused by load shedding can also induce a positive response in this module. The inter-area oscillation trigger module possesses a high accuracy on measuring system dynamics. Power system oscillations, which are associated with events load shedding and generation trips, can be monitored and detected according to both FNET phase angle and FNET frequency recordings.

A FNET system was well designed for high volume data transfer, processing, storage and utilization. Due to the desired sensing ability of FDR, FNET system now comprises a variety of real-time dynamic monitoring applications. Because FNET system is a mature, multifunctional, low-cost voltage phasor measurement system with stable performance, it is expected that it will be capable to dynamically estimate and control the grid in a real-time manner. These desired features make FNET system a suitable monitor and control system for smart transmission grid. Some more works on SG transmission systems can be referred to [9] and [10].

2) Cognitive Radio Based WRANs for SG: Due to scarce frequency resources, works have been reported in the literature to apply cognitive radio (CR) technologies to SG communications to access unlicensed bands and white space available in TV bands. In [11], the authors proposed to use CR based IEEE 802.22 standard in wireless regional area networks (WRANs) for SG backhaul data flows. They proposed two different architectures for CR-based WRANs, i.e., stand-alone radio and secondary radio, for SG communications according to specific circumstances and applications. They suggested that CR-based WRANs work appropriately as a secondary radio particularly in urban areas and as a backup in disaster management. When there exist higher capacity requirements and hence less availability of unused TV bands, CR-based WRAN can opportunistically transmit non-critical SG data and provide a backup radio in case of a natural disaster or a security breach. In rural areas, i.e., like the places in which customer density is low and there is more white space available in TV bands, they suggested that a stand-alone radio based on IEEE 802.22 can provide broadband access for utility backbone communications because of wide area coverage due to the good propagation characteristics of TV bands.

The authors highlighted the issues that, in both of their proposed architectures, transmission of SG time-critical data is challenging because of inherent sensing delays and cognitive nature specified in IEEE 802.22. Accordingly, the authors proposed a concept of dual-radio architecture for CR-based WRAN transmission where one radio chain is used only for SG data transmission and reception, while the other chain is dedicated for spectrum sensing. The sensing radio constantly searches for new available channels, so that transceiver chain does not have to postpone its data transmission in order to seek for idle channels. By employing the proposed dual-radio architecture, a higher spectrum efficiency and sensing accuracy can be achieved compared with a single-radio architecture, since spectrum sensing is performed all the time, and thus a clear channel for SG data flow can be quickly allocated whenever required.

According to their discussions, it is convinced that their proposed CR-based WRAN is well suited for SG backhaul networks and offers four benefits, which are briefly discussed and listed as follows.

a) Soft capacity limit: The proposed CR-based WRAN for SG communications has a soft capacity limit as it can opportunistically and dynamically use available TV channels to increase system capacity.
b) Wide coverage area: The BS coverage area for IEEE 802.22 standard is much larger than the other 802 standards, which means that less BSs and hence less capital expenditure will be required by CR-based SG communication systems.
c) Fault tolerance and self-healing: Their proposed architecture is inherently robust to failures because if one link has a breakdown due to a natural disaster or security breach, a new connection can be established in a timely manner to maintain connectivity due to the fact that available channels are constantly sensed.
d) Ease of upgradability: CR-based systems are generally implemented using software-defined radio (SDR) systems, which are usually implemented by means of software on a personal computer or embedded computing devices. Consequently, they are more flexible and can be easily modified through software upgrades.

Fig. 5 illustrates the role of CR technology in SG. In conjunction with the control center, there is a spectrum manager that plays an important role in sharing spectrum resources amongst different NANs concentrators and the main information stations in wide areas.

C. Communications in SG Distribution Systems

Distribution system forms another critical part of SG. In this subsection, we will discuss those relevant communication technologies implemented in distribution grid.

1) Coexistence of SUNs With Other Networks: IEEE 802.15.4g smart utility networks (SUNs) task group, i.e., TG4g, founded in December 2008, was established to create a PHY amendment to IEEE 802.15.4 to provide a global standard that expedites large-scale process control applications such as SG distribution network [12], [13]. SUNs enable multiple applications to operate over shared network resources, providing monitoring and control of a utility system. The major technology that employs SUNs is the advanced metering infrastructure (AMI), which has the abilities of monitor, command, and control for service providers at the end-side of the grid, as well as measurement, data collection, and analysis for electricity usage at utility's back office.

Since IEEE 802.15.4g is a newly developed standard that operates in regionally available and license-exempt bands, the coexistence characteristics required by this new standard need to be addressed. Furthermore, the focus of SUNs are the elements that fit between existing standards, which may be used in the utility backbone and in-premises process, industrial and home area networks. In this context, the SUNs form part of a heterogeneous network, filling the gap between wide area networks (WANs), neighborhood area networks (NANs), and home area networks (HANs). Therefore, it is essential to provide coexistence mechanisms that enable SUNs to coexist with the other heterogeneous standards in the same license-exempt bands. The authors in [12] provided an overview of all the mechanisms specified or proposed in IEEE 802.15.4g that are applicable for interference avoidance and mitigation, which are able to facilitate coexistence amongst heterogeneous and homogeneous systems. These coexistence mechanisms include multi-PHY management scheme, clear channel assessment, and link quality indicator (LQI), to just name a few. It is believed that more advanced on-demand coexistence mechanisms should be developed for SUNs in order to mitigate the interference from the heterogeneous systems in crowded license-exempt bands.

2) SUNs in TV White Space: An overview of the recent innovative concept of deploying SUNs in TV white space (TVWS) was presented in [13], in which the main purpose is to provide readers with a detailed discussion to explore the potential of combining these two technologies based on their current development as well as their regulatory status. The authors reviewed SUNs and TVWS as two different green technologies, and then merged them to propose a hybrid solution that integrates their respective merits.

A usage model for SUNs was depicted in [13], in which there exist four kinds of SUN components, i.e., utility provider base stations (BSs), data collectors, smart meters, and mobile data collectors. In SUNs usage model, smart meters of different utilities in a neighborhood area network (NAN) are connected via SUN radio frequency (RF) link. Each house is connected to at least one of its neighbor, and therefore an *ad-hoc* topology is formed by SUNs. A collective number of households form a service area that is covered by a data collector. Data collectors form a mesh network and are connected to the utility provider BSs via wireless or other wired solutions. Data collectors may be deployed as an alternative in the case of an emergency or malfunctions of fixed data collectors are encountered.

Unlicensed TVWS devices, also known as TV band devices (TVBDs), can be classified into two different types, i.e., fixed and portable devices. Fixed devices operate at a fixed location with a high-power outdoor antenna like BSs of a cellular network. Portable devices operate at a lower power and could act as an access point in HAN. Portable devices can be further divided into two different modes, in which Mode I devices are client portable devices controlled by a fixed device, and Mode II devices are independent portable devices with the ability to access available channels.

In order to utilize unused spectrum in TVWS, SUNs must comply with governing rules and communication protocols which are specific to access the TVWS. With an aim to achieve this, SUNs and TVWS must be developed and deployed with a certain level of homogeneity in terms of implementation scenario and system behavior. Consequently, the authors mapped the SUN components into TVWS communication system architecture. They suggested that the utility providers have high-power BSs at headquarters and control centers for establishing metropolitan area networks, so that BSs at utility's headquarters can be viewed as fixed TVBDs. From the perspective of TVWS regulations, they considered that the data collectors can be viewed as Mode II independent

TVBDs. The smart meters are equivalent to Mode I client TVBDs because data collectors are connected to the customer's premises. A mobile data collector in SUNs can be regarded as a sensing-only device with low power consumption and no geolocation awareness capability.

The future of SUN and TVWS combining technologies is promising, but there still exist some limitations to their potential. Several crucial recommendations were made by the authors from both regulatory and technical standpoints for the sake of making SUN able to fully utilize the advantages of TVWS. From a regulation standpoint, the authors suggested that, the requirements specified by regulators for occupying TVWS should be relaxed and the TVWS licensing issue should be considered. On the other hand, from a technical standpoint, it is recommended that the differences in respective system demands must be aligned or regulators should make efforts to engineer a brand-new system that includes merits from both eco-friendly technologies.

3) Hybrid Communication Networks in Smart Grid: Although WiMAX may not be able to compete with LTE-A as a most popular 4G broadband technology, it has been considered to be utilized as a communication backbone in SG. The pilot SGs that use WiMAX as part of their data communications have already been implemented in San Diego, Michigan, Texas, and parts of Australia. A hybrid network architecture using WiMAX and wireless mesh networks (WMNs) was described in [14], as shown in Fig. 6. In this hybrid architecture, a group of electric utility subscribers are clustered into wireless mesh domains, each of which can be easily managed by a local control center using wireless standards such as IEEE 802.15.4g (SUNs), IEEE 802.11 family, or wireless sensor networks (WSNs). The remote control center in a global network monitors each wireless mesh cluster over WiMAX. With the integration of WMNs and WiMAX, electrical utilities can exploit full advantages of multiple wireless networks.

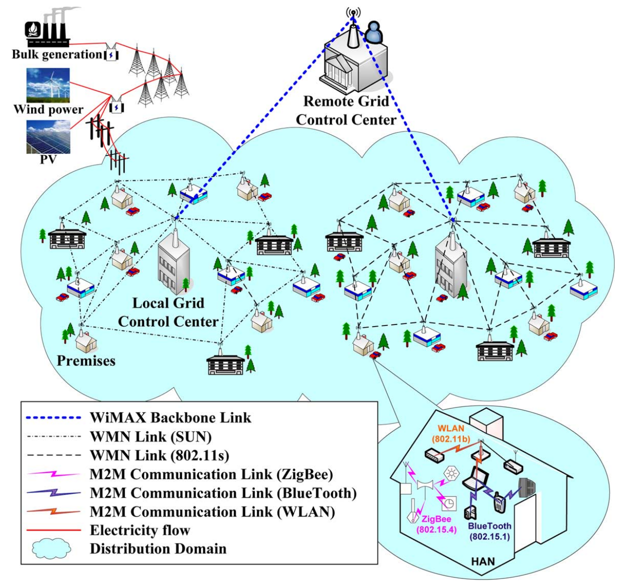

Fig. 6. A hybrid network architecture uses WiMAX and wireless mesh networks, where ZigBee, BlueTooth, and WLAN are adopted for M2M communications in HANs. Local grid control centers monitor each wireless mesh domain using SUNs, IEEE 802.11s, or WSNs. The remote grid control center in a global network monitors each wireless mesh cluster using WiMAX.

The wireless mesh domain in a hybrid network is also known as NAN, which bridges the gap between HAN and WAN. A NAN usually contains thousands of communication nodes distributed in a very large area, and the formation of WMN can improve reliability and self-healing of the whole network. Needless to say, SUN is the most suitable standard for SG NANs. On the other hand, IEEE 802.11s might be another choice as it extends IEEE 802.11 MAC protocol for WMNs and supports frame delivery and route selection at MAC layer through radio-aware metrics. In the topology of an IEEE 802.11s mesh network, a central gateway is used for data transmission to mesh stations. Mesh access points offer the access interfaces to the end users in either static or dynamic state. IEEE 802.11s supports high-speed data transmission, which is different from SUNs. Therefore, it might serve as an option to implement reliable and high-speed wireless NANs in SG.

With the help of of WiMAX technology, the capacity of a network backbone can be increased up to 1 Gbps fixed speed. Furthermore, electric systems suffering from environmental impairments can benefit from WiMAX technology to improve the performance of their communication systems, since WiMAX is characterized by its ability to cover a long distance. A large coverage as well as sufficiently high data rates makes the hybrid network topology more suitable for wireless automatic meter reading (WAMR) as part of utility automatic metering infrastructure [15]. Implementation of WAMR for revenue metering offers several advantages to electric utilities and service providers by eliminating the needs for human meter readers. Hybrid network can be used to provide real-time pricing information based on real-time energy consumption of the customers. This capability is very beneficial to let customers to shift off their loads during peak load times and lower their electricity bills. Due to the advancement achieved in wireless communications and digital electronics, hybrid network architectures can enable scalable wireless communications and provide different quality of service (QoS) requirements of electric systems in an economical manner. Major benefits of hybrid network architectures include improved communication reliability, lower installation costs, larger network coverage, and better network connectivity.

4) M2M Communications for HEMS: Recently we have seen increased attention given to machine to machine (M2M) communications in wired and wireless links. The aim of M2M communications is to enable M2M components to be interconnected, networked, and controled remotely with low-cost, scalable, and reliable technologies. Diverse applications of M2M have already started to emerge in various sectors such as healthcare, smart home technologies, and so forth. The evolution of M2M has also taken place in SG.

The focus of network infrastructure has shifted over from an emphasis on wired and fixed communications to flexible connectivity of wireless communications. The paper [16] provided extensive discussions of a number of existing communication technologies that can be adopted for M2M communications in SG, such as Bluetooth, IEEE 802.11 (WiFi), ultra-wideband (UWB), IEEE 802.15.4 ZigBee, 6LoWPAN, and so forth.

Fig. 6 shows the roles of M2M in SG HANs. As demonstrated by the authors, ZigBee is a superior technology for HAN communications due to its characteristics of low power consumption, flexibility and short wake-up time. In addition, they presented a technique to improve the performance of conventional ZigBee-based M2M communications in SG by incorporating intelligence in the gateway (GW) and M2M devices of the HAN. In a conventional HAN, if M2M devices always attempt to send their periodic messages to a HAN GW, the HAN GW is expected to receive a relatively large number of messages. To this end, the authors proposed a new strategy for transmitting power requirement message, in which a M2M device remains in silent mode unless its power requirement changes. Therefore, a HAN GW will not receive any repeated requests from the same M2M devices and thus is less likely to be overwhelmed by incoming requests from many M2M devices at the same time.

In [17], the authors presented an overview of M2M communications. The enabling technologies as well as the open research topics on M2M communications, such as standardization, traffic characterization, protocol re-design, spectrum management, and optimal network design. They addressed the network design issues of M2M communications for a home energy management system (HEMS) in SG. The HEMS traffic from the smart meter in each house can be aggregated at a concentrator (i.e., gateway) to minimize installation and communication costs. Concentrator installation cost stands for the physical deployment (i.e., routing path) and the bandwidth used by HEMS to transmit data to the base station. This cost is assumed to be fixed over a certain time period. On the other hand, the deployment cost of a concentrator has to be minimized due to QoS degradation from packet delay and losses. For QoS degradation, the corresponding cost (i.e., the impact of QoS degradation on HEMS) is increased if HEMS traffic is not delivered to a control center quickly and reliably. To minimize the total cost, the nodes have to be divided into clusters, and each concentrator is assigned to one of the clusters. This is actually an optimal cluster formation problem, which can be solved by utilizing dynamic programming algorithms. For more works about SG distribution systems, the reader may refer to [21]–[23].

D. Smart Grid Communication Security

The authors in [18] discussed several key security technologies for a SG system, including public key infrastructure (PKI) and trusted computing methodologies. Based on the security requirements of SG, the system structure and the required availability, the authors believed that utilizing PKI technologies together with trusted computing elements is the most desirable solution for SG security.

The basic steps in utilizing a PKI are summarized as follows. First, in order to communicate with a secure resource (i.e., a relying party), the device (i.e., a certificate subject) begins to send a certificate signing request (CSR) to a registration authority (RA). The RA performs a validation function check to determine whether the requested bindings are correct or not. If the requested bindings are correct, RA signs the CSR and forwards it to the certificate authority (CA), which then issues a certificate. CA will issue the certificate and let the validation authority (VA) know the certificate information of the certificated subject at the same time. Later, when a device wants to access a secure resource, it transmits a certificate to the relying party, i.e., the secure resource. The relying party validates the certificate, typically by requesting the certificate status from a VA. Eventually, VA will reply a positive response if the certificate is valid. While PKI is known for being complex, the authors suggested that many of the items responsible for the complexity can be significantly reduced by including the following four major technical elements, e.g., PKI standards, automated trust anchor security, certificate attributes, and SG PKI tools. The authors demonstrated that only by including these PKI elements into the overall security architecture, a comprehensive and cost-effective solution for SG security can be achieved.

Trusted computing platforms are comprehensive security plans that encompass virtually all aspects of grid operations. Platforms and associated mechanisms in the trusted computing model are used to ensure that malware is not able to access to devices of software processing. The main functionality of trusted computing is to allow any devices which want to join in a grid network to verify that authorized code runs on that system. The adoption of strict code signing standards by SG suppliers and operators was also suggested in this paper. Mechanisms for enforcing such standards have been put forward by the Trusted Computing Group and have been also well documented and available on demand.

As a whole, the authors pointed out that SG security solution requires a holistic approach including PKI technologies based on industry standards and trusted computing techniques. They also concluded that PKI technical elements, for examples, certificate lifecycle management tools, trust anchor security, and attribute certificates, are existing technologies that can be tailored specifically for SG networks, resulting in an efficient and effective solution. To achieve their vision for the proposed secure SG networks, the authors suggested that the primary step that should be taken is to develop a cohesive set of requirements and standards for SG security. For more works about security issues for SG communications, the reader may refer to [3] and [19].

III. WSNs in Smart Grid

To support many innovative SG applications, the communication networks in a SG should be highly scalable and pervasive. To this end, the employment of wireless sensor networks (WSNs) seems to be particularly important because it enables realization of advanced communication networks without constructing complex infrastructure. At the same time, WSNs possess a set of intrinsic merits such as wide coverage, low cost, and fault-tolerant transmission.

A. WSNs for Transmission Line Monitoring

Considering constrained transmission range of transceiver module of a wireless sensor, it is generally assumed that data generated by a sensor have to be delivered to a substation through a set of sensors in-between, resulting in a multi-hop linear network model (LNM). In [20], the authors first analyzed the performance of LNM in handling the traffics extracted from a system architecture they modeled. According to their modeling, it was found that the LNM may not be sufficient to support future SG applications due to the problems of transmission delay, unbalanced network loading, unbalanced energy depletion, and low reliability. Therefore, they proposed a new network model called reconfigurable network model (RNM), in which sensor nodes can optionally communicate with the other nodes using WANs such as cellular networks (e.g., GSM). Each relay node can send its data to GSM base stations directly, and the GSM base stations are connected to a data collector server (utility back-office) with low latency, high bandwidth, and low cost links. It should be noted that the communicating cost and energy cost of GSM links are very high when compared to the links between relay sensor nodes. On the other hand, less cost is required by data transmission to the sink node through a set of nodes in-between, but this generally incurs the aforementioned problems in the network. Consequently, a certain trade-off exists and the best way to send traffic to the data center that strikes a balance between delay and cost must be found based on a given system architecture.

In the proposed RNM, an urgent message from a relay node can be transmitted back to a substation almost instantly by turning on its WAN interface. For this reason, RNM is more capable of handling emergency in SG than a conventional LNM. Besides, it is anticipated that several nearby spans should experience similar event, and hence these relay nodes can collaborate to turn on one of the WAN devices in-between so as to balance the delay and cost. It was highlighted by the authors that, the network can still provide information on most of its coverage areas even two or more relay nodes fail due to multiple link failures caused by transient ambient disturbances because the fact that the data can always be sent out by enabling WAN capabilities in relay nodes.

In brief, the authors analyzed the performance of existing LNM and identified its insufficiencies in supporting future SG applications. To deal with these issues, they proposed an extension of capability of relay sensors in transmission grid by equipping relay sensors with WAN communication capability. We think their works are valuable because the three-layered RNM can be reconfigured based on application requirements to deliver information to substations and utilities' back-office in a more efficient and effective manner, which further enhances the reliability of SG communications in transmission grid.

B. In-Home Energy Management

In [24], the authors evaluated the performance of an in-home energy management (iHEM) scheme. The performance of iHEM was compared with an optimization-based residential energy management (OREM) scheme aiming to minimize energy expenditure of the end-users. OREM can reach an optimal scheduling for the appliances, but it is not practical since consumer requests are usually not given in advance. Consequently, the authors showed that iHEM is better than OREM since iHEM is able to decrease energy expenses, reduce the contribution of the consumers to the peak load, decrease carbon emissions of the household. Most importantly, iHEM has a more flexible scheduling mechanism than OREM with its power savings being very close to OREM.

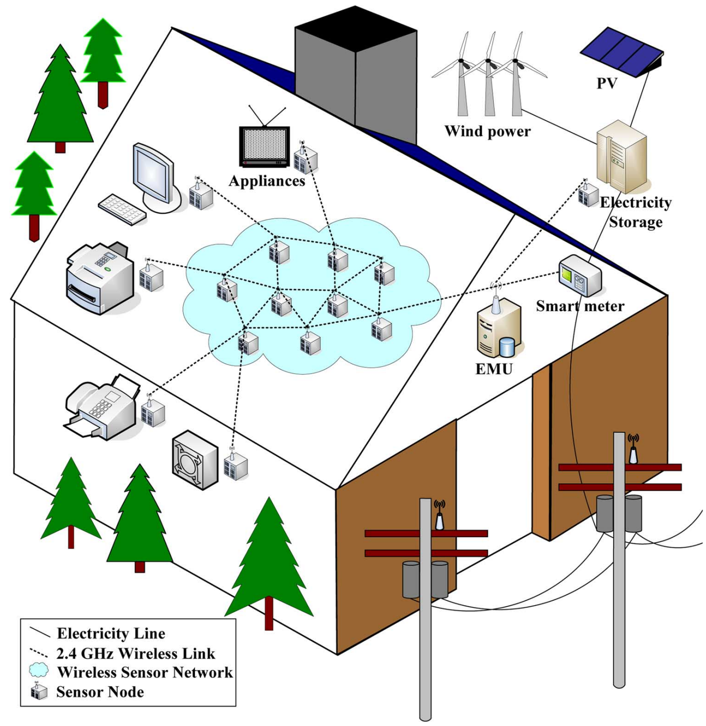

Fig. 7. Architecture of ACORD-FI scheme, where wireless sensor nodes send or relay signals between appliances, electricity storage, smart meter, and EMU to reduce the total energy consumption.

The iHEM application considered in [24] is based on an appliance coordination scheme which was proposed in their previous work, in which the authors developed an Appliance Coordination with Feed In (ACORD-FI) scheme for energy-aware smart homes, which helps consumers to manage their demand and supply profile. The architecture of the ACORD-FI scheme is shown in Fig. 7. Compared with ACORD scheme, the ACORD-FI scheme takes locally-generated energy into consideration.

According to their simulation results, the iHEM application was showed to decrease the load on peak hours as well as the power-related carbon emissions. They also assessed the performance of iHEM under various scenarios, e.g., iHEM with the presence of local energy generation, iHEM with prioritized appliances, and iHEM with real-time pricing. In each case, it was showed that iHEM reduces the expenses of consumers compared to the cases without energy management. It was also demonstrated that the more appliances are involved in energy management leads to a greater reduction in the total energy bill, which is foreseeable because more appliances involved means that more appliances will take the advantages of the iHEM applications. Through their simulations, they also observed that as packet size of iHEM applications decreases, the delivery ratio increases, and the delay decreases, which means improved network performance. With the help of WSHANs, iHEN applications can help customers to respond to electricity prices, and hence reduce their expenditures. This work also showed that WSN applications are very promising for the future SG applications, especially for those implemented in homes or buildings.

C. Cooperative WSNs for Voltage Quality Monitoring

In [6], the authors proposed to employ self-organizing WSNs to construct a fully-decentralized voltage quality monitoring architecture. They used a cluster of sensor networks, where each one of those WSNs monitors a specific electrical grid section. Each node in the WSNs has a sensor, which monitors the voltage waveforms and computes the corresponding quality index (i.e., node index), and a dynamical system (oscillator) which is initialized by sensor computation. Their work showed that if the oscillators of nearby nodes in the same WSN are mutually coupled by proper local coupling strategies, then each oscillator on each node will converge to the global voltage quality index of the monitored grid section. This feature allows power system operators to obtain system voltage quality index for each grid section by querying any node in the corresponding sensor network without having a central control center. In this way, their strategy makes the overall monitoring architecture highly scalable, self-organizing and distributed. These features perfectly meet the design principles of the monitoring networks for SG.

D. Frequency Agile WSNs for Smart Grid

ZigBee is a wireless mesh networking scheme based on IEEE 802.15.4 standard. ZigBee is low in cost, power, data rate, and complexity, and it is easy for deployment and implementation. These features, together with its use of unlicensed spectrum and its advantages of being a public standard rather than proprietary protocol, make it the most suitable wireless technology to monitor, collect, and analyze data on energy usage in real time for SG applications. However, almost all ZigBee channels are overlapped with wireless local area networks (WLANs) based on 802.11 specifications, because they all use the license-free 2.4 GHz ISM frequency bands. This coexistence results in a significant performance degradation when ZigBee based WSNs and WLANs are operating simultaneously within a SG network. The authors in [25] proposed a frequency agility based interference avoidance algorithm, which utilizes energy detection and active scan to perform smart channel selection. In order to dynamically avoid WLAN interferences, their algorithm can detect interferences and adaptively switch sensor nodes to unused channels.

The authors used packet error rate (PER) to evaluate their proposed scheme in a ZigBee and Wi-Fi coexistence test bed. The measured results in their field trial demonstrated that their algorithm efficiently mitigates the effect of Wi-Fi interferences upon ZigBee networks. Just like cognitive radios, which avoid the interference with licensed users based on active monitoring of a radio environment, their interference avoidance algorithm overcomes the coexistence problem of Wi-Fi and ZigBee in a similar way. Due to the increasing popularity of ZigBee-based WSNs in SG applications, it is believed that how to effectively solve the coexistence problem in 2.4 GHz ISM band will largely affect the sensing performance of the SG.

E. Smart Grid WSN Channel Modeling

In many SG applications, severe and complex environments of electric power systems may pose great challenges to the reliability of WSN communications. Because of the fact that communication link-quality characterization in power delivery process or industrial facilities has not been sufficiently studied, the authors in [5] made their efforts on characterizing wireless link-quality in different electric power system environments by conducting many field tests. The field tests were performed to measure background noise, wireless channel characteristics, and attenuation in various real-world environments, e.g., an indoor power control room, a 500-kV substation, and an underground network transformer vault.

They modeled wireless channels in different grid environments using a log-normal shadowing path-loss model through a combination of analytical and empirical methods. Additionally, they showed the corresponding radio propagation parameters in the model. The parameters were calculated from the measured data, which were collected for various locations and network configurations in electric power system environments. The parameters were derived by using linear regression such that the difference between the measured and estimated path losses is minimized in a mean square error sense over a wide range of different experimental conditions.

More works on WSNs in SG applications can be found from the [26]–[29] at the end of this paper.

IV. Challenges and Opportunities

Although lots of works have been done in order to transform the current power system into SG, there are still three major challenges that utility companies or other SG participants will face. These challenges include ensuring standard interoperability, cognitively accessing the unlicensed spectrum, and improving cyber security.

Identification of suitable communication standards and development of interoperable communication protocols for SG are necessary because there are too many diverse technologies and standards existing in the market. NIST is now working towards coordinating the development of a framework that includes protocols and standards for information management to achieve interoperability of SG devices and systems. As mentioned earlier, due to the scarcity and hence the high cost of licensed RF bands, the recent trends of implementing SG communications is to operate in unlicensed bands. This can be evidenced by the newly developed IEEE standard for SUNs [12], [13], in which most of the specified RF bands are license-exempt. Therefore, coexistence mechanism for mitigating interference from the other unlicensed/licensed systems must be developed. In [11], [13], it was pointed out by the authors that CR can be a good choice for tackling this coexistence issue and they further tried to make SG communications operate in TVWS. These attempts will not only lead to a higher penetration as well as a wide coverage due to the VHF/UHF bands, but also result in globalized compatibility of SUN devices, hence to fuel the competition among vendors, which stimulates healthy growth of the SG industry. It is emphasized that the major challenges along the path to incorporating TVWS into SUN applications is service reliability. In spite of diversity algorithms, such as dynamic frequency switching and multi-channel utilization which may provide solutions to the reliability problems, the "secondary" characteristic of TVWS is considered as a fundamental issue, for which SUN systems in TVWS must postpone all its operations upon detecting the existence of an incoming incumbent service. How to mitigate the unreliability caused by the inherent "secondary" characteristic for SG communications in license-exempt bands remains to be solved. Cyber security is another serious challenge we will face. While new applications for SG systems and networks can improve its efficiency and reliability, they may also create vulnerabilities at the same time if not deployed to address the appropriate security concerns.

WSNs, which have the ability of pervasive sensing, are very important to the realization of SG. Although WSNs bring significant advantages over traditional communication networks, the properties of WSNs also impose unique communication challenges. There are several technical challenges for using WSNs in SG, including reliability and latency requirements, packet errors and variable link capacity, harsh environmental conditions, and resource constraints. In order to tackle these challenges, a good link quality metric and a statistical characterization of the real-world wireless channel in power system environments are important to construct a reliable and energy-efficient communication system in a WSN-based SG.

Mainly for historical reasons, the existing electrical grid consists a large amount of isolated islands of transmission and distribution micro-grids. These micro-grids are often with very limited communications among them because of their different communication protocols. Hence, while dedicating to investigate new SG technologies, we should not compromise the interoperability of the communication systems in traditional grids and SGs.

Some of the above challenges have been intensively discussed recently, but there is still a long way to go to find the optimized solutions for them. We must know that these challenges should be carefully tackled, since the benefits behind them are significant. With those great opportunities and challenges that SG can present to us, the future trends and directions of the SG research can be summarized as follows.

1) To propose interoperable SG communication standards and protocols;
2) To incorporate TVWS into SUN applications and enhance its service reliability;
3) To incorporate SG communication applications into the regulations of license-exempt band and enhance its service reliability;
4) To enhance cyber security for SG applications;
5) To develop more SG applications for DR, as shown in Fig. 1;
6) To make the governmental policies and regulations more friendly to SG communication applications.

V. Conclusion

In this paper, the key communication technologies for SG have been identified and their state-of-the-art research activities were reviewed. In addition, the issues on security and wireless sensor networks for their applications in SG have also been discussed. Future SG should comprise intelligent monitoring systems to keep a track of all electricity flows and must be flexible and resilient to accommodate new communication techniques. To achieve these goals, WSNs will certainly play an important role in SG. The issues on evolutional path toward SG communications and future trends of SG research are also identified in this paper. With more emerging technologies, SG should preserve its interoperable and secured communications within a hybrid system where both new and legacy grids coexist. Therefore, SG communication systems should be built up on open protocols with security.

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Ruofei Ma received the B.S. and M.S. degrees in information and communication engineering from Harbin Institute of Technology (HIT), Harbin, China, in 2008 and 2010, respectively. He is currently working toward the Ph.D. degree in information and communication engineering at at School of Electronics and Information Engineering, HIT.

His current research interests include wireless communication and networking technologies in smart grid, and coexistence issues of IEEE 802.15.4g (smart utility networks, SUNs) and other wireless networks on the unlicensed bands.

Hsiao-Hwa Chen (F'10) obtained his B.Sc. and M.Sc. degrees from Zhejiang University, China, and a Ph.D. degree from the University of Oulu, Finland, in 1982, 1985 and 1991, respectively.

He is currently a Distinguished Professor in the Department of Engineering Science, National Cheng Kung University, Taiwan.

Dr. Chen is the founding Editor-in-Chief of Wiley's *Security and Communication Networks Journal* (http://www.interscience.wiley.com/security). Currently, he is also serving as the Editor-in-Chief for IEEE WIRELESS COMMUNICATIONS. He is a Fellow of IET and a Fellow of BCS.

Weixiao Meng (SM'10) obtained his B.Sc., M.Sc., and Ph.D. degrees from Harbin Institute of Technology (HIT), Harbin, China, in 1990, 1995, and 2000, respectively.

He is currently a Professor at School of Electronics and Information Engineering, HIT. From 1998 to 1999, he worked at NTT DoCoMo on adaptive array antenna and dynamic resource assignment for beyond 3G as a Senior Visiting Researcher.

Dr. Meng is a Senior Member of China Institute of Electronics, China Institute of Communication, and Expert Advisory Group on Harbin E-Government. He has been an editorial board member for Wiley's *WCMC Journal* since 2010.