Spectrum Sharing in Cognitive Radio Enabled Smart Grid: A Survey

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Abstract. Smart grid is viewed as the next-generation electric power system to meet the demand of communication and power delivery in an intelligent manner. With large scale deployment of electric power systems, smart grid faces the challenge from large volume data and high spectrum needs. To realize efficient spectrum utilization in the fact of spectrum scarcity, cognitive radio (CR) is involved in smart grid and generates the cognitive radio enabled smart grid. Cognitive radio enabled smart grid coexists with primary network by employing CR technologies including spectrum sensing, sharing, access and so on. Spectrum sharing is an important CR technology which realizes network coexistence without harmful interference through radio resource allocation. In this paper, a comprehensive survey is provided to review the state-of-the-art researches on spectrum sharing in cognitive radio enabled smart grid. We identify the network architecture and communication technology issues of cognitive radio enabled smart gird, and illustrate the investigation of spectrum sharing in different radio resource dimensions to highlight the superiority in efficient spectrum utilization.

Keywords: Smart grid · Cognitive radio · Spectrum sharing

1 Introduction

Smart grid has been regarded as the most promising next-generation power grid by overcoming the challenges faced by conventional power grid including increasing power demands, old electric power facilities and decreasing reliability. Through involving a series of advanced information technologies, smart grid supports two-directional communication between utilities and customers, and has the superiorities of self-monitor, self-healing and energy storage [1]. Compared with traditional power grid, smart grid realizes the efficiency, reliability and security of the electrical power grid system [2].

The features and superiorities of smart grid rely on effective communication between utilities and customers to exchange control and consumption information. Therefore,

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smart grid communication plays an important role in the design and construction of smart grid [3]. Wired communication and wireless communication are two categories of communication technologies employed in smart grid. For wired communication, powerline communication utilizes the electric power wiring to realize communication function. Compared with wired communication, wireless communication is more flexible and economical for the deployment of an electric power system [4]. Zigbee, WiMAX and cellular communication are common wireless communication manners in smart grid. With large scale deployment of electric power systems, wireless communication technologies in smart grid face the challenge from large volume data and high spectrum needs. The traditional spectrum allocation manner is fixed to licensed users, which is not efficient any more.

Cognitive radio (CR) is a promising technology applied in smart grid to achieve efficient utilization of spectrum resources [5]. There are two types of communication networks: the primary network and secondary network. The primary network is the licensed user of spectrum resources, and the secondary network is unlicensed user and has lower priority than the primary network to access the spectrum resources. Different from fixed spectrum allocation manner, CR allows secondary network to sense the spectrum of primary network, share and access the spectrum of primary network without harmful interference. In CR enabled smart grid, the smart grid communication opportunistically accesses the communication resources of other wireless applications. Through the exploitation of communication resources, the CR enabled smart grid can utilize the spectrum in an efficient manner to support large volume data and high spectrum needs in smart grid.

Spectrum sharing is an essential technology of CR. When spectrum is occupied by primary network, the secondary network applies spectrum sharing technology to share the spectrum with primary network without harmful interference to primary network. In CR enabled smart grid, smart grid communication can access spectrum of other communication systems through spectrum sharing. In the view of resource dimensions, existing researches of spectrum sharing in CR enabled smart grid can be divided into spectrum sharing in time, frequency, space, power and code domains.

- Spectrum sharing in time domain allows smart grid to communicate when spectrum is not occupied by primary network, which is spectrum sensing technology of CR [6].
- Spectrum sharing in frequency domain allocates spectrum resources to avoid harmful interference to primary network [7].
- Spectrum sharing in space domain, also known as spatial spectrum sharing, allows secondary network to access the spectrum of primary network in specific geographic regions [8].
- Spectrum sharing in power domain allocates the transmitted power of secondary network to keep the interference to primary network below interference threshold [9].
- Spectrum sharing in code domain allows secondary network to utilize different code words from primary network to access spectrum [10].

There are several related survey papers about CR enabled smart grid. The survey in [11] briefly illustrates how to apply CR in smart grid communication and realize the operation and control of smart grid. In [1], a comprehensive overview is provided including network architecture of CR enabled smart grid, spectrum sensing mechanism and network protocol progress. An up-to-date review on standards and security issues is offered in [12] for smart grid based on cognitive radio technologies. To the author's knowledge, there are no surveys paying attention to spectrum sharing technology in CR enabled smart grid. In this survey, a comprehensive survey is provided which illustrates the architecture and technologies of CR enabled smart grid and highlights spectrum sharing technology from different resource dimensions.

2 Cognitive Radio Enabled Smart Grid

2.1 Architecture and Paradigm

Architecture. CR enabled smart grid has three communication architectures including cognitive home area network (HAN), cognitive neighborhood area network (NAN) and cognitive wide area network (WAN).

A cognitive HAN is designed to perform commissioning and control functions through adopting cognitive radio technologies in a HAN [13]. By employing cognitive home gateway (HGW), a cognitive HAN contains the ability of self-configuration and self-adaptation. A cognitive HAN performs the function of commission by identifying the appearance and leave of devices, constructing a communication network, and maintaining the network link. Cognitive radio technologies guarantee a HAN not to conflict with the primary communication.

A cognitive NAN is treated as the intermediate node between cognitive HANs and cognitive WANs. By employing a cognitive NAN gateway (NGW) as the center, a cognitive NAN firstly connects a number of HANs to collect consumer information such as power consumption, then transmits the consumer information to the control center through cognitive WAN [14]. With cognitive radio technologies, cognitive NANs can access the spectrum of other communication networks on the premise of communication security.

As the upper tier of the SG communication architecture, a cognitive WAN is constructed by several cognitive NANs and conducts communication between cognitive NANs, smart grid devices and substations. On one hand, a cognitive WAN utilizing cognitive radio technologies communicates with cognitive NANs to collect consumer information and transmit control information. On the other hand, a cognitive WAN is connected to core network through licensed communication fashions such as cellular network and wired network to guarantee communication capacity and security [15].

Figure 1 briefly shows the relationship among three communication architectures. Cognitive HANs are responsible for collecting consumer data and transmitting the data to cognitive NANs through HGWs. Each cognitive NAN is connected with several cognitive HANs and responsible for transmitting the data from cognitive HANs to the control center. A cognitive WAN is constructed by several cognitive NANs, which collects consumer data via cognitive radio technologies and transmits to control center via licensed communication fashions.

Paradigm. According to the spectrum access fashion, there are three kinds of communication paradigms for CR enabled smart grid: underlay, overlay and interweave [16].

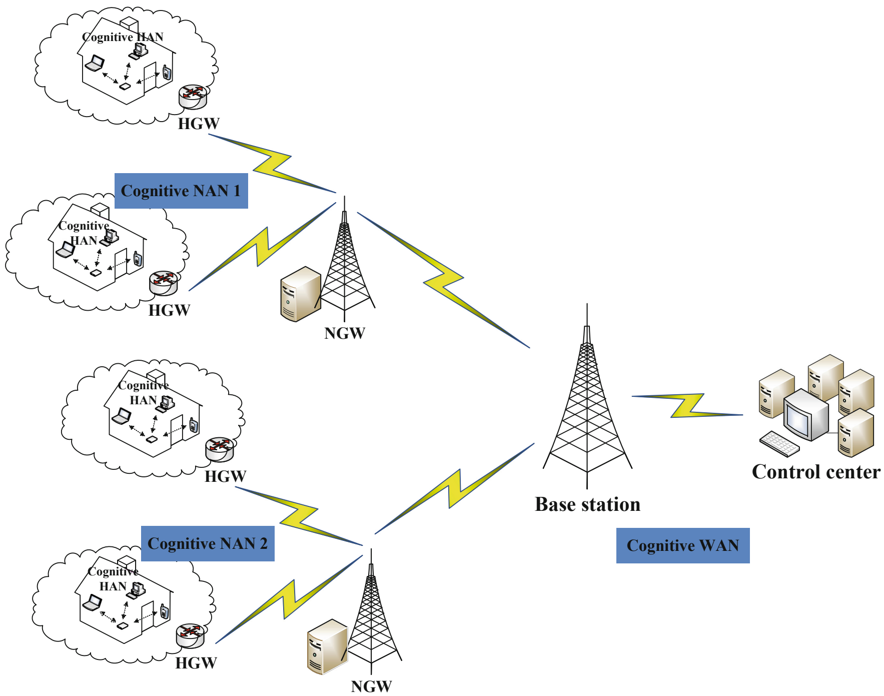

Fig. 1. Architectures of CR enabled smart grid.

The choice of communication paradigms is mainly determined by occupancy of spectrum, interference threshold of primary network, cost efficiency of CR enabled smart grid.

For underlay communication paradigm, CR enabled smart grid shares the spectrum with other communication systems simultaneously. Through adjust transmitting parameters, CR enabled smart grid controls the interference to primary network below a certain interference threshold depending on the performance requirement of primary network. The underlay communication paradigm is suitable for HAN due to the characteristics of low data rates and short ranges [1].

In overlay communication paradigm, CR enabled smart grid has prior information of primary network such as transmit pattern and strategy, mitigates interference from primary network and relays primary data to the receiver in primary network. Through identifying primary network and relaying primary data, CR enabled smart grid cooperates with primary network and thus achieves high security and data rates.

Interweave communication paradigm utilizes spectrum sensing technology to make CR enabled smart gird access spectrum which is not occupied by primary network. When spectrum is occupied by primary network, CR enabled smart grid as the secondary network continues to monitor the spectrum so as to communicate when primary network stops transmitting. Like underlay communication paradigm, interweave communication paradigm is suitable for HAN.

2.2 Standardization

For cognitive radio technologies and smart grids, there have been a lot of efforts to promote the standardization. For instance, IEEE 802.22 is the first standard for cognitive radio communication, which specifies how wireless regional area networks (WRANs) can operate in TV white space (TVWS) [5]. A lot of international organizations are driving the standardization of smart grid such as U.S. National Institute of Standards and Technology and European Union Technology Platform [17].

The standardization of CR enabled smart grid is still on the way. IEEE 802.15.4 g [18] and IEEE 802.15.4e [19] are two standards for CR enabled smart grid on TVWS. As a supplement standard of IEEE 802.15.4, IEEE 802.15.4 g provides the physical layer design of CR enabled smart grid. IEEE 802.15.4e is another supplement standard of IEEE 802.15.4, which specifies the medium access control layer design of CR enabled smart grid.

2.3 Application

CR enabled smart grid is flexible to be employed in licensed or unlicensed spectrum with different architectures and paradigms. Meanwhile, it's feasible to adjust the transmitting parameters of CR enabled smart grid to satisfy different quality of service (QoS) requirements of both CR enabled smart grid and primary network. Based on the advantages above, CR enabled smart grid has various applications [12].

According to QoS requirements of smart grid, the applications are divided into three categories: robust-aware application, real-time application and security-aware application. Table 1 shows the specific applications of CR enabled smart grid.

Table 1. Applications of CR enabled smart grid

Application	QoS requirement	Example
Robust-aware application	High stability and reliability of power grid system	Distributed generation system [20]; Automatic generation control [21]
Real-time application	High transmitting speed	Real-time pricing and demand response management [22]
Security-aware application	Safety, reliability, and security of smart grid	Wide area situation awareness [12]

3 Spectrum Sharing

3.1 Motivation and Classification

Spectrum sharing is an essential technology of CR enabled smart grid. With the large scale deployment of smart grid and increasing demand for spectrum resources, spectrum sharing can support large scale access to spectrum and high spectral efficiency through sharing the spectrum of other communication systems.

As classified by communication paradigms, spectrum sharing is divided into three categories: underlay, overlay and interweave spectrum sharing. Underlay spectrum sharing enables smart grid to transmit secondary signals when primary spectrum is occupied by primary network. In overlay spectrum sharing, secondary network has prior information of primary network, utilizes the prior information to mitigate interference from primary network, and transmits primary signals as a relay to generate cooperation relationship with primary network. For interweave spectrum sharing, smart grid senses the occupation of spectrum, opportunistically shares the spectrum of primary network when the spectrum is not occupied.

When classified by resource dimensions, existing research of spectrum sharing in CR enabled smart grid can be divided into spectrum sharing in time, frequency, space, power and code domains.

3.2 Spectrum Sharing in Resource Dimensions

Spectrum sharing in time domain, that is spectrum sensing technology, allows smart grid to communicate when spectrum is not occupied by primary network. The survey paper [1] provides a comprehensive survey of spectrum sensing technologies employed in smart grid. The commonly used spectrum sensing methods in CR enabled smart grid are energy detection, matched filter and feature detection. The study in [6] employs energy detection method to enable spectrum utilization of smart grid, where the spectrum sensing time of CR enabled smart grid is optimized under the constraint of protection on primary network. [23] also pays attention to the optimization of spectrum sensing time, which researches a cognitive radio based switching procedure to optimize the spectrum sensing time. The research in [24] utilizes spectrum sensing combined with channel switching technologies to realize high reliability and timeliness, where the spectrum sensing time is optimized to reduce the packet loss and delay time. In [25], spectrum sensing method is improved by proposing a multi-objective approach which satisfies the optimization of spectrum sensing time and communication cost.

Spectrum sharing in frequency domain allocates spectrum resources to avoid harmful interference to primary network. The research in [7] allocates spectrum resources to multiple secondary users in CR enabled smart grid with the aid of clustering technology under practical constraints. In [26], the authors consider the requirements difference of secondary users including serving priority and spectrum bandwidth, and employ binary particle swarm optimization method to optimize the spectrum allocation problem. An improved spectrum allocation method of [26] is proposed in [27], which considers the difference of secondary user priority and spectrum idle time, and utilizes hidden Markov model to make the spectrum allocation decision. Markov model is also utilized for spectrum allocation in [28], where a spectrum allocation based spectrum sharing scheme is proposed based on Markov chain model. In [29], a spectrum allocation scheme is proposed to allow hierarchical data transmission in CR enabled smart grid based on clustering technology considering spectrum availability and secondary user priority. The study in [30] concerns the optimization of spectrum allocation strategy in cognitive radio NAN gateway using differential pricing and admission control.

Spectrum sharing in space domain, also known as spatial spectrum sharing, allows secondary network to access the spectrum of primary network in specific geographic regions. In [8], a joint spatial and temporal spectrum sharing scheme is proposed for demand response management in cognitive radio enabled smart grid. The proposed scheme utilizes the geographic distribution difference of secondary users caused by large scale deployment of smart grid in a large geographic area. Traditionally, spectrum sensing and sharing performance of secondary users in different region is regarded as the same. The proposed scheme in [8] exploits the spectrum opportunities in joint spatial and temporal domain to improve the spectrum sharing performance in CR enabled smart grid.

Spectrum sharing in power domain allocates the transmitted power of secondary network to keep the interference to primary network below interference threshold. Several optimization methods can be employed to optimize the power allocation to secondary users [9, 31]. Iterative water filling is a conventional optimization method in power allocation, which utilizes the information of channel noise and interference to calculate the transmit power of each secondary user until convergence. Game theory is a common method used by spectrum sharing in power domain. In game theory, each secondary user is treated as a player in game, and plays with other players with a certain payoff until achieving Nash equilibrium. Genetic algorithm is suitable for the spectrum sharing problem whose optimal solution in closed form is hard to derive. For genetic algorithm based spectrum sharing, each secondary user is regarded as the chromosomes while the possible solutions are the genes inside a chromosome. The weakness of genetic algorithm is that it is difficult to get global optimum, even simulation is not guaranteed to be convergence.

Spectrum sharing in code domain allows secondary network to utilize different code words from primary network to access spectrum. In [4], spectrum sharing in code domain is investigated based on linear precoding technology, which enables the secondary users in CR enabled smart grid to share spectrum with primary network without harmful interference. Through deploying pre-coder and decoder, the interference among multiple secondary users and primary network is avoided when sharing the same spectrum to communicate. In [10], code division multiple access is utilized to realize the coexistence between CR enabled smart grid and primary network. By proposing a specific kind of orthogonal chip sequence allocation in spread spectrum communications, spectrum sharing is realized in code domain to improve the spectral efficiency of CR enabled smart grid.

4 Conclusion

Smart grid is the most promising next-generation electric power system to solve the problems of traditional power grid. Smart grid communication is an important function which is satisfied by wired communication and wireless communication. In the face of large volume data and high spectrum needs, fixed spectrum allocation fashion is not suitable for smart grid. By employing cognitive radio technologies, cognitive radio enabled smart grid can realize efficient spectrum utilization. Through adjusting transmitting parameters of cognitive radio enabled smart grid, spectrum sharing technology enables cognitive smart grid to share the spectrum resource with primary network while avoiding harmful interference to the primary network. In this survey paper, we have surveyed the architecture, paradigm, standardization and application of cognitive radio enabled smart grid. Moreover, we have illustrated the investigation of spectrum sharing in different radio resource dimensions. In conclusion, spectrum sharing is essential to improve network capacity and spectrum utilization in cognitive radio enabled smart grid.

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