Cognitive Radio for Smart Grids: Survey of Architectures, Spectrum Sensing Mechanisms, and Networking Protocols

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***Abstract*—Traditional power grids are currently being transformed into smart grids (SGs). SGs feature multi-way communication among energy generation, transmission, distribution, and usage facilities. The reliable, efficient, and intelligent management of complex power systems requires integration of high-speed, reliable, and secure data information and communication technology into the SGs to monitor and regulate power generation and usage. Despite several challenges, such as trade-offs between wireless coverage and capacity as well as limited spectral resources in SGs, wireless communication is a promising SG communications technology. Cognitive radio networks (CRNs) in particular are highly promising for providing timely SG wireless communications by utilizing all available spectrum resources. We provide in this paper a comprehensive survey on the CRN communication paradigm in SGs, including the system architecture, communication network compositions, applications, and CR-based communication technologies. We highlight potential applications of CR-based SG systems. We survey CR-based spectrum sensing approaches with their major classifications. We also provide a survey on CR-based routing and MAC protocols, and describe interference mitigation schemes. We furthermore present open issues and research challenges faced by CR-based SG networks along with future directions.**

***Index Terms*—Advanced metering infrastructure (AMI), communication architecture, cognitive radio network (CRN), smart grid (SG).**

I. Introduction

A. Motivation: Communication Needs of Smart Grid

CONVENTIONAL power grids are large interconnected networks that widely distribute energy from suppliers to consumers. The electric power only flows from the power generating stations to the consumers and information monitoring is handled only in the distribution networks that distribute electrical power within a city to the individual consumers. These power grids face new challenges, such as growing energy demands, aging infrastructure, emerging renewable energy sources, as well as reliability and security problems. To overcome these challenges, the Smart Grid (SG) paradigm has been introduced with a variety of state-of-the-art enabling information technologies [1]–[3]. These technologies cover the areas of embedded sensing, broadband wireless communication, pervasive computing, adaptive control, as well as automated and intelligent management. These SG technologies can achieve significant improvements in the efficiency, effectiveness, sustainability, reliability, security, and stability of the electrical grid [2], [3].

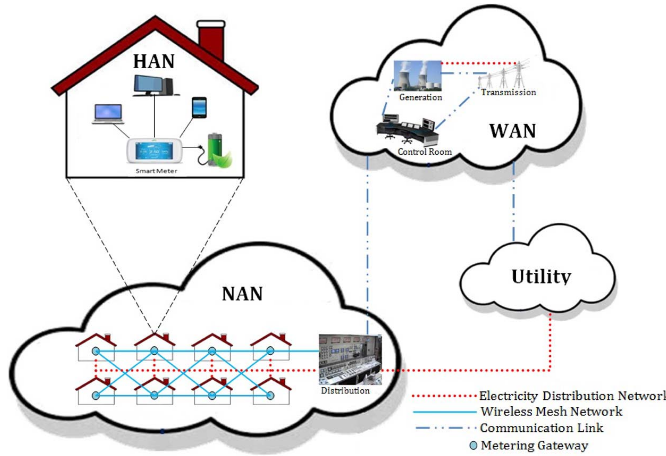

Fig. 1. Illustration of smart grid (SG) architecture with three major network types: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN).

Several features distinguish SGs from conventional power grids. These are supervisory control and data acquisition (SCADA), advanced metering infrastructure (AMI), i.e. smart meters, load balancing through real-time demand side management with respect to real-time energy pricing, fault-tolerance, remote meter reading, power quality, and detection of unauthorized usage [4]–[7]. Moreover, an SG benefits from self-healing, i.e., detection, isolation, and recovery from faults [8]. As illustrated in Fig. 1, an SG includes three main network types, namely Home Area Networks (HANs), Neighborhood Area Networks (NANs), and a Wide Area Network (WAN). The acronyms in this survey are summarized in Table I.

Unreliable communication and monitoring, inefficient routing and dispensation of electricity and non-smart customers appliances are prominent sources of energy wastage in traditional power systems. It is very difficult to store generated electrical energy in the traditional power grids. This problem can be mitigated by SGs that generate electricity closely matching the

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TABLE I
LIST OF ACRONYMS AND CORRESPONDING DEFINITIONS

Acronyms	Definitions
AMI	Advance Metering Infrastructure
AP	Access Point
CM2M	Cognitive Machine-to-Machine
CPE	Customer-premises Equipment
CR	Cognitive Radio
CRN	Cognitive Radio Network
CR-WSN	Cognitive Radio based Wireless Sensor Network
DER	Distributed Energy Resources
DRM	Demand Response Management
DSA	Dynamic Spectrum Access
DSM	Demand Side Management
EIRP	Effective Isotropically Radiated Power
FAN	Field Area Network
FBS	Femtocell Base Station
HAN	Home Area Network
HGW	Home Area Network Gateway
ISM	Industrial, Scientific and Medical
M2M	Machine-to-Machine
MAC	Medium Access Control
MBS	Macrocell Base Station
MU	Macrocell User
NAN	Neighborhood Area Network
NGW	Neighborhood Area Network Gateway
PLC	Power Line-based Communication
PU	Primary User
QoS	Quality of Service
RTP	Real-time Pricing
SCADA	Supervisory Control and Data Acquisition
SCBS	Small Cell Base Station
SG	Smart Grid
SU	Secondary User
SUN	Smart Utility Network
TVWS	TV White Space
TVBD	TV Band Device
WAN	Wide Area Network
WCD	Wireless Cloud Data
WRAN	Wireless Regional Area Network

demand [9]–[11]. Optimized electricity usage, real-time power pricing, self-healing, power consumption scheduling, and many other decisions can be made according to energy demands [4]. These decisions can contribute to achieving a balance between power generation and usage to significantly improve the power quality and efficiency of the electrical grid. Incorporating intelligent electronic devices, such as intelligent sensors and smart meters, can support various network functions throughout the power generation, storage, transmission, and distribution domains [12].

A number of communication technologies can be adopted for the communication needs of the SG. Among wired communication technologies, powerline communication is a natural candidate, as it utilizes the existing wiring infrastructure for distributing the electrical power. However, electromagnetic interference is a major challenge for powerline communication [13], [14]. The continuous developments in wireless networking technology make wireless networking suitable for many SG applications, eliminating the installation of wires. Wireless networks are particularly preferred for short-distance connections with comparatively low data rates [2]. With proper design and implementation of sensor nodes [15]–[17], wireless sensor networks (WSNs) can support several SG applications. Conventional wireless networks are typically regulated by a fixed spectrum assignment policy that assigns the spectrum to license holders on a long-term basis for large geographical regions. This fixed spectrum allocation can result in inefficient spectrum utilization. Cognitive radios (CRs) operating on the principle of Dynamic Spectrum Access (DSA) may be a suitable option to solve these spectrum inefficiency problems [18]. CRs use the existing spectrum through opportunistic access to the licensed bands without interfering with the licensed users. CRs determine the spectrum portions unoccupied by the licensed users known as spectrum holes or white spaces, and allocate the best available channels for CR communication [19], [20].

After identification of available spectrum holes, the spectrum utilization can be improved through joint spatial and temporal spectrum sharing. SG applications, especially demand response management, can benefit from joint spatial and temporal spectrum sharing [21]. Machine-to-machine (M2M) communication is an emerging paradigm for providing ubiquitous connectivity between devices to communicate autonomously without human intervention. However, a high number of connected devices can heavily congest the spectrum in existing communication networks. CR technology may be a suitable option for mitigating the potential spectrum shortage arising from M2M communications in the SG [22].

B. *Contribution of This Survey Article*

While a few overview articles have outline some selected aspects of CR communication in the SG [23]–[25], to the best of our knowledge, there is no prior survey that comprehensively covers CR-based SGs. In this survey, we comprehensively cover architectures, applications, spectrum sensing approaches, MAC and routing protocols, interference mitigation, as well as power and energy related schemes in CR-based SGs. In summary, we make the following contributions:

- We provide an in-depth survey of architectures for the CR-based SG.
- We identify potential applications which can benefit from CR-based SG architectures.
- We provide detailed surveys of strategies and architectures for integrating and employing CR communication in the SG.
- We survey spectrum sensing approaches as well as routing and MAC protocols, in addition to providing details about interference mitigation schemes in the CR-based SG.
- We outline open issues, challenges, and future research directions for CR-based SG systems.

C. *Review of Related Survey Articles*

Our present survey on SGs is different from previous surveys as we comprehensively cover the area of CR-based SG systems. There is an extensive literature of prior surveys that focus on either CR communications or SG systems in isolation; however, to the best of our knowledge there are no prior detailed surveys that cover the intersection of CR communications and SG systems.

Surveys focused on CR communications in isolation have considered the general principles of CR communications [20], [26]–[30] as well as CR network structures [31]–[37]. Studies on spectrum occupancy modeling and spectrum sensing have been surveyed in [38]–[44], while mechanisms for spectrum access and radio channel resource assignment have been covered in [45]–[57]. Routing protocols in CR networks have been surveyed in [58], while the security and secrecy aspects of CR communications have been surveyed in [59]–[64]. Several surveys have specifically focused on the benefits of CR wireless communications for improving reliability [65], energy efficiency [66]–[72], as well as emergency and public safety services [73]–[75].

Purely SG focused surveys have presented general overviews of the SG concept [11], [76]–[79] as well as the general communications needs and applications in the SG [80]–[82] and SG communication architectures [2], [83]–[88]. Mechanisms for data collection and networking of SG sensors have been surveyed in [89], while information management strategies have been reviewed in [90]. Another group of surveys has focused on SG pricing methods [91], energy efficiency [92], and power demand forecasting [93], [94], as well as the control of renewable energy in the SG [95]. Security issues in the SG have been surveyed in [82], [96]–[98], while privacy-aware metering is considered in [99]. Simulation methods for SG analysis have been reviewed in [100], [101].

A few surveys on the SG have briefly noted the possibility of supporting SG through CR communications, without delving into the details of CR-based SG systems. In particular, the survey [5] on cloud computing in the SG briefly mentions CR networks. The survey [6] gives a brief overview of the general principles of CR applications in the SG without a detailed survey of CR mechanisms for the SG. The overview article [11] on communications in the SG briefly notes the potential of CR for supporting SG communications. The survey [12] on the neighborhood area network (NAN), a component of the SG network structure (see Section II-B), briefly notes CR as a potential NAN networking mechanism. A case study of CR-based wireless sensor networks (WSNs) in the SG for a specific implementation in Pakistan has been presented in [23]. A review of Smart Utility Networks (SUNs), a specific form of an SG network, operating in TV White Space (TVWS), which is a specific CR communications technique, has been presented in [24]. The brief article [25] pioneered the survey of CR-based SG systems by giving brief overviews of the 2012 state-of-the-art in motivations and applications of CR communications in the SG as well as CR architectures and spectrum management for SG applications. Complementary to [25], our present survey gives a comprehensive up-to-date review of CR-based SG communications, including spectrum sensing mechanisms and interference mitigation schemes, as well as routing and MAC protocols.

D. Article Structure

The remainder of this paper is organized as follows: In Section II, we give a brief overview of CRNs and the SG. In Section III, we present case studies to illustrate how CR can be used in SG applications. Section IV details potential CR-based applications in the SG. Section V presents the strategies for integrating CR-based communication into the SG. Section VI surveys CR-based SG architectures. We survey CR-based spectrum sensing approaches and CR-based MAC protocols in Sections VII and VIII. Sections IX and X cover routing protocols and interference mitigation schemes for the CR-based SG. Security and privacy related issues are discussed in Section XI. Power and energy related schemes for the CR-based SG are the focus in Section XII. Section XIII describes open issues and challenges, while Section XIV concludes the paper.

II. Cognitive Radio and Smart Grid: An Overview

A. Cognitive Radio Networks

Traditionally, wireless networks are regulated by a spectrum assignment policy which makes fixed assignments of spectrum to license holders on a long term basis for large geographical regions. This fixed assignment under-utilizes spectrum with typical utilization levels ranging from 15% to 85% [20]. Dynamic Spectrum Access (DSA) may be a promising option to solve these spectrum inefficiencies. A DSA network is implemented with the help of cognitive radios (CRs). CRs use the existing spectrum through opportunistic access without interfering with the licensed users. CRs determine the available portion of the spectrum known as spectrum hole or white space. The best available channel is then used by the CR users if there are no licensed users operating in these licensed bands [20].

A Cognitive Radio Network (CRN) is a network comprising of CR devices that are equipped with cognitive capability and reconfigurability, and can change their transmitter parameters based on interactions with the environment in which they operate [102]. In a CRN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed/legitimate/authorized users, which have the license to operate in a prescribed spectrum band accessing the primary base station. Secondary users (SUs), which are also referred to as "CR users," or as "CRs" for brevity, are unlicensed users without a spectrum license. These CR users need additional functionalities to share the licensed spectrum band. SUs look for opportunistic access to both licensed and unlicensed spectrum and are allowed to operate only if no interference is caused for licensed PUs [20], [103].

There are four major functions for cognitive radios: 1) Spectrum sensing, i.e., detecting unused spectrum a.k.a spectrum holes or white spaces and the presence of the PUs [104]; 2) Spectrum management which is the selection of the best available channels in terms of the received signal strength, interference, energy efficiency, transmission power, number of users, QoS, and security requirements; 3) Spectrum mobility maintains seamless communication and vacates the channel when a licensed PU is detected through a spectrum handoff, i.e., changing the physical regions traversed by the existing path or switching to a new unused spectrum band; 4) Spectrum sharing coordinates access by several CRs and focuses on power allocation [20], [25].

There are three CR paradigms: Interweave CR communication, Underlay CR communication, and Overlay CR communication [20], [105]. In the interweave paradigm, an SU is allowed to use spectrum resources only if no PU is active. In case of PU presence, the PU activities are continuously monitored to avoid any interference due to SU transmissions. In the underlay paradigm, SUs transmit with low power irrespective of PU activity. The transmit power of the SUs is so low that it lies below the noise threshold of the PU communication. The underlay and interweave CR-based SG communication paradigms have typically low data rates and short ranges, making them suitable for the HAN.

Overlay CR-based SG communication utilizes code books and messages to identify the PU, thus mitigating the interference. CR user can transmit at any power and the interference to non-cognitive users can be offset by relaying the non-cognitive users' messages. These methods satisfy reliability, security and high data rates, and thus are suited for NANs and WANs.

B. Smart Grid

Replacing traditional power grids, the smart grid (SG) is envisioned to be the next-generation electric power system. The SG will incorporate diversified renewable energy resources in addition to supporting current power systems. Smart control centers will utilize modern communication technologies to monitor and interact with remote smart electric devices in real time. The SG has functional domains including power generation, transmission, and distribution by service providers to customers (consumers). In the current top-down layer approach of the power grids, the communication flow is uni-directional from the service provider to the consumers. The SG will feature a bi-directional communication flow between service provider and consumer. The consumer can benefit from real-time pricing through demand response management, thereby facilitating energy conservation and cost-effectiveness [2], [6], [106].

As illustrated in Fig. 1, a smart grid network typically consists of three segments (subnetworks): Home Area Network (HAN), Neighborhood Area Network/Field Area Network (NAN/FAN), and Wide Area Network (WAN). The HAN connects smart meters with on-premise appliances, plug-in electrical vehicles, and distributed renewable sources, such as, solar panels. The NAN is the second layer of the communication architecture. The NAN transfers information among premises via smart meters and an aggregation point or network gateway. The gateway is often a power substation, a utility pole-mounted device, or a communications tower. The NAN collects the metering and service information from multiple HANs and transmits this information to the data collectors that connect the NANs to the upper layer of the communication architecture, i.e., the WAN. The WAN serves as backbone for communication between network gateways or aggregation points, NANs, SG substations, distributed grid devices, and the utility data center. Both wireless and wired communication technologies can be used for meeting the communication needs of the grid elements in the WAN [25], [107].

In addition to the three layers (i.e., HAN, NAN, and WAN), we will also focus on hybrid architectures, particularly on advanced metering infrastructures (AMIs). An AMI is a collection of several smart meters, located at customer premises capable of communicating with a local access point. This local access point is further connected to a control center for storage, processing, and management of meter data [108], [109].

C. Unique Challenges of SG Communications

This section summarizes the main unique challenges and features of the communication required for SG applications. Communication in the SG environment often faces harsh wireless signal propagation conditions, e.g., through high power disturbances [110]. At the same time, many SG applications require high communications quality of service, e.g., demand response applications [9] require reliable communication. These unique challenges of SG communications have prompted the development of CR communications mechanisms that are tailored for the SG, as surveyed in the core sections of this article.

1) Harsh Wireless Communication Conditions: As illustrated in Fig. 1, the SG encompasses a wide range of settings from inside private homes to outdoor areas in a neighborhood, and on to electrical power distribution stations. These settings feature challenging wireless communication conditions. A key challenge is wireless communication in the vicinity of electrical power equipment, which often contains coils. The electrical wiring loops in coils can act as antennas that radiate electromagnetic waves which can interfere with wireless communication [111]. In particular, impulse noise and high power transients, e.g., from switching power electronics components, can disrupt wireless communications [14], [15], [112]–[117]. Moreover, the wireless communication from indoor appliances to outdoor meters can suffer from high path losses [118]–[120].

2) Application Demands for Reliable and Low-Delay Communication: Several key SG applications require stringent communications quality of services [81], [82], [121]. For instance, demand response control [9] adjusts the operation of electrical appliances in homes and businesses to reduce demands on the power grid. Specifically, in direct load control [106], the power utility directly controls the power consumption, i.e., the electrical appliances, in the homes. Reliable bi-directional communication between the homes and the control center of the utility is required for proper functioning of the direct load control [122], [123]. As another example, monitoring and control of the power grid critically depend on the low-delay delivery of real-time data [124]–[126].

3) Heterogeneous SG Network Structure and Traffic: The power grid delivers electricity to areas with highly heterogeneous population densities, ranging from sparsely populated rural areas to densely populated urban areas. The SG communication network similarly has to cover these highly heterogeneous service areas [121]. Thus, CR-based communication mechanisms for the SG should accommodate a wide range of network structures, ranging from sparsely populated and connected networks to densely populated and connected network structures. At the same time, the network traffic from SG applications covers a vast range of traffic (bit) rates, ranging from tens or hundreds of bytes at periodic (e.g., few seconds or minutes) intervals to high bit rates for applications involving multimedia [81], [82], [127].

D. Motivations for Employing CR in the SG

CRNs have the potential to flexibly support a wide range of communications applications and may be a good choice for many of the communication needs of SG systems [3], [6], [128], [129].

In this subsection, we outline some of the main motivating use cases for employing CR communications in the SG:

- Various radio systems, such as Zigbee, Bluetooth, and WiFi, operate in the 2.4 GHz license-free Industrial, Scientific, and Medical (ISM) frequency band. At the same time, domestic appliances may produce strong electromagnetic waves. In addition, the harsh electromagnetic interference from electrical power components, see Section II-C1, degrades wireless channel conditions. Due to economic reasons, SG meters in a HAN operate usually in the 2.4 GHz ISM band. The interference in the ISM band in conjunction with potentially multiple meters competing for data transfer will likely endanger reliable SG communication. However, parameter-adaptive CRs may flexibly bypass the interference in HANs to achieve reliable SG meter communication [25], [130].
- The collection and transmission of the large volumes of data related to electrical energy poses a significant challenge for existing communication networks. CR-based SG networks can help to efficiently collect and transport the large data volumes while improving spectrum utilization.
- The SG communications architecture covers home areas, neighborhood areas, and wide areas. Intelligent CRs with hardware reconfigurability and context awareness can help manage the communication within each subarea and the communication across the different service ranges.
- CR transmission over white spaces can provide dedicated low-latency communication links for time-sensitive SG data [3], [131], [132].
- CRs may reduce power consumption (and thus operating cost) through sensing the environment and adaptively adjusting transmission power levels.
- The vacant TV spectrum, referred to as TV White Space (TVWS), has reduced congestion and better indoor signal propagation compared to the unlicensed 2.4 GHz band. The power consumption is typically also low at the lower frequencies of the TVWS [133], [134]. The incorporation of CRNs that reuse vacant TVWS can provide high bandwidths in AMIs and NANs/FANs.
- Establishing CR-based links with the IEEE 802.22 standard in SG networks does not require initial capital investment in the licensed spectrum as the long range (up to 100 km) of IEEE 802.22 WRANs, see Section II-F, reduces the number of required base stations [10], [11]. In WANs, there are typically many sensors for wide area monitoring along with meters dispersed over wide areas, making data collection difficult. CR WAN architectures based on IEEE 802.22 WRANs can readily support the WAN data collection [86]. Table II compares IEEE 802.22 with various wireless communication technologies considered for the SG [81].

TABLE II
COMPARISON OF CANDIDATE WIRELESS COMMUNICATION TECHNOLOGIES FOR THE SMART GRID

Standard/protocol	**Data rate**	**Range**
Z-Wave	40 kbps	Up to 30 m
Bluetooth 802.15.1	721 kbps	Up to 100 m
ZigBee	250 kbps	Up to 100 m
ZigBee Pro	250 kbps	Up to 1600 m
WiFi 802.11x	2–600 Mbps	Up to 100 m
WiMAX 802.16	75 Mbps	Up to 50 km
Cellular 2G	14.4 kbps	Up to 50 km
Cellular 2.5G	144 kbps	-
Cellular 3G	2 Mbps	-
Cellular 3.5G	14 Mbps	-
Cellular 4G	100 Mbps	-
Satellite Internet	1 Mbps	100–6000 km
IEEE 802.22 WRAN	18 Mbps	30–100 km

- In case of TVWS, the network gateways and smart meters remain fixed and require up to 4W EIRP (effective isotropically radiated power) transmission power for operation in the fixed mode. The high transmission power and superior TV band propagation characteristics result in better access to all the smart meters at one or two hops. The vast availability of TVWS channels in rural areas could mitigate the spectrum shortage [107].
- Demand response management (DRM) [9], e.g., through multi-price energy meters and load shedding, is an important SG feature. However, DRM is only possible if reliable and timely consumption information is relayed to control centers. Traditional communication options may not be available all the time but employing CR schemes can secure efficient demand response management [128].
- Future SGs will likely encompass distributed generation power plants, such as solar cells and micro-turbines that are often in remote areas. The successful usage of electrical power from such remote distributed plants will greatly depend on ensuring the electrical power quality. Satisfying power quality typically requires collaboration among different SG components. This collaboration needs a flexible and scalable communication technique and CRs are one promising candidate [128], [135].
- Power outages and low power quality have severe financial impact. One main reason for these problems is the weak monitoring of power systems. As power systems may span over large areas, efficient communication mechanisms with good performance characteristics, i.e., sufficiently high data rate, low delay, and low probability of error are desired at a low cost. Incorporating monitoring devices and sensors with cognitive capabilities may help in reducing power outages and increasing power quality [128], [135].

E. Why Use CR Instead of Other Communication Technologies?

Both wired and wireless communication technologies are typically adopted in the SG. The selection of a communication technology depends on a number of factors, such as number

TABLE III
NOTABLE FEATURES OF COMMUNICATION TECHNOLOGIES FOR THE SMART GRID

Standard/ Protocol	**Advantages**	**Disadvantages**	**Licensed/ Unlicensed Spectrum Operation**	**Suitable SG Architecture Layer**	**Applications Areas in SG**
ZigBee	16 channels with 5 MHz of bandwidth in the 2.4 GHz band; Low power usage; Low complexity; Low deployment cost	Limited battery energy supply; Short range; Low data rate; Low processing capabilities; Interference with appliances utilizing license-free ISM frequency band, including IEEE 802.11 WLANs, WiFi, Bluetooth and Microwave	Unlicensed	HAN; AMI	Smart lightning; Energy monitoring; Home automation; Automatic meter reading
Bluetooth	Low power usage	Short range; Low data rate; Weak security; Prone to interference from IEEE 802.11 WLAN	Unlicensed	HAN	Home automation
Mobile Broadband Wireless Access	High bandwidth; High mobility; Low latency	Moderate data rate; Communication infrastructure is not readily available; High cost	Licensed	NAN; WAN	Broadband communication for plug-in electric vehicles, Wireless backhaul for electric grid monitoring and SCADA systems
Digital Microwave Technology	High data rate; Long range (up to 60 km)	Susceptible to precipitation; Multi-path interference; Additional latency due to encryption for security	Licensed	HAN; NAN	Alarms between DERs and distribution substation feeder
Wireless LAN	Robust; High speed point-to-point and point-to-multipoint communication; Minimum interference to out-of-band users; High data rate; Easy installation; Low cost	Slow data transmission due to electromagnetic interference in high voltage environment; Prone to RF interference; Limited availability of industrial-hardened wireless LAN equipment; Complex design for high reliability and availability	Unlicensed	HAN; NAN; AMI	Distribution substation automation and protection, Monitoring and control of DERs
WiMAX	High data rate; Long range	Network speed degrades with increasing distance; High power in licensed spectrum; Costly RF hardware; High frequencies do not penetrate through obstacles; Licensing required for low frequencies	Both	HAN; AMI	Wireless Automatic Meter Reading; Real-time pricing; Outage Detection and Restoration
Cellular Communications	Extensive data coverage; Improvement in QoS with recent growth in cellular technology	Range depends on the availability of cellular service; Delays due to call establishment; Large data exchange due to call drops; High monthly fees for individual connection; Expensive call costs	Licensed	HAN; NAN; AMI	SCADA; Monitoring and metering of remote DERs
Powerline Communication	High speed; Low cost due to already available infrastructure; Low latency; Widespread availability	Harsh and noisy medium; Low bandwidth; Signal quality is affected by the network topology, the number and type of the devices connected to the powerlines, and wiring distance between transmitter and receiver; Sensitive to disturbances	-	HAN; NAN; AMI	Automatic Meter Reading; Low voltage distribution
Digital Subscriber Lines	High speed; Low cost due to already available infrastructure; Low latency; High Capacity; High data rate; Long range; Widespread availability	Throughput depends on the distance of the subscriber from the serving telephone exchange; Lack of standardization; High installation cost for new connections; Requires regular maintenance; Not feasible in low-density area due to the high cost of installing fixed infrastructure	Licensed	HAN; NAN; WAN; AMI	Smart Grid city; Smart metering
Optical networks	High speed; Large bandwidth; High degree of reliability; Long range	High cost; Interoperability	Licensed	NAN; WAN	Physical network infrastructure
IEEE 802.22 CR WRAN	High data rate; Long range; Immunity to interference; Extensive data coverage; Adaptive power levels	Susceptible to disruptions due to PU activity; Security; Interoperability	Both	HAN; NAN; WAN; AMI	Smart metering ; SCADA, Demand Response Management; Wide Area Monitoring Control and Protection

of users/devices, network architecture, data type, environmental conditions, and cost. We would like to emphasize that although CR communication has been suggested for a wide range of SG applications, CR communication should not been considered as a “magic bullet” replacement of all other communication techniques. Instead, CR communication should be carefully considered as a potentially highly attractive communications technique that can complement and operate in collaboration with other communications techniques to satisfy the communication needs of SG applications. In this subsection, we contrast the CR communication technique with other communication techniques.

1) CR versus General Wired and Wireless Communication: Table III provides a summary comparison of various communication technologies that can potentially be employed in the SG [136], [137].

- Mobile Broadband Wireless Access, Digital Microwave Technology, and Cellular Communication provide reasonable coverage ranges but support only licensed users.

CR communication avoids the license costs. In rural areas with low population densities there has been a recent trend to replace cellular communication for SG AMI applications by CR communication to avoid the spectrum license costs [86].

- Each layer of the SG architecture has its own environmental conditions and bandwidth requirements and it is very difficult to adopt a single communication technique. Wireless LAN and WiMAX provide good coverage ranges with high data rates and operate on unlicensed and both unlicensed/licensed spectrum, respectively. However, they cover only a limited set of the SG architectural layers and application areas. In contrast, the highly adaptive CR communication is suitable for all SG architectural layers and a wide range of SG application areas [25].
- SG distributed power systems cover typically large geographical areas, which may be governed by different spectrum regulations. CRs can flexibly support SG applications independent of the different spectrum regulations, e.g., by communicating through sensed spectrum holes. Moreover, CRs can efficiently share (utilize) the spectrum of multiple communication networks [25].
- If licensed networks are disrupted through disasters or a security breach, SG data can be transmitted through CRNs over unlicensed spectrum or TVWS [11].
- Software-defined radio (SDR) systems on personal computers or embedded computing devices can be used for the implementation of CR communication. These SDR systems can flexibly adapt to changes in the SG environment through software upgrades [11].
- Among wired communication technologies, powerline communications (PLC) has high speed, but the PLC performance is severely affected by the harsh and noisy medium. Also, PLC covers only HAN, NAN, and AMI. The Digital Subscriber Line (DSL) technology matches IEEE 802.22 WRAN in many aspects and the DSL application areas cover each layer of the SG architecture. However, DSL supports only licensed users.

We conclude that CR communication, e.g., through the IEEE 802.22 WRAN standard, has several appealing features for SG applications compared to other wired and wireless communication technologies. However, CR communication has also a few shortcomings, such as susceptibility to disruptions due to extensive PU activity, as well as security and interoperability concerns. However, CRs can flexibly support a wide range of SG applications. CR communication is therefore a promising communication technology for the SG and deserves thorough study and evaluation in the context of the SG.

2) CR versus 4G Wireless Communication: Long Term Evolution (LTE) is a fourth generation (4G) communication technology with a completely packet-switched core network architecture. LTE has large coverage area, high data rates, and supports high-speed mobility. LTE utilizes Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink, achieving scheduling flexibility and power efficiency [82], [138], [139]. 4G cellular technology operates on licensed frequency bands. The network topology has cells, served by many low power wireless transmitters [137].

Due to the high 4G bandwidth, many channels can be allocated to the growing needs of the SG [2]. The unique features of 4G cellular networks make them a suitable candidate for NAN and WAN [82], [86]. One of the most prominent features of the 4G is the use of the existing cellular communications infrastructure [82], [86].

Due to high monthly charges and high call costs for individual connections, 4G communications will likely be prohibitively expensive for many remote SG sites and for many regular data SG transfers [82], [137]. Other shortcomings of 4G communications are potentially long time delays due to call establishment and large data exchanges due to call dropout. Also, 4G services are limited to the coverage areas of cellular communication systems [82], [85].

4G communication supports high data rates, whereas individual SG meters/aggregators need to send typically small amounts of data. This mismatch may be solved by integrating CR technology in the 4G LTE network. The LTE resource blocks can be subdivided into smaller subchannels of predefined size. CR devices can then dynamically contend for the subchannels that remain vacant after scheduling by the BS [4], [108].

3) CR versus 5G Wireless Communication: Fifth generation (5G) wireless systems are currently being developed with very high carrier frequencies and transmission bandwidths. 5G systems are envisioned for very high base station and device densities [140]–[142]. 5G systems are furthermore envisioned to interface with LTE, WiFi, and Bluetooth to provide universal high-rate coverage and seamless user experiences [143], [144].

5G communication appears attractive for the SG applications that fit well for cellular communication, such as smart metering [145]. Depending on the pricing of 5G services, however, 5G communication may or may not be a cost-effective strategy in the future.

The 5G network architecture will be comprised of many small cells. CR technology is generally more feasible in small cells compared to macrocells due to the lower transmission power requirements. However, for a successful implementation of CRs in 5G several open challenges, such as global standardization and interoperability, need to be resolved [142], [146].

F. Standardization in CR-Based Smart Grid

In this section we briefly review that standardization efforts for the CR based SG. We first give background on the standardization of SG technologies and the standardization of CR communication, before reviewing the standardization of the CR based SG.

1) SG Standardization: The SG is an evolving technology with extensive communication aspects that can benefit greatly from standardization [136], [147]. The standardization of the SG strives to develop a unified SG application data model that ensures that SG interfaces, messages, and workflows are interoperable [147]. Besides interoperability, a compact set of protocols, information security, and increased safety of SG devices and systems are other potential objectives of standardization activities. Global SG standardization efforts are being pursued by several organizations worldwide, including the European Union Technology Platform and the U.S. National Institute of Standards and Technology [136].

2) CR Communication Standardization: IEEE 802.22 is historically the first standard in the CRN domain. IEEE 802.22 is dedicated to CR technology for wireless regional area networks (WRANs) operating in TVWS. IEEE 802.22 WRAN supports long-distance communications of high-bandwidth and high-power terminals [132]. The regulatory framework for the IEEE 802.22 standard allows CRs to exploit TVWS within the very high frequency (VHF) and ultra high frequency (UHF) channels [148]. The related IEEE 802.19 Wireless Coexistence Technical Advisory Group (TAG) focuses on the coexistence of the plethora of unlicensed wireless networking standards in the IEEE 802 standards family [24], [149], [150].

Standardization of TVWS has also been studied by some other working groups. The IEEE 802.11af and IEEE 802.11ah standards committees are the leading regulatory bodies to develop an IEEE 802.11 amendment for WLAN operation in TVWS [107], [132]. They are working to define PHY and MAC layer design modifications with reference to the WLAN legacy standard IEEE 802.11 Revision 2007. Weightless is a stand-alone body developing the standards specifically for M2M communications in the TVWS [132].

3) Standardization of CR-Based SG: While standardization activities for the general SG area and the general CRN area are well underway, standardization efforts for the area of CR-based SG systems are in their infancy. We review in this subsection the few standardization efforts on the specific CR-based SG area that have been completed and outline applications of existing CRN standards for SG applications as well as avenues for future standardization efforts on the CR-based SG.

Standardization efforts for smart utility networks (SUNs) communicating over TV white space (TVWS) have resulted in the IEEE 802.15.4g [151] and IEEE 802.15.4e [152] standards [153]. The IEEE 802.15.4g standard specifies the SUN-related physical (PHY) layer design amendments with respect to the legacy IEEE 802.15.4 standard. The corresponding medium access control (MAC) layer amendments are specified in the IEEE 802.15.4e standard. Depending on deployment scenarios and traffic conditions, these IEEE 802.15.4 standards target data rates from 40 to 1000 kb/s. An additional IEEE standardization effort, namely project 802.11ah (TGah) addresses PHY and MAC designs to communicate in the license-exempt bands below 1 GHz; these designs can be employed for smart utility communications [24].

The IEEE 802.22 standard specified TVWS-based wireless regional area networks (WRANs) for ranges up to 10–100 km [154]. These long ranges make IEEE 802.22 a potential technology for large-scale SG networks, in particular large-scale SUNs [6], [155], [107],. The unlicensed usage of TVWS is governed in the U.S. by Federal Communications Commission (FCC) regulations. The devices operating in the TVWS bands are referred to as TV band devices (TVBDs). There are two types of TVBDs: fixed devices operating at a fixed location with a high power antenna, and portable devices operating at lower power (e.g., in form of a WLAN access point or WPAN module in a handheld device). The usage of TVWS for SUNs can result in plentiful spectrum resources for the SUN system with a relatively long reach and high penetration capabilities. However, SUN deployment and operation must comply with the FCC TVWS regulations in the U.S. [24].

A specific application of the IEEE 802.22 standard for SG backhaul and distribution networks is examined in [148]. One design uses CR as a secondary link for non-critical data and as backup link for emergency situations. Another design uses CR as a stand-alone radio for rural areas. However, sensing delays in both designs make the transmission of SG time-critical data challenging. To solve this problem, a dual-radio architecture is proposed for CR-based transmission, where one radio chain transmits/receives data while the other radio chain continuously senses the spectrum [148]. Similarly, the new white space communications standard named "Weightless" developed for low-cost and low-power TVWS-enabled chips can also be used for SG communications [119].

Many challenges remain to be addressed in the standardization of CR-based SG systems. Future standardization efforts needs to address a wide range of protocol layer interoperability issues and QoS provisioning, as well as security and privacy [147], [156].

III. Case Studies on CR Communications for SG Applications

In this section, we present four case studies to demonstrate how CR communication can support SG applications.

A. Cognitive M2M Communications in AMI Networks [22]

This case study demonstrates how CR can be used in AMI networks. Specifically, a Packet Reservation Multiple Access (PRMA)-based MAC protocol is investigated to develop a scheduling algorithm for smart meters. In this case study, smart meters are placed on power users, served by a single bus (whereby a "bus" is a common structure connecting multiple electrical devices in a power system). An access point capable of performing spectrum sensing provides wireless connectivity to all the smart meters within the range of the bus. The channel availability and power pricing information is conveyed by the preamble. The multiframe is periodically scheduled and divided into a fixed number of timeslots according to the requirements of utility provider and the power system dynamics. A two state Markov chain models the power load variations. A scheduling algorithm is developed to balance the supply and demand by modifying the backoff procedure such that the smart meter with the highest power load variation is given higher scheduling priority than other meters with lower power load variations. The simulation results for the AMI network case study indicate that the developed power load variation based scheduling approach outperforms cognitive carrier sense multiple access [157] without consideration of power load variations.

B. Data Encryption in CR-Based Wireless Sensor Networks [147]

This case study examined the reliability of CR-based sensor data transmission for SG surveillance. Temperature

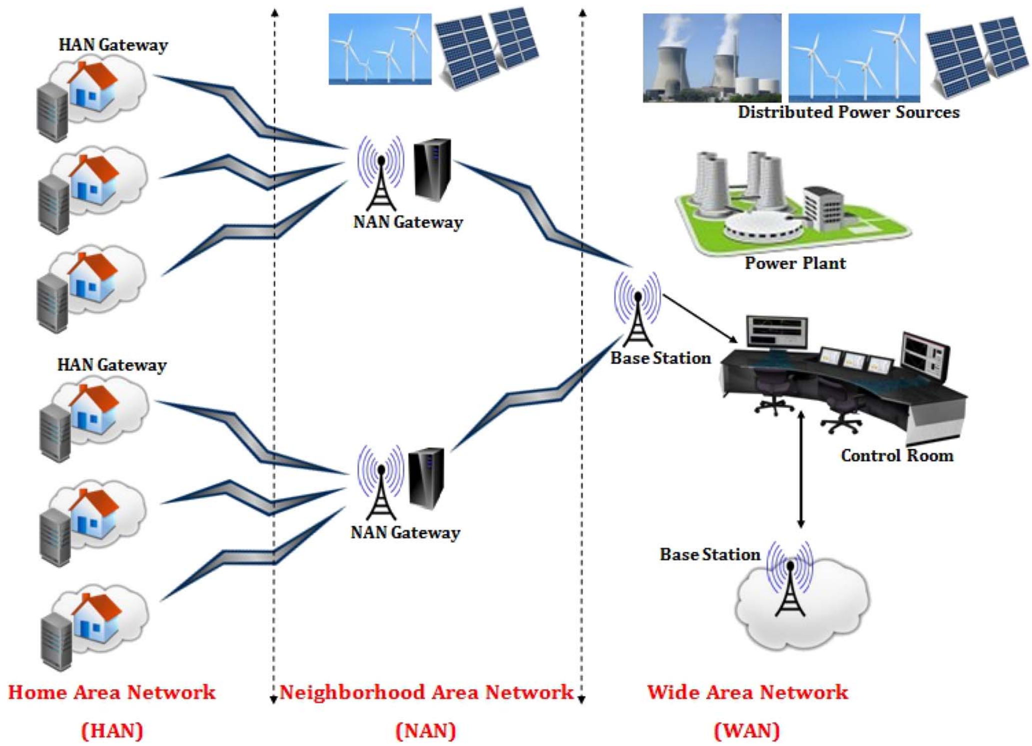

Fig. 2. Illustration of organization of smart grid (SG) communication networks into three architectural layers: HAN, NAN, and WAN. When a cognitive radio network (CRN) is incorporated into this architecture, then the HAN gateway becomes the HAN cognitive gateway, the NAN gateway becomes the NAN cognitive gateway, and the base station becomes the CR base station.

measurements are communicated over a CRSN to detect cable fires and to initiate reliable demand response management. The results indicate that a suitable energy-aware key size is useful to encrypt surveillance sensor data for a reliable SG surveillance.

C. Reliability Analysis of CR-Based Wireless Sensor Nodes [158]

This case study conducts a reliability analysis of CR sensor nodes in the SG. The performance evaluation considers the packet delivery rate and average packet receiving interval. It is observed that increases in the spectrum sensing duration and probability of PU presence degrade the packet delivery rate. Also, increasing PU activity increased the average packet receiving interval.

D. Priority-Based Traffic Scheduling and Utility Optimization [135]

A CR channel allocation and priority-based traffic scheduling approach for CR-based SG systems is examined in [135]. The scheduling approach is designed for heterogeneous SG traffic, including control commands, multimedia sensing data, and meter readings. The scheme takes the channel switch and spectrum sensing errors into account to optimize the system utility. The scheduling approach prioritizes data traffic into three classes: highly prioritized vital messages between nodes and the control center for control, protection, and management; monitoring information from sensors, including multimedia surveillance, is classified into the second highest priority; and meter readings are the third highest priority data traffic.

The network architecture has orthogonal channels with identical bandwidth in a spectrum band, shared by PUs and SUs. All SUs send information to the CR base station and all the users in the CR network system are categorized into priority levels. The base station makes spectrum allocation decisions subject to available resources and informs each SU according to their priority. Each SU has an information queue to buffer source packets according to the packet priority. Each SU is also capable of relinquishing the channel in case of PU reappearance. The dropping probability and blocking probability of SUs are evaluated to analyze the QoS of the CR network. The performance evaluation demonstrates that the optimized channel selection gives an improved average multimedia quality, better service to the SU with higher priority traffic, and improved system utilization for the SUs.

IV. Applications of CR-Based Smart Grid

SG applications generate a wide range of traffic types with heterogeneous QoS requirements, such as maximum tolerable delay, minimum required throughput, as well as required reliability level. In order to organize the presentation of the SG applications and their networking requirements, we categorize the different network types in the SG communication architecture from Fig. 1 into layers. Specifically, we define the SG network types HAN, NAN/FAN, and WAN as layers, as illustrated in Fig. 2.

The HAN, which can be considered the bottom layer, provides communication paths between home appliances, in-home displays, energy management systems, and energy dashboards.

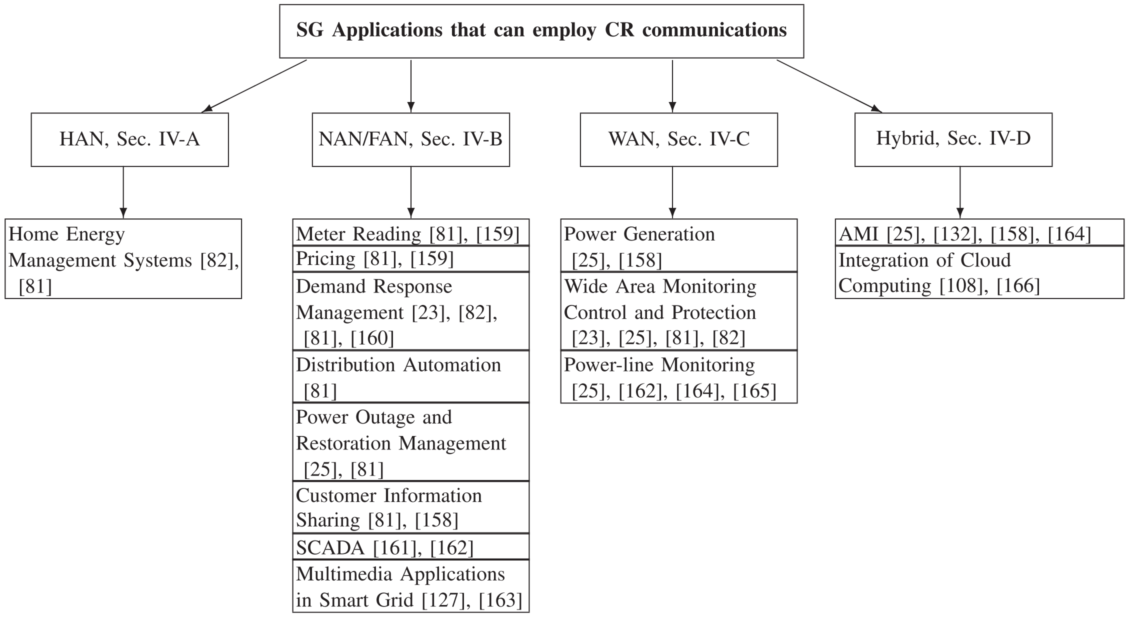

Fig. 3. Classification of smart grid (SG) applications that can benefit from cognitive radio (CR) communications based on the layered SG network structure of Fig. 2.

There may be multiple smart meters in a given HAN, responsible for collecting energy-related data and transmitting the data to a local access point; thus forming an AMI. The NAN, which can be considered the middle layer, collects the metering and service information from multiple HANs and transmits the information to the data collectors, connecting the NAN to the top layer, i.e., the WAN. The presence of AMIs constitutes a hybrid architecture spanning the HAN and NAN layers. In the following subsections, we discuss SG applications that can benefit from CR communications. Following the layered network structure illustrated in Fig. 2, we provide an overview of these SG applications in Fig. 3.

A. Applications in HAN

HANs support communication at the customer end of the SG network architecture. A typical SG application in the HAN that can benefit from CR communications is networking of Home Energy Management (HEM) systems. HEM systems provide home automation and control through household appliances that communicate with smart meters, in-home displays, and other smart devices. HEM systems can reduce energy costs through adaptive control, e.g., load balancing. Commercial and industrial customers can use HEM systems for building automation, heating, ventilation, and air conditioning (HVAC) control, and other industrial energy management applications.

A HAN is typically connected to other SG services or utility providers via a smart meter or an Internet gateway. The reliable and efficient operation of HEM systems requires real-time information transmission. A CRN may be beneficial for the real-time information sharing among HEM Systems [81], [82].

B. Applications in NAN/FAN

A NAN collects data from customer HANs in a neighborhood and transfers the data to the WAN. Several SG applications operate in NANs/FANs, such as meter reading, distribution automation, and power outage management. The data rates and coverage distances of these applications cover wide ranges [81]. A CRN may be a good option for supporting a wide range of NAN/FAN applications, as outlined in the following.

1) Meter Reading: Meter reading is the collection of data from smart meters and the data transfer to a central database for billing and analysis. There are three types of meter reading: on-demand, which is carried out when required; scheduled, which is performed at prescribed time intervals; and bulk transfer, which reads all meters in a prescribed service area. A CRN can provide the information transfer service for all three types of meter reading [81], [159].

In [119], the performance and power levels of smart meters operating in the TVWS were studied. The study found that the communication within a building is generally feasible. However, indoor-to-outdoor communication, e.g., from a indoor smart meter to an outdoor central coordinator, presents challenging trade-offs: due to high wall shielding and fading on the indoor-to-outdoor propagation channel, the TVWS communication by the smart meters causes typically only negligible interference to outdoor PUs. However, successful indoor-to-outdoor data transmission requires careful setting of the transmit power levels as well as a relatively dense network of outdoor coordinators (so that the distance from the building to the outdoor coordinator is short).

2) Pricing Applications: Pricing applications broadcast pricing information to smart meters and smart appliances. Pricing information may be time-of-use (TOU) pricing, real-time pricing (RTP), or critical peak pricing (CPP). A smart meter can connect or disconnect the service according to the pricing information. Moreover, service providers can calculate billing information for their customers and initiate necessary actions, such as warning messages [81], [159].

3) Demand Response Management (DRM): With the help of DRM, service providers can communicate with smart devices at customer premises to reduce the load on the distribution grid during peak demand periods. However, reliable bidirectional communication between consumers and utility providers is needed for effective DRM [123]. DRM enables users to turn selected devices on or off by sending unicast, multicast, or broadcast commands to a load controller installed at customer premises [81], [82]. Sensor-based intelligent control systems, such as sensor-based lighting systems [160], can assist the DRM.

4) Distribution Automation (DA): Distribution Automation (DA) monitors and controls the distribution grid. DA gives real-time operational information about distribution-level devices, such as capacitor bank controllers, fault detectors, switches, and voltage regulators. The communication requirements for DA typically vary from utility to utility. CRNs may be employed to flexibly fulfill the particular DA requirements of a given utility [81].

5) Power Outage and Restoration Management: Power outages have significant negative economic consequences, but are often not detected in real-time due to lack of automated analysis. As CR nodes can be deployed over large areas in power distribution systems, the utility and the consumer can sense and monitor power outages [25]. This enables an electric utility to detect an outage as soon as power loss occurs through smart meters and outage detection units. These devices can also report over- and under-voltage instances. An additional interface module is typically added to a smart meter to enable the outage detection functionality [81].

6) Customer Information Sharing: Customer information sharing applications allow customers to obtain information about their account and energy usage, which is collected and stored in a data warehouse. CRs may be beneficial for transferring energy usage data from the consumers to the central data warehouse and for data retrieval from the data warehouse by customers [81]. The transferred customer data can aid in predictive and robust electrical power load balancing strategies [158].

7) SCADA: Supervisory Control and Data Acquisition (SCADA) systems are critically important for modern power systems and industries. SCADA system based on the IEEE 802.22 CR communication standard have been proposed in [161], [162].

8) Multimedia Applications in Smart Grid: Wireless multimedia sensor and actor networks [167]–[170] can assist in the monitoring of energy generation facilities, transmission and distribution equipment, as well as consumer premises through video surveillance [127]. These multimedia applications require large bandwidths that can be provided through the DSA capability of CRNs [163].

C. Applications in WAN

1) Applications in Power Generation: To prevent overload in power grids and to balance the power demand and supply, power can be generated through distributed renewable resources, e.g., wind and solar power, near the customer premises [25]. However, power generation systems are often also in remote areas requiring transmission to distribution stations. Remote monitoring applications for power generation systems can be challenging due to overcrowding in the unlicensed spectrum bands. The CR-based SG can access the spectrum opportunistically to improve the overall network performance so as to better support remote monitoring of distributed power generation [158].

The "green environment" concept of the SG involves the integration of renewable energy resources into the SG system. Distributed generation is only possible if power quality, voltage, and frequency stability are measured and analyzed. A robust and reliable communication network is required for the operation of the overall distributed generation system in the SG. Traditional wired communications have high deployment costs, thus wireless networks may be suitable alternative. However, wireless networking faces several challenges, such as network contention, noise, obstructions, and interference. One possible approach is to improve spectrum utilization and wireless communication performance through the opportunistic spectrum access of CR communications [25].

2) Wide Area Monitoring Control and Protection: Wide area monitoring involves real-time data monitoring from intelligent electronic devices (IEDs) and phasor measuring units (PMUs). Wide area control provides automatic self-healing with local control and faster response than manual control by a control center. Wide area protection can fully and automatically protect power systems against widespread blackouts or unexpected events [81], [82].

Wide area monitoring in SGs not only monitors the transmission, generation, and distribution components of the grid but also retrieves information about components, e.g., transformers, capacitor banks, and network protection devices. Many licensed and unlicensed communication technologies can be used for this purpose. However, licensed bands are costly. Unlicensed technologies have low cost and easy deployment but perform poorly in the harsh RF conditions of the power grid. CR networks with their opportunistic spectrum access are a promising alternative for wide area SG monitoring, control, and protection [25].

3) Power-Line Monitoring: The transmission lines face many hazards, including lightning strikes, icing, hurricanes, landslides, bird damage, and overheating. The distributed and large-scale nature of the transmission lines creates challenges for wireless sensors in terms of maintenance, spectrum regulations, electromagnetic interference, and fading. CR-based wireless communication can be employed for cost-effective power line and substation monitoring [25], [162], [164], [165].

D. Applications in Hybrid Communication Architectures

1) Advanced Metering Infrastructure (AMI): The advanced metering infrastructure (AMI) is a measurement and collection system. The AMI includes smart meters and other intelligent devices at the consumer side, communication networks between consumer and service providers, and data management systems. The collected data is important and has large volume so that a reliable, secure, scalable, and cost-effective communication backbone is needed. There may be many smart meters along with many access points. Thus, a mesh network is typically considered in AMI communication models. In urban areas, the ISM band is occupied by many devices. Hence, data communications between AMI components faces interference. The crowded heterogeneous spectrum characteristics degrade performance, and result in high latency and packet losses, while undermining reliability and security.

The use of licensed bands for data communication between access points and utility is typically costly. CR technology can be suitable for the AMI communication backhaul system, providing dynamic and opportunistic spectrum access for improved data communication performance [25]. CR can also benefit AMIs by integrating self-configuration and easy deployment. With the spectrum-aware communication capability of CRs, AMI meters and equipment can be easily deployed at remote sites to achieve seamless and reliable communication between a utility control center and AMIs. CR-based communication systems can also achieve increased reliability, security, and efficiency as compared to other heterogeneous wireless networks [132], [158], [164].

2) Integration of Cloud Computing: The application of CR communication in a 4G LTE network with a cloud data center has been proposed in [108]. The cloud data center can facilitate the SG energy services by enabling convenient, on-demand network access to a shared pool of configurable computing resources, such as, networks, servers, and storage. The concept of a cloud computing data center as the central communication and optimization infrastructure for a CR-based AMI network has been further developed in [166]. The netbook advance metering infrastructure (Net-AMI) [166] has been proposed as a low-cost infrastructure for AMI meter communication. The Net-AMI proposal strives to keep costs low by installing additional antennas for CR communication on existing cellular communication towers. The AMI meters apply CR communication to access the cloud data center. The NeT-AMI cloud data center is envisioned as the central provider for services and protocols that help to optimize the SG operation. These services provided by the cloud data center range from cognitive radio services to energy management and control. The Net-AMI is designed as a persistent communication infrastructure guarding against power line failures during power information transmission between utilities and consumers [5], [166].

V. Integration of CR Into the Smart Grid

In this section we outline strategies for integrating CR-based communications into the SG organized according to the three-layered hierarchical structure, consisting of HAN, FAN/NAN, and WAN, as illustrated in Fig. 2.

A. Home Area Networks (HANs)

HANs perform commissioning and control functions. Commissioning refers to the identification of new devices and management of self-organizing networks. Control functions establish the communication links between devices and guarantee reliable operation among different layers of the SG network [3], [171]. HANs use two-way communication for demand response management (DRM) services. Real-time transmission of power data and load information of smart meters is provided from the user side to the utility center. At the same time, dynamic electricity pricing information is communicated from the utility center to consumers [171]. Interweave and underlay CR communication are preferable in HANs. Interweave CR communication avoids interference and is well suited for short distances, while underlay CR communication is well suited for short-range applications and low data rates [105].

The basic features to be considered when integrating CR communication into the HAN are:

1) Topology: HANs may have a mesh topology [105] or a star topology and have either wired (e.g., power line communications) or different wireless communication technologies (e.g., Zigbee, Bluetooth, and WiFi). Hence, a flexible service gateway is needed to manage communication within the HAN and communication between different HANs. There may be a variety of components in a HAN along with many intelligent devices, such as a cognitive home gateway (HGW), smart meters, load control devices (e.g., pool pumps, water heaters, and appliances), plug-in electric vehicles, as well as sensors and actuators [3], [172]. A HGW can be integrated into smart meters or some in-home devices to establish contact with various devices/terminals within the HAN to periodically collect power-related data [173].

2) Dynamic Spectrum Sharing in Cognitive HANs: The cognitive home gateway (HGW) operating in a HAN should have advanced cognition capability to autonomously adapt to different radio technologies. The HGW senses unused frequencies in the surroundings and changes its transmitter parameters to utilize the unused frequencies subject to interference constraints. Enabling bi-directional communication, the HGW periodically collects power-related data in the forward direction from various devices/terminals within the HAN. This data is then transferred to destinations outside of the NAN. In the backward direction, the HGW behaves as a central node within the cognitive NAN [3], [172] to receive data, such as pricing and demand responses. The received data is then distributed to the smart meters or to various devices/terminals. While operating within a HAN, the HGW can utilize the license-free spectrum bands [3], [173]. Apart from managing spectrum sharing, the HGW plays an important role in facilitating the networking of devices and sensors in the HAN. The HGW coordinates the communication between the devices and assigns channel and network addresses to each device [172].

3) Cross-Layer Spectrum Sharing in HAN: Many smart meters as well as intelligent sensors and actuators employing different wireless technologies may coexist in a HAN. Thus, these wireless systems may overlap in the radio spectrum, resulting in severe interference. The spectrum access of the heterogeneous wireless systems can be coordinated by an HGW-assisted cross-layer cognitive spectrum sharing mechanism [172].

B. Neighborhood Area Networks/Field Area Networks (NANs/FANs)

The communication technologies adopted for NANs/FANs have to cover the radius of over a thousand meters. Hence, reliable communication channels between the data aggregation points (DAPs) and the smart meters must be exclusive or interference free. Therefore, licensed or leased wireless techniques may be a suitable option [134]. In NANs, a concentrator receives data from smart meters and forwards the data via a wide area link to the utility providers. Both overlay- and underlay-based

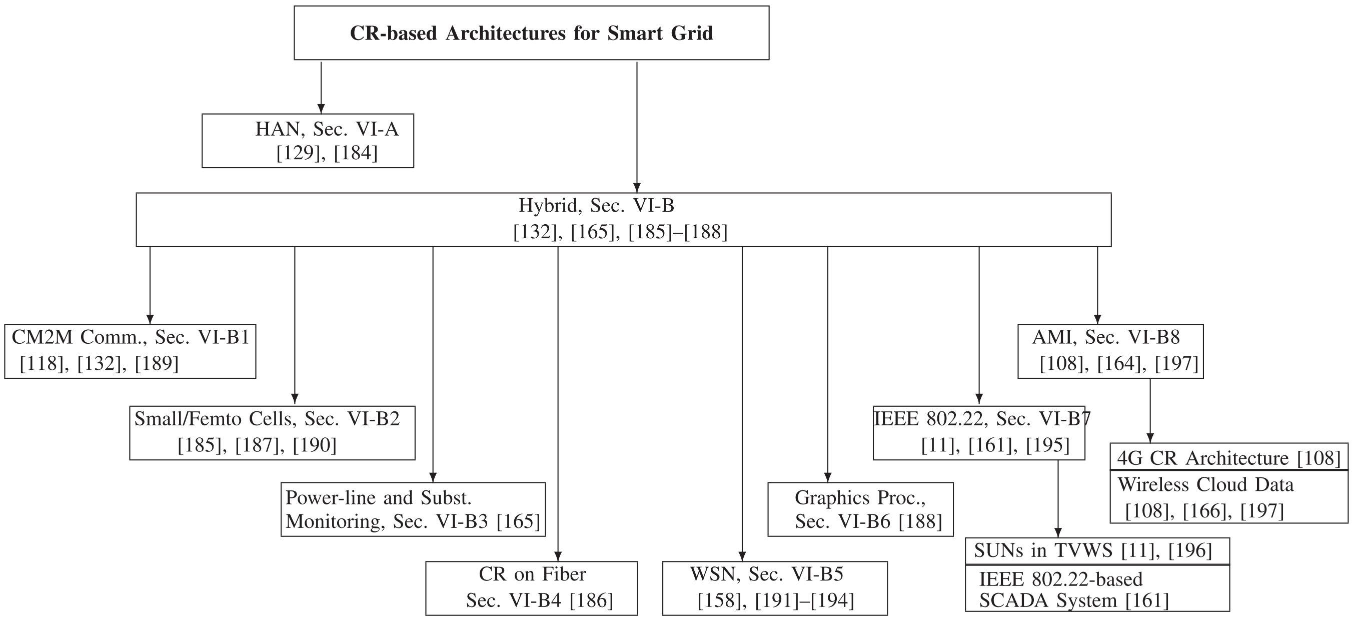

Fig. 4. CR-based SG architectures organized into two main categories: Architectures for Home Area Networks (HANs) and architectures for hybrid networks combining multiple layers of the SG network architecture in Fig. 2.

CR models are considered in NANs. The overlay model is recommended for high-rate data traffic and underlay is considered for low-rate data traffic [105].

The cognitive communication in NANs/FANs involves the following aspects:

1) Topology: The NANs/FANs gather energy consumption data from consumers and deliver the data to a utility company through either open or private WANs. The NAN topology has two types of network devices, i.e., NAN cognitive gateways (NGWs) and HAN cognitive gateways (HGWs). An NGW acts as a central node, provides interfaces, connects several HGWs from multiple HANs together, and serves as the CR access point to provide single-hop connection with HGWs in a hybrid access manner. HGWs are data aggregators of HANs operating in a single-hop mode with the NGW.

2) Spectrum Access: The HGWs transfer their data from/to NGW in licensed bands using CR technology. Hybrid dynamic spectrum access in NANs has also been proposed to utilize both licensed and unlicensed spectrum bands in a hybrid dynamic manner [3], [12], [172], [173]. Hybrid dynamic spectrum access [3] utilizes some licensed spectrum bands to access the HGWs. The NGW allocates these bands to the HGWs (which act as PUs) according to the transmission demand. Large data amounts in the SG may additionally require unlicensed access. For the unlicensed access, the HGWs and NGW are considered as SUs, and opportunistic communications links are set up between them in the unoccupied spectrum bands.

C. Wide Area Networks (WANs)

In the WAN, each NGW can behave as a cognitive node instead of an access point with the capability to communicate with the control center through unused frequency bands. The control center is connected with CR base stations, which manage the communications of the NGW and are spread over a large geographic area. A spectrum broker coordinates the sharing of the spectrum resources among multiple NANs. Real-time variations of the data amounts in the network and varying channel capacities require quick responses from the spectrum broker so that the licensed bands are efficiently distributed. In NANs, NGWs may not be within the geographic coverage areas of the CR base stations. Therefore, NGWs should share unoccupied licensed and unlicensed spectrum bands to improve the spectrum efficiency and reduce the cost of purchasing spectrum bands. The high data rate of the WAN base station suggests the overlay CR technique [105].

The WAN consists typically of two interconnected types of networks, namely the core networks and the backhaul networks. The core networks use fiber optics or cellular wireless networking to access the control center with high data rates and low latency. The backhaul networks provide the broadband connection to NANs and monitoring devices and can in turn be based on optical [174]–[179], or wireless networks [180], or hybrid fiber-wireless networks [181]–[183]. When using CR technology in backhaul networks, each NGW serves as a cognitive node instead of an access point in the CR-based backhaul network. This cognitive approach can reduce the investment cost and lead to more flexibility, capacity, and coverage [173].

VI. Architectures for CR-Based Smart Grid

In this section we survey the architectures for CR-based SG systems. Fig. 4 illustrates the organization of the architecture survey into two main classes, namely architectures for home area networks (HAN) and architectures for hybrid networks covering combinations of HAN, NAN, WAN, and AMI.

A. HAN Architectures

1) CR-Based Wireless Sensor Network Architecture for SG: A multi-layered external sensing architecture of CR-based

Wireless Sensor Networks (CR-WSN) has been proposed in [184]. In the CR-WSN, spectrum sensors in collaboration with a coordinator and a geo-location database gather information about the spectrum at the SG utility. An 802.15.4 radio with the ZigBee protocol stack is used. The geo-locator database maintains information about white spaces at a particular location up to a distance of 50 m. The coordinator performs the role of the network manager, collects reports about free channels, performs as a gateway or root node, schedules quiet periods for spectrum sensing, ensures synchronization, and communicates on a non-ZigBee channel with the geo-location database to prepare the list of PU channels to be scanned. Spectrum sensors issue a channel switch notification as soon as a PU has been detected. They also prepare an updated channel back-up list through sensing across licensed and unlicensed channels and report this list to the coordinator.

2) Radio Access Technology-Based SG Architecture: Consumers in a HAN may have next-generation heterogeneous wireless systems comprising of several Radio Access Technologies (RATs). To accommodate best-effort and real-time traffic from SG applications, smart devices should have reconfigurable radios. The system architecture proposed in [129] addresses this need by consisting of smart devices equipped with reconfigurable radios (RRs) capable of supporting one or more Radio Access Technologies (RATs). There are two resource-controlling operators: a Global Network Resource Controller (GRC) in the back-end network and a Base Station (BS)/Access Point (AP) for each RAT. The GRC assigns the most appropriate BS/AP for connectivity to each RR on long time-scales (seconds). Operating on short time scales (milliseconds), the BSs/APs manage the resources of their corresponding RAT. Each BS/AP also leases any additional open spectrum after sharing information with a Spectrum Manager located in the Internet to maintain a database of available and leased open spectrum. Information from multiple HANs is sent to a NAN which relays the data to back-end systems [129].

B. Hybrid Architectures

We sub-divide the hybrid structures into two categories: a large set of general architectures for combinations of HAN, NAN and WAN (which are surveyed in Sections VI-B1–VI-B7), and architectures for the Advanced Metering Infrastructure (AMI) (which are surveyed in Section VI-B8).

1) Cognitive Machine-to-Machine Communication: Cognitive machine-to-machine (CM2M) communication has been proposed in [118], [132] to exploit CR technology for M2M communications in HANs, FANs, and NANs. These studies focus on justifying the use of CRs in M2M communications and study the CM2M network architecture for the SG. Within this architecture, [118], [132] develop an energy-efficient spectrum discovery scheme for smart metering applications. The evaluations highlight the trade-off between the protection of PUs and the energy consumption in a cluster of smart meters.

a) M2M over TVWS for smart metering: A master-slave architecture for M2M communication with the help of CRs over TVWS is examined in [118]. The smart meters are clustered whereby one node is designated as master and coordinates multiple slaves. Each smart meter can serve as master or slave depending on the scheduling policy. The master searches for available channels and coordinates the spectrum utilization of the slaves. The master starts the spectrum sensing process and each slave sends its data only to its master. The master and the slaves remain in sleep mode if they are not performing any operation. The architecture is analyzed to evaluate the cluster lifetime and the system fairness as a function of the number of devices.

b) CM2M for renewable energy FANs: The addition of renewable energy sources (e.g., solar, wind, and geothermal) is a prominent feature of the SG. Specifically, in future energy distribution systems with wind farm FANs, there are three types of M2M communication scenarios: M2M among wind turbines within the wind farm, M2M between the wind farm and the remote control center, and M2M between the wind farm and the local community. As wind farms are widely spread in remote geo-locations, TVWS may be available [132].

c) CM2M for grid protector FANs: A FAN may have a number of power grid protectors to quickly execute protection algorithms upon detection of fluctuations, disturbances, or a power outage. The CM2M can be a quick and flexible solution for minimizing loss of power in such abnormal situations [132]. Grid protectors can protect distribution power systems with quick signaling. Upon detecting any abnormal behavior of power components, the CM2M communication infrastructure can be employed to promptly isolate faulty areas.

M2M communication between CR-based smart meters and a remote area power management (RAPM) server has been proposed in [189]. The proposed network employs TV band devices (TVBDs) for the communication layer that manages and coordinates the power consumption in the SG. TVBDs provide easy two-way communication between power utility devices and consumer devices, and give good energy efficiency and spectrum utilization. To find a good trade-off between power efficiency and spectrum efficiency, CR functions based on multi-objective genetic algorithms have been proposed for different operating environment in [189].

2) Cognitive System Models for Small/Femto Cells: Multimedia applications in the SG have high data rate demands and thus increase energy consumption for communication. To improve energy efficiency for these applications, cognitive mobile networks with small cells are a promising strategy [185], [187]. However, the power networks should be incorporated in the study as they provide power to mobile networks. An energy consumption model for a cognitive mobile network with small/femto cells in the SG context has been proposed in [185], [187]. The studied mechanisms not only sense the radio spectrum, but also the SG environment, so that power allocation and interference management are jointly performed. The small cells network has been modeled with real-time pricing (RTP) for demand side management (DSM).

In this time-slotted system model, one macro cell base station (MBS) connects multiple small/femto cell base stations (SFCBSs) over a broadband connection, such as a cable modem or a digital subscriber line. A SFCBS serves several users in each small cell. The MBS is equipped with CR capability so that it can monitor the spectrum access by the SFCBSs. The

SFCBSs also have cognitive technology to sense the surrounding radio spectrum environment for intelligent sub-channels access. The spectrum band licensed to the MBS is divided into multiple sub-channels in each time slot. The spectrum sharing between macro cell and small/femto cells increases spectrum efficiency but also causes cross-tier interference. The interference effect can be counteracted when the MBS charges the SFCBSs an interference price. This charging results in an adaptive adjustment of transmit power by each SFCBSs based on the channel condition and the interference price charged by the MBS. Interference can also be minimized by a sparse SFCBSs deployment [185], [187].

ZigBee personal area networks likely have to coexist with wireless local area networks (WLANs) [198]–[200]. To resolve this coexistence issue, a protocol for a cognitive SG network for monitoring home appliances has been proposed in [190]. Initially, the home appliances send request to send (RTS) messages and if a clear to send (CTS) message is observed, they first estimate the WLAN transmission timing and channel information. Then, the appliances transmit electricity usage data to the smart meter simultaneously when an active WLAN device transmits a data frame. In this way, a cognitive SG shares the spectrum with the existing WLAN. The performance evaluation of the architecture includes the required transmission power at the home appliance and the average energy consumption for transmitting different smart metering file sizes [190].

3) CR-Based Power-Line and Substation Monitoring: A hybrid CR-based design for an SG power line and substation monitoring system has been proposed in [165]. The proposed design is for the transfer of monitoring data from sensors. The design highlights communication efficiency and energy supply as key challenges for system implementation. The integrated technologies for this system include ZigBee, WiFi, and WiMAX. The ZigBee and WiFi techniques are preferred for data transmission over short distances, while the WiMAX technique is employed for multiple sensors' data transmission with relatively high bandwidth. This system includes sensors, WiFi/ZigBee Customer Premises Equipment (CPE), and a Sensor Gateway. Sensors acquire data and transmit data to a WiFi/ZigBee CPE communication module through an Ethernet or RS232/485 interface. After receiving data, the WiFi/ZigBee CPE transmits the data through the radio air interface to the sensor gateway (SGW). The SGW consists of five parts: the AP module for collection of data transmitted from the WiFi/ZigBee CPE, the sensor proxy (SP) module to complete the signal transformation between WiFi/ZigBee and WiMAX, a spectrum detection module, a spectrum allocation module, and the WiMAX CPE module to send the signal to the WiMAX base station (BS) located at the substation.

4) CR on Fiber Technology: A system architecture consisting of CR networks with Virtual Radio (VRa) Free Space connections for high-speed monitoring and control of community SGs has been proposed in [186]. The architecture uses multiuser Radio on fiber_MIMO (RoF_MIMO) technology [186]. At both ends of the optical fiber, multiple input-antenna and output-antenna are utilized. There are three types of RoF_MIMO for CR networks: Serial RoF_MIMO, Parallel RoF_MIMO, and Digital RoF_MIMO. Serial RoF_MIMO is used for remote site connection. Parallel RoF_MIMO is favored to mitigate interference in spectrum-congested areas. Digital RoF_MIMO employs the Internet or digital broadband networks to make use of radio space transmission in the digital pulse format. The radio signals are band pass sampled and digitized at the input port. A D/A conversion at the output port recovers the radio signals. A variety of multiplexing methods, including optical Sub Carrier Multiplexing (SCM), optical Time Division Multiplexing (TDM), and optical Code Division Multiplexing (CDM), are employed in the RoF_MIMO system [186].

5) CR-Based Wireless Sensor Networks (WSNs): For WSNs-based SG applications, a spectrum-aware cognitive sensor network (SCSN) architecture has been proposed in [158] to overcome spatio-temporally varying spectrum characteristics and harsh SG environmental conditions. The proposed SCSN architecture is introduced as a potential candidate for reliable, low-cost remote monitoring applications in the SG, particularly in the generation, transmission, and distribution domains. The reliability of transport is analyzed by comparative performance evaluations in terms of packet delivery rate and average packet receiving interval.

Wireless sensor networks can be utilized in the SG to achieve real-time information exchange, so that the SG can promptly react to environmental changes. To ensure minimum delay, a cognitive WSN data transmission architecture for the SG with a data classification scheme has been proposed in [192]. Data is collected, processed, and then classified into different priority levels according to various features, including the redundancy level. The classification methods use the data deviation to estimate the redundancy level. The priority levels may vary with time and environmental changes. Abnormal data is separated from normal data and then classified into different priority levels. The classification process identifies the most important data, which accounts for a small portion of the total data volume. A proposed CR scheme transmits this data with minimum delay through common sensor nodes to the sink sensor node as verified by performance evaluation [192].

A CR-based Wireless Sensor and Actuator Network (WSAN) architecture has been proposed in [191] for distribution grid automation. The network accommodates random PU appearances in its dynamic spectrum access. In SG FANs, the study [191] found that a CR-based network outperforms a legacy Wi-Fi network in terms of latency, power efficiency, and network simplicity due to higher range and fewer hops in a NAN. The CR network also achieved a lower packet loss rate.

A cross-layer CR-based wireless sensor network architecture for control and monitoring has been proposed in [193]. Priority classes are defined to represent the traffic heterogeneity and diverse QoS requirements of the SG applications. The problem is described as a weighted network utility maximization (WNUM) to maximize the weighted sum of flows service. A cross-layer heuristic solution is provided to solve the resulting utility optimization problem. The heuristic jointly considers routing, dynamic spectrum allocation, medium access, and physical layer functions. The cross-layer design considers the routing protocol as an on-demand distributed algorithm that interacts with the MAC and physical layers to select a suitable channel. The QoS requirements in terms of channel interference and capacity are met by prioritizing the transmission through setting the contention window size of the MAC protocol.

An extension of [193] has been proposed in [194]. The extension leverages the CR capability to avoid the noisy and congested spectrum bands by dynamically switching to different channels and finding the channel with the lowest noise level. This in turns gives reliable and high capacity links for wireless communication in SGs. The problem is formulated as a Lyapunov drift optimization to enhance the weighted service of the traffic flows related from different classes. The presented Suboptimal Distributed Control Algorithm (DCA) efficiently supports QoS through channel control, flow control, scheduling, and routing decisions. The DCA dynamically selects a channel in accordance with signal interference in the power system environment and the estimated channel capacity. This CR-based cross-layer solution thus considers the unique characteristics of the power system environment and can fulfill the QoS needs of the SG applications in terms of data rate, packet delay, and packet delivery ratio [194].

6) Graphics Processing Technique: Graphics processing techniques can achieve fast spectrum sensing and dynamic access [188]. In the architecture proposed in [188], CR communication over license-free bands is employed in the HANs, while CR communications over licensed bands is employed in the NANs and WAN. The study examines how the hierarchical infrastructure of cognitive HANs, cognitive NANs, and cognitive WANs can employ DSA for avoiding interference and adapting the data throughput.

a) CR communication in HAN: In CR-based HANs, each sensing sender node periodically determines its Packet Error Rate (PER). If the PER is above a prescribed threshold, then a report is sent to the access point (smart meter) to check its link quality. If the link quality deteriorates below a prescribed value, the controller initiates a spectrum sensing command. Distributed spectrum sensing nodes then sense the spectrum and periodically send sensing information to the controller. The controller decides about unoccupied bands and allocates these unoccupied bands to the sender node.

b) CR communication in NANs and WAN: In CR-based NANs, data can be categorized and prioritized for successful delivery across heterogeneous networks. Emergencies and disasters generate time-critical data, e.g., voltage drops, switching commands, and removal of physical network links. In such cases, data transmission through traditional wireless communication networks, such as cellular wireless networks or the Internet is preferred. On the other hand, general data, such as automatic meter reading data, logs and energy quality information can be transmitted with CR communication. CR communication is also beneficial for critical data transmissions by providing a backup radio in emergency situations. This model incorporates the characteristics of the IEEE 802.22 standard, i.e., adaptive data throughput, soft capacity limit, and wide coverage area [188].

7) IEEE 802.22 and TV White Space (TVWS): IEEE 802.22 is a standard designed for a wireless regional area network (WRAN) exploiting TV white space (TVWS) [201] with CR technologies. Cognitive devices for the TVWS spectrum have a bandwidth of 6 MHz and operate within the very high frequency (VHF) channels and the ultra high frequency (UHF) channels. These channels range form 54 to 72 MHz, 76–88 MHz, 174–216 MHz, and 470–806 MHz. According to the IEEE 802.22 standard, a cellular CR network consists of base stations (BSs) and customer-premises equipment (CPE) nodes. The BS manages the medium access for all the CPEs in its cell. Table IV summarizes key parameters of IEEE 802.22 WRAN.

TABLE IV
SUMMARY OF KEY IEEE 802.22 WRAN PARAMETERS

Parameter	Specification
Range	30–100km
Methodology	Spectrum sensing to identify free channels
Channel bandwidth	6, 7, 8 MHz
Modulation	OFDMA
Channel capacity	18 Mbps
User capacity	Downlink: 1.5Mbps, Uplink: 384 kbps

A UHF white space communications testbed for SG communications has been presented in [196]. The network architecture is designed for analyzing the distributed generation of electricity in communities. The SG applications, such as remote meter reading and load balancing, often lack communications infrastructures in remote rural areas. The proposed system is based on a network of radio relay nodes to support SG communication in rural areas. The system has bi-directional communication links and uses an 802.11 protocol for transmission over the unlicensed UHF 758–766 MHz channel. The proposed system gives broadband access to remote communities and provides point-to-multi-point connections in both the 5 GHz WiFi spectrum as well as the TVWS white space spectrum for more remote or non line-of-sight connections [196].

Two CR-based WRAN architectures for SG backhaul data flows have been proposed based on the CR-based IEEE 802.22 standard: the stand-alone radio architecture and the secondary radio architecture. Rural areas with low customer density have typically high availability of white space in the TV bands, thus a stand-alone radio has been proposed for providing broadband access for utility backbone communications [11], [195]. The TV bands have good propagation characteristics leading to wide area coverage as demonstrated through path loss measurements in urban and rural regions [148]. IEEE 802.22 CRs has been proposed as a secondary (backup) radio to opportunistically transmit non-critical SG data in case of a natural disaster or security breach, or when the customer density is high relative to the available TVWS [11], [148], [195]. A graphic processing unit platform has also been proposed as the computing engine can accelerate spectrum sensing algorithms [195].

To counter inherent sensing delays, a dual-radio architecture may be adopted for CR-based WRAN transmission [11], [148]. The dual-radio architecture employs one radio chain for SG data transmission and reception, while the second chain is dedicated to spectrum sensing. The sensing radio continuously searches for new available channels, so that data transmission does not need to be interrupted in order to search for idle channels. This proposed dual-radio architecture gives higher spectrum efficiency and sensing accuracy as compared to a single-radio architecture that only allocates prescribed time slots for spectrum sensing [11], [148].

The benefits of the proposed IEEE 802.22 based secondary CR radio communications architecture for the SG are [11], [148], [195], [202]:

- Soft capacity limit: The system can opportunistically and dynamically utilize available TV channels to increase system capacity, e.g., to accommodate future applications. The IEEE 802.22 standard has defined a total data rate of 18 Mbps in a 6 MHz TV channel. The IEEE 802.22 PHY layer can achieve higher rates up to 24 Mb/s through channel bonding, i.e., using more than one TV channel.
- Wide coverage area: The IEEE 802.22 standard has a much larger base station (BS) coverage area than the other 802 standards. For example, the maximum coverage range for IEEE 802.16a/d/e is limited to less than 5 km. In contrast, IEEE 802.22 has a BS coverage of 33 km if the CPE power level is 4 Watts EIRP. This coverage may extend to 100 km if higher power levels are permitted. Hence, few BSs are needed, reducing capital expenditure.
- Fault tolerance and self-healing: Loss of any link due to a natural disaster or security breach is compensated by formation of a new connection in a timely manner to maintain connectivity.
- Continuous spectrum sensing: The constant spectrum sensing with the dual-radio architecture allows for a clear channel dedication so that SG data can flow quickly.
- Easy upgrade: CR-based systems are typically implemented with software-defined radio (SDR) on a personal computer or embedded computing device, resulting in high flexibility and easy modification through software upgrades [203]–[205]. SDR implementations are commercially available for SG communications both in BSs and routers. For instance, WiMAX radios can be easily customized to specific licensed bands. The easy upgrades made possible with SDR systems are very important to utility customers who want to avoid that their communications infrastructure capital investments become prematurely obsolete [11], [148], [195].

Overall, these advantages make CR-based communication over the TVWS based on the IEEE 802.22 standard very attractive. To further leverage this attractive communication solution, working groups have been formed to investigate the coexistence of wireless technologies in the TVWS, such as IEEE 802.19.1 and IEEE 802.15.4g smart utility networks (SUNs) [11], [107]. We proceed to survey TVWS communication techniques specifically developed for the SG distribution grid.

a) Smart utility networks (SUNs) in TV white space: For large-scale process control applications, such as the SG distribution network, a global standard is required. The IEEE 802.15.4g smart utility networks (SUNs) task group has been established to formulate a PHY amendment to IEEE 802.15.4. Besides providing monitoring and control of a utility system, SUNs allow many applications to operate over shared network resources. For instance, the AMI, which monitors, commands, and enables control for service providers at the SG side and facilitates measurement, data collection, and analysis for electricity usage at the consumer side, can be based on SUN technology [24], [196].

Recently, there has been increased interest in the deployment of SUNs in TVWS [11], [24], [107] because of the green technology aspect. More precisely, a SUN is a telemetry system designed to modernize the traditional electrical grid. SUNs have been proposed to facilitate the management of a wide range of utilities, such as water, electricity, sewage, and natural gas [24]. A usage model for SUNs has four types of components, namely utility provider base stations (BSs), data collectors, smart meters, and mobile data collectors. Smart meters of different utilities in a FAN/NAN are connected via a SUN radio frequency (RF) link. SUNs form an ad hoc topology as each house is connected to at least one of its neighboring houses [24]. A data collector covers a service area formed by a collective number of households. Connected through a mesh network, data collectors communicate with the utility provider BSs via wireless or wired links. In case of emergency situations or malfunctioning of the fixed data collectors, mobile data collectors may be deployed. Unlicensed TVWS devices or TV band devices (TVBDs) may be of two different types: (*i*) fixed devices operating at a fixed location with a high-power outdoor antenna similar to the BSs of a cellular network, or (*ii*) portable devices operating at low power, which can act as an access point in a HAN.

SUNs must have certain communication protocols in order to utilize the unused TVWS spectrum. Therefore, both the SUN system and the TVWS system must possess a specific level of homogeneity in terms of implementation scenario and system behavior. The study [11] mapped the SUN components to the TVWS communication system architecture. In this mapping, the BSs at the utility headquarters are viewed as fixed TVBDs because the BSs at headquarters and control centers have high-power for establishing metropolitan area networks. From the perspective of TVWS regulations, the data collectors can be viewed as independent TVBDs, while the smart meters are equivalent to client TVBDs because data collectors are connected to the consumer premises. A sensing-only device serves as a mobile data collector in SUNs, having low power consumption and no geo-location awareness. While this SUN to TVWS mapping appears promising, there are still some hurdles to overcome; for instance, the requirements specified by regulators for occupying TVWS would need to be relaxed and TVWS licensing would need to be re-examined [11].

b) IEEE 802.22-based SCADA system: To analyze the potential of IEEE 802.22 for SCADA systems, detailed system design studies examining the feasibility and benefits over wired and other wireless systems have been presented in [161]. An IEEE 802.22 system has a BS and a number of users (equipments) located within a cell. A BS is connected with the main network for downlink (downstream) data transmission to the users (receivers). One or more cells may have human machine interfaces (HMI), supervisory control rooms, SCADA server rooms, remote terminal units (RTU), master terminal units (MTU), and intelligent electronic devices (IEDs) [161]. The control center consists of a control server (MTU), communications routers, HMI, and engineering workstations. These are connected by a local area network through wired or wireless links. The control center is responsible for collecting data from the field sites and displaying the data to the HMI [161]. The control centers also generate actions based on detected events, provide centralized alarming, as well as trend analyses and reporting. The field site has remote access capability and regulates the local control of actuators and monitors sensors using standard and proprietary serial communication protocols based on the IEEE 802.22 standard [161], which also connects all SCADA components and manages the CR aspects of the SCADA system. With the help of SCADA equipment, the BS performs distributed measurement of the signal levels on various channels to make decision about frequency, best available channel, and transmission power. IEEE 802.22 has a range of 33 km at 4 W EIRP and in some cases up to 100 km range. To cover longer distances, multiple base stations should be placed. The download speed is about 1.5 Mb/s at the cell edge, while the uplink speed is 348 kb/s.

MTU-RTU communication architectures can have various topologies [161], including point-to-point, series, series-star, and multi-drop topologies. Large SCADA systems have hundreds of RTUs and employ sub-MTUs to alleviate the burden on the primary MTU. Both the BS and equipment sense the spectrum for three variants of licensed transmissions [161]. These three variants are analog television, digital television, and licensed low-power auxiliary device transmission. The air interface in IEEE 802.22 system is flexible and adaptable so that harmful interference to the incumbent PUs can be avoided [161]. An OFDM modulation system has been adopted to counter multi-path propagation and selective fading. For multiple users, OFDMA with a variety of modulation schemes such as QPSK, 16-QAM, and 64-QAM with convolution coding rates of 112, 3/4, and 2/3 may be used for both upstream and downstream data links. For improved performance, IEEE 802.22 has to adopt "channel bonding," which utilizes multiple channels simultaneously. The SCADA server polls and issues high-level commands, and looks for priority interrupts coming from field site alarm systems.

8) Advanced Metering Infrastructure: The Advanced Meter Infrastructure (AMI) estimates, collects, and analyzes energy usage and interacts with smart meters through some communication media. A two-layer architecture has been proposed for AMI communication [164]. The two-layer architecture utilizes TVWS and has two types of wireless networks in a hierarchy. The lower level has small scale white space networks implemented through WhiteFi [206]. WhiteFi is similar to WiFi, however, WhiteFi exploits white spaces in the ultra high frequency (UHF) band, which includes the TVWS. The upper level in the hierarchy consists of 802.22 networks operated by independent broadband service providers to interconnect WhiteFi access points and the utility company. These networks may also serve other clients, such as residential households and mobile devices. This cost-effective two-layer architecture provides high data rate connections to the smart meters owned by the utility. However, the 802.22 service provider benefits from the spectrum sensing data of smart meters through the WhiteFi base stations. The 802.22 service providers can also obtain spectrum sensing data from other clients of the 802.22 service or sensors deployed specifically for spectrum sensing. Also, if there are transmitter databases available, the list of available channels from both spectrum sensing and transmitter databases are intersected to derive the list of available channels. All of these features require coordination among the WhiteFi and 802.22 base stations using co-existence techniques [164].

a) 4G cognitive radio architecture: A CR LTE network (4G CR) with a cloud data center infrastructure based on a CR network coexisting with a PU network has been proposed in [108]. In the proposed network, the coverage of both the CR base station and the PU network base station remain the same. The PU base station is responsible only for PUs as it does not have the CR protocol capabilities to support SUs. A CR antenna is placed on the BTS tower in addition to the deployment of the cellular provider antenna. The CR senses a wide frequency band, particularly the spectrum in the cell region. After identification of the unused bands, information is relayed to the cloud data center. All services, including CR service, waveform service, protocol service, and security service, as well as scheduling and control services, are conducted in the cloud data center. When an unused frequency band has been identified, a clear-to-send (CTS) message is generated by the relevant cognitive services residing in the cloud data center. The CTS message is then transmitted back via the base station to the AMI meters using a feedback channel. Finally, the CR antenna transmits CTS message to every AMI in the cell region for uplink transmission. In the proposed system model, the 4G cellular network is considered with secondary users (fixed AMI meters) sharing the spectrum simultaneously with PUs. The purpose is to present a 4G CR network framework that is capable of controlling a high number of geographically dispersed smart meters through concurrent communication with a private cellular network. The performance analysis considers throughput and fairness. This system model has five important features in context of SG information systems: spectrum sensing, energy detection, PU activity model, optimum sensing time, and scheduling algorithms for CR users [108].

b) Wireless Cloud Data (WCD) architecture: The Wireless Cloud Data (WCD) architecture proposed in [108] is organized into four principle layers: application layer, platform layer, CR communication and networking layer, and infrastructure layer, as illustrated in Fig. 5. The top two layers are similar to present cloud architectures [207], but the lower two layers are enhanced for CR networking and wireless services. The CR communication and networking layer is related to CR services, waveform services, Radio Link Control (RLC), and Medium Access Control (MAC) services. The infrastructure layer enables the effective integration of computing resources, storage, networks to deploy applications and operating systems [108].

The MAC and the PHY layers of IEEE 802.22 perform the CR related tasks. The cloud-related tasks, such as the SG application services and the communication platform services, are performed through cloud micro-processor servers and radio servers. With the help of the WCD center, sophisticated spectrum sensing is possible correlated to the directional and frequency sensing patterns of the antenna in the CR protocol [197]. A wide frequency band is sensed by a CR antenna and the sensed signals are sent to WCD center over a broadband fiber optic link. The coexistence of a large number of distributed systems in the SG, such as smart meters, can result in simultaneous uncoordinated access to frequency bands. The WCD can alleviate this situation by analyzing the effects of the MMSE

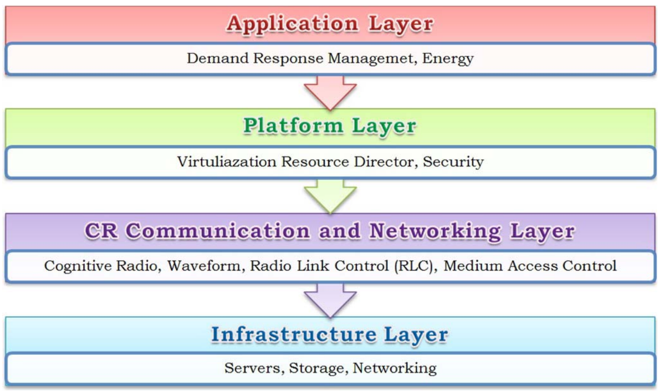

Fig. 5. Layer-wise architecture of wireless cloud data (WCD) center model.

beamformer to suppress self-interference in the uplink channel of CR-based SG systems.

A centralized communication and optimization architecture with a cloud computing data center has been proposed in [166] for supporting a CR network of AMI meters. The proposed infrastructure is a potential solution for an extensible and persistent SG information network. This framework is called the netbook advance metering infrastructure (Net-AMI). Similar to the WCD in [108], the microgrid cloud is structured into the four layers illustrated in Fig. 5. All Net-AMI meters formally register with the utility service provider. The WCD center ensures long-time services by equipping the Net-AMI network with legacy system protocols, proprietary protocols, and future systems protocols. The AMI meters access the shared pool of configurable computing resources in the WCD center through CR channels. The proposed CR method can secure time-frequency bands for wireless communication of important power service applications independent of a cellular or other network infrastructure. For 1 W uplink and 10 W downlink CRs, data rates, ranges, and capacity configurations reveal highly reliable data rate configurations from 1–3 km. An important feature of this solution is the duplex information relaying between the Net-AMI and CR antenna and the WCD center via fiber optic techniques, known as radio over fiber (ROF) [166].

In particular, CR antennas and cellular provider antennas are deployed on the base transceiver station on the utility and NET-AMI sites to provide wireless connectivity. Using the existing base transceiver stations minimizes infrastructure cost and path loss. CRs sense for unused channels in the cell to enable communication between utilities, NeT-AMI, and the cloud data center. The information about sensed channels is sent to the cloud data center through fiber. A CR antenna is then accessed through ROF to prepare and send/receive responses to the NET-AMI through cloud data center services. Data from the Net-AMI is analyzed by the cloud data center to prepare and send a control signal to the NET-AMI in order to control devices [5], [166].

C. Summary

We have surveyed the existing architectures for CR-based SG systems according to the classification illustrated in Fig. 4. The survey indicates that the majority of existing studies have examined hybrid structures. Only a few studies have focused exclusively on one architectural layer, and those few studies have examined HANs. We recommend that future research should first focus on practical solutions for individual layers, i.e., either HAN, NAN, or WAN, and then examine the combined effects of interacting layers on the SG system as a whole.

Our survey has found that CR-based communication architectures typically involve also other communication techniques. Only very few studies have examined the adoption of only CR communication, usually based on the IEEE 802.22 WRAN standard. Thus, we recommend that future research should first examine and thoroughly understand stand-alone CR-based communication, i.e., pure CRNs, for SG applications. Subsequently, the detailed understanding of pure CRNs can be brought into the study of hybrid architectures that employ CR communication in conjunction with other communication techniques. Similarly, cooperation among different architectural layers in terms of cognitive behaviors is largely an open research area.

In addition to these two outlined broad future research directions, our survey has identified a few specific open research issues. We observed that the optimal location of CR antennas remains an open research issue. In HANs, there may be several smart meters, however it remains unexplored how to incorporate the HAN CR antennas. Data storage has been idealized with cloud computing data centers, however, the effects of disruptions, e.g., if CRs do not find unused channels or there is a disaster, have yet to be studied in detail.

VII. CR-Based Spectrum Sensing Approaches in SG

CR-based spectrum access has two main participants: (*i*) The primary user (PU) owns a licensed channel and has priority for channel usage. (*ii*) The secondary user (SU) opportunistically senses the licensed spectrum, identifies the spectrum holes, and maintains a set of locally available channels that do not interfere with the PU. Spectrum sensing involves the process of gathering information about the available spectrum bands and the presence of the PUs, as well as the detection of spectrum holes. The spectrum sensing process consumes power and makes cost-effective CR communication challenging. Cost-effective sensing solutions commonly use minimized hardware or short sensing durations [25]. In a common application of the CR-based SG, smart meters act as SUs and opportunistically search for the available spectrum to transmit power-related data to a data aggregator unit in a cost-effective manner [218].

SUs operate on a specific frequency band as long as the band is not used by a PU. Upon arrival of a PU, SUs switch to another vacant band. The CR capability allows the SG devices to sense the unused spectrum opportunities in the surroundings and benefit from these, subject to interference constraints [6]. There are four on-line tasks in the cognitive cycle that interact through the RF environment, as illustrated in Fig. 6: spectrum sensing, spectrum sharing, spectrum mobility, and spectrum management [20].

- Spectrum sensing analyzes the radio-scene by estimating the interference temperature of the radio environment and detecting spectrum holes [6]. The interference temperature defines a metric for the effects of the transmit power level of a user on its neighboring receivers on the same frequency band.

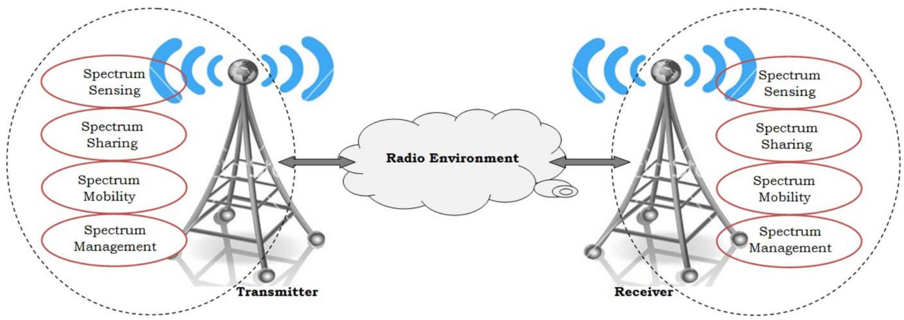

Fig. 6. The cognitive cycle consists of four on-line tasks: spectrum sensing, spectrum sharing, spectrum mobility, and spectrum management. The tasks are executed at each of cognitive radios (CRs), whereby distinct CRs interact through the radio environment.

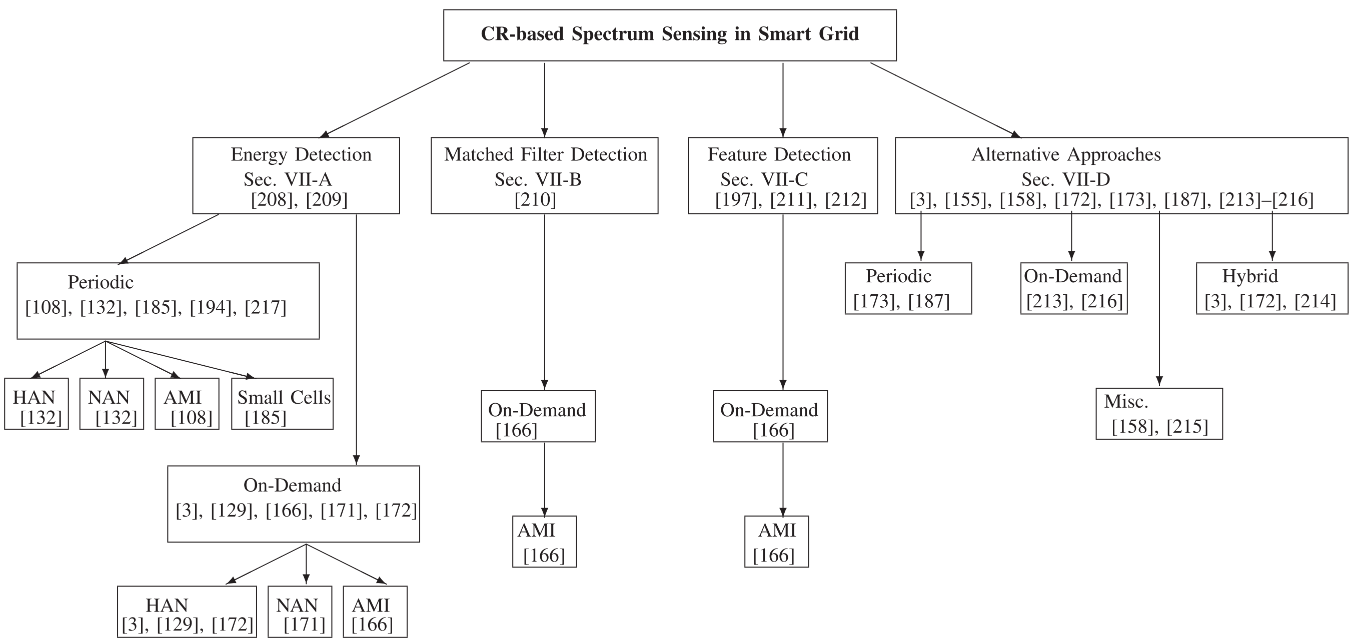

Fig. 7. Illustration of classification of CR-based spectrum sensing approaches according to detection method (energy, matched filter, or feature detection) with sub-classification into periodic and on-demand sensing. Alternative approaches from studies that focus on other aspects of sensing are sub-classified into periodic, on-demand, and hybrid (periodic-on-demand) approaches as well as miscellaneous studies.

- Spectrum sharing coordinates access to spectrum holes with other users.
- Spectrum mobility vacates a channel when a licensed PU is detected, while maintaining seamless communication for the SU.
- Spectrum management selects the best available channel among spectrum holes for communication.

Three sensing methods have commonly been investigated in the context of the SG [108], [158], [219], as illustrated in Fig. 7: Energy detection, Matched Filter, and Feature detection. In the following sub-sections we survey the spectrum sensing studies that have been conducted in the context of the SG. As depicted in Fig. 7, we classify the studies according to their focus on either energy, matched filter, or feature detection in the spectrum sensing or the focus on alternative aspects of spectrum sensing. The studied approaches are sub-classified according to the type of operation, i.e., periodic, on-demand, or collaborative operation. We further sub-classify the studied approaches according to the considered communication architecture.

A. *Energy Detection-Based Spectrum Sensing*

The study [208] has proposed a CR-based scheme for the SG with spectrum sensing and channel switching and analyzed the sensing-performance tradeoff problem. The spectrum sensing and channel switching allows smart meters to transmit data either on an unlicensed channel or on a licensed channel in order to reduce communication outages. The analysis in [208] examines how the spectrum sensing in CR communication influences the communication quality, and how, in turn, the communication quality influences the SG control performance, specifically, the performance of demand response management (DRM). The implications of the quality of the DRM control on the profit of the power provider and the SG social welfare defined as the consumer satisfaction minus the power provider cost are also analyzed. Through this analysis, an overall tradeoff between the CR sensing and the performance of the CR-based SG is established. The results in [208] identify the analyzed energy detection spectrum sensing a unique optimal sensing time that yields the maximum tradeoff revenue subject to protection of the PUs.

The sensing-delay tradeoff is further examined in [209] by applying the concept of energy detection sensing to two channels. The optimal sensing time is estimated to minimize the packet loss rate and delay while protecting the PU. The main purpose of the study [209] is to provide timely access to meter data in the SG. The examination of the sensing-delay tradeoff problem revealed that the unique optimal sensing time yields the minimum delay.

1) Energy Detection-Based Periodic Spectrum Sensing:

a) General sensing frameworks: A dynamic spectrum access method to mitigate channel impairments in the SG environment has been proposed in [194]. The proposed cross-layer framework employs CR communication to support QoS for SG applications. The SG QoS requirements are defined in terms of minimum to maximum ranges for three metrics, namely data (bit) rate, delay, and reliability. A particular combination of ranges of these three metrics is defined as a QoS (service) class. The framework dynamically switches among different spectrum bands to seek a channel with a constrained noise signal. A Lyapunov drift optimization is employed to maximize the weighted service of application flows of different service (QoS) classes. A suboptimal distributed control algorithm (DCA) is proposed to jointly optimize the routing, medium access, and physical layer functions. The DCA dynamically selects the channel depending on the perceived signal interference and the estimated channel capacity, and supports QoS through dynamic spectrum access [194]. The numerical performance evaluation presented in [194] considers four QoS (service) classes, including a critical real-time QoS class with very low delays, e.g., for emergency messages, and a QoS class with low data rate and moderate reliability, e.g., for smart meter reading. The presented evaluation results indicate that the proposed framework is generally successful in meeting the specified QoS requirements.

In the SG, SCADA systems may interfere with other devices using occasionally the same spectrum band. The study [217] designed a periodical sensing (PS) process for a WiMAX-based CR system to manage in-band interferences during normal wireless communication in power distribution station's monitoring. The process gathers real-time interference information. A cross-layer message between the PHY and MAC layers delivers the interference location information to downlink and uplink. The PS data is analyzed in the time and frequency domains and received interferences are classified into several types. Based on these classifications, corresponding management methods are executed to minimize interferences. The spectrum sensing has two stages: an initial sensing stage at the Wireless Edge Appliance (WEA) layer network entry in the power distribution monitoring system and a periodical sensing stage for normal communication. The WEA collects information about the operating frequency through initial sensing to find a relatively clear white space. The periodical sensing scans the 1.1 MHz working spectrum of the WEA at the uplink receiver. The scanned interference information is forwarded to the Wireless Access Appliance (WAA) layer, which is a part of the power distribution monitoring system within the modified WiMAX protocol. The approach is verified through analysis of coverage and throughput results [217].

b) Energy detection-based periodic sensing in HAN, NAN, AMI, and small cells: In a cognitive machine-to-machine (CM2M) communications architecture for the SG, an energy-efficiency driven spectrum discovery scheme is proposed in [132]. We review the general spectrum sensing features of this proposal in this section, the green energy-saving aspects of this proposal are reviewed in Section XII-A. For HAN and NAN architectures, the network components are divided into two main parts, the primary network referring to the existing licensed wireless network and the secondary M2M network. Cognitive machines coexist with PUs and opportunistically utilize the spectrum. A cognitive Access Point (AP) gathers or delivers information in a local area CM2M network. A Secondary Base Station manages the cognitive machines, and an optional spectrum broker or spectrum geo-location database coordinates the spectrum allocation among multiple CM2M networks [132]. Moreover, a coordination based energy-efficient spectrum discovery scheme is presented [132].

Green cognitive mobile networks with a small cells architecture (see Section VI-B2) have been proposed in [185] to meet the high-data-rate requirements of mobile multimedia communications in the SG. The energy-detection based sensing scheme proposed for this architecture not only senses the radio spectrum environment, but also senses the SG environment. The macrocell base station (MBS) and small cell base stations (SCBSs) sense the SG environment to adapt their electricity consumption by performing energy-efficient resource allocation. The proposed scheme assumes one MBS and multiple SCBSs in each service region. Every SCBS provides service for several users, and is connected to the MBS over a broadband connection, such as a cable modem or a digital subscriber line. Equipped with CR capability, the MBS attains information of spectrum access by the SCBSs, whereas SCBSs can search for channels in the surrounding radio spectrum environment and are allowed to intelligently access the subchannels. Operating in a time-slotted manner, the spectrum resource licensed to the MBS is divided into multiple subchannels in each time slot. The macrocell users (MUs) use OFDMA technology to communicate with the MBS. To mitigate cross-tier interference, an interference price mechanism is utilized that enables the MBS to protect its users by charging the SCBSs and SCBSs adjust their transmit-power accordingly [185].

An energy detection spectrum sensing approach for throughput analysis in AMI meters has been proposed in [108]. The scheme is suitable for multiband sensing as energy detection sensing has low computational and implementation complexities. The system model utilizes OFDM modulation with subcarriers and IEEE 802.22 for opportunistic SU access to the TV spectrum. The CR service in the WCD detects the RF energy in a prescribed subcarrier to detect the presence of the active users. Two performance parameters for spectrum sensing are defined, namely the probability of detection and the probability of false alarm along with the optimum sensing time.

2) Energy Detection-Based On-Demand Sensing in HAN, NAN, and AMI: The presence of multiple smart devices in home areas and the co-existence of different wireless technologies causes a spectral overlay which may result in severe interference. Coordinating the spectrum access by these heterogeneous wireless systems through cognitive spectrum sharing can mitigate the interference. This reasoning has motivated an HGW-assisted cross-layer cognitive spectrum sharing mechanism in HANs [3], [172]. The scheme is utilized to transmit data from smart devices in HANs through dynamic spectrum access over unlicensed bands. The spectrum sharing approach has two main components: the spectrum access controller and the power coordinator. The cross-layer scheme operates at the MAC and PHY layers. The access controller grants spectrum access to each wireless node in a HAN and the power coordinator manages the transmit power. More specifically, the spectrum access controller controls the number of new wireless nodes to ensure the QoS of all in-service wireless nodes. A new node is only admitted to the network if it does not deteriorate the achievable rate of one or more existing nodes. The admission control decisions are made through a game-theoretic framework that determines the optimal power control and achievable rates of all nodes, including the new node [3], [172].

For efficient SG services in cognitive NANs, a hybrid spectrum access mechanism has been proposed that intelligently schedules the licensed and unlicensed spectrum bands [171]. The optimal number of leased and reserved channels is derived through a two-dimension Markov chain analysis based on transmission demands. The proposed strategy significantly improves the network capacity compared to the traditional fixed spectrum access strategy [171].

An SG HAN communication infrastructure solution based on next-generation heterogeneous wireless systems comprising of several Radio Access Technologies (RATs, see Section VI-A2) at consumer premises has been proposed in [129]. A central Global Resource Controller (GRC) informs a smart device to use a particular RAT at any given time. The reconfigurable radio (RR) initially senses the RATs and then registers itself with the GRC before transmitting or receiving data. The GRC performs device-to-RAT association using a two-step scheduling algorithm. A Dynamic Spectrum Access (DSA) method makes the solution scalable by obtaining additional open spectrum. A Spectrum Manager is also present to maintain a database of available and leased open spectrum. The Access Point (AP)/ Base Station (BS) of each RAT may obtain additional open spectrum through DSA techniques after communicating with the spectrum manager. The approach achieves an 80% increase in real-time traffic support and an 726% increase in best-effort traffic support with re-configurable radios as compared to static radios [129].

For a CR-based cloud computing data center of Net-AMI networks (see Sections IV-D2 and VI-B8b), a communication and networking layer is designed in [166] to provide on-demand radio link control (RLC), and medium access control (MAC) services. The cloud data center offers CR services, including spectrum sensing and spectrum management. A CR antenna on the high BTS transmitter maximizes CR sensing for spectrum management services. Sensing is defined as the combination of signal detection, modulation, and classification and is performed over a wide frequency band, particularly over the spectrum in the cell region. The sensed information about unused spectrum bands (whether owned by cellular companies or licensed) is relayed over a fiber link to the cloud data center [166].

B. Matched Filter Detection-Based Spectrum Sensing

Dimensionality reduction techniques, such as principal component analysis (PCA), kernel PCA, and landmark maximum variance unfolding (LMVU), on Wi-Fi signal measurements are examined in a spectrum sensing context in [210]. Compressed sensing algorithms, such as Bayesian compressed sensing and compressed sensing Kalman filters, are also proposed. Compressed sensing finds sparse solutions to underdetermined linear systems. The Bayesian compressive sensing and compressed sensing Kalman filter are applied for sparse smart meter reading by the access point or central control unit when the noise is Gaussian distributed. The SG data recovery problem is treated as a linear regression problem and is considered from a Bayesian perspective in Bayesian compressive sensing. The Kalman filter performs optimal prediction estimation of the true system state. An error is estimated in the prediction and a weighted average is computed of the predicted value and the measured value. The Kalman filtering approach is used for the recovery of sparse signals. The compressed sensing allows the smart meters to transmit simultaneously, in contrast to the CSMA protocol, which uses a random backoff to avoid collisions [210].

1) Match Filter Detection-Based On-Demand Sensing in AMI: An on-demand matched filter detection scheme for AMI networks (see Sections IV-D2 and VI-B8b) is proposed in [166]. The services in secondary Net-AMI users need a priori knowledge of PU signal statistics. The matched filter sensing requires less detection time than energy detection or feature detection sensing, but generates optimal results only when stationary signals are detected in the presence of Gaussian noise [166].

C. Feature Detection-Based Spectrum Sensing

1) General Sensing Approaches: A beamforming approach based on the minimum mean squared error (MMSE) method to effectively counter the self-interference effects of the smart meter channel is proposed in [197]. This approach requires an accurate channel and noise-plus-interference power estimation. A two-way estimation scheme that exploits the preamble feature of IEEE 802.22 WRANs is proposed [197]. The framework utilizes a cloud computing SG infrastructure (see Section VI-B8b) suitable for metropolitan area networks that incorporate the IEEE 802.22 WRAN CR standard. The CR protocol recognizes the surrounding radio environments and operates in unused spectrum without causing harmful interference to PUs. The wireless cloud data (WCD) center in this model allows for sophisticated spectrum sensing based on the directional and frequency sensing patterns of the antenna in a CR protocol. The CR antenna senses the spectral environment over a wide frequency band and forwards the sensed information to the WCD center over a broadband fiber optic link. The CR services in the WCD center perform spectrum sensing, spectrum management, spectrum decision, and spectrum sharing [197].

A powerful cyclo-stationary sensing method for a CR-based SG infrastructure has been proposed in [211]. Based on White Gaussian Noise (WGN) analysis and interferences, cyclo-stationary sensing allows the CR to detect licensed signals with a particular modulation type in a background of noise and other modulated signals for distributed automation systems and distributed energy resources in the SG [211].

A spectrum sensing solution for a real-time CR network testbed for SG applications has been examined in [212]. The algorithm evaluates the signal feature as leading eigenvector in an online manner and then uses the feature for signal detection. As this feature-based detection does not use any energy information, there is no noise uncertainty problem. The proposed detector outperforms other blind detectors under -20 dB SNR at the expense of a small amount of overhead for feature extraction [212].

2) Feature Detection-Based On-Demand Sensing in AMI: The feature detection in [166] correlates with reoccurring specific features of wireless signals, such as pilot signals, synchronization channels, or cyclo-stationary signal properties. The scheme in [166] can differentiate the noise energy from the modulated signal energy in a cognitive radio network of AMI meters. Suitable for low SNR, the scheme requires quite long and complex processing, which is conducted in a cloud computing data center (see Section VI-B8b). However, the long computation time can be minimized by utilizing cooperative detection. Prior knowledge of the PU or SU information statistics is required. The detection sensitivity and detection time requirement can be reduced by collecting observations from multiple CRs at the expense of increased overhead and control for the CR network.

D. Studies on Other Aspects of Spectrum Sensing

In this section, we give a comprehensive overview of spectrum sensing studies that do not focus on a particular detection scheme (i.e., energy, matched filter, or feature based detection) but examine other aspects of spectrum sensing in CR-based SG systems. We organize these studies on other aspects of spectrum sensing according to their timing as operating periodically or on demand.

1) Periodic Spectrum Sensing in HAN, NAN, WAN, and Femtocells: A CR-based SG communication infrastructure with back-up bands in the ISM bands and leased bands for ensuring data communications QoS has been proposed in [173]. A time-to-stop spectrum sensing and access ISM bands is analyzed and a communication scheme is proposed for distributed power generation systems. The HGWs sense the spectrum in a cognitive HAN and cognitive NAN until unoccupied spectrum bands are found. If the sensing time is very long, then there would not be enough time for data transmission, reducing the network throughput. Therefore, a time is defined in [173] at which the HGWs stop sensing for unoccupied licensed bands and instead access the leased ISM bands. As there are a typically few leased bands, which also serve as back-up bands for the transmission of critical data in emergency situations, the NGWs periodically sense the spectrum. If an NGW finds an unoccupied spectrum band, then it exits the leased bands.

A framework to periodically sense both the radio spectrum environment and the SG environment for cognitive heterogeneous mobile networks with femtocells (see Section VI-B2) is analyzed in [187]. This sensing scheme decides power allocation and interference management. In each femtocell, there is a femtocell base station (FBS) serving multiple users. FBSs monitor the surrounding radio spectrum environment and randomly access the spectrum. The macrocell base station (MBS) monitors the spectrum access by the femtocells with CR technology. The MBSs protect themselves from cross-tier interference by charging the femtocell users an interference price. The femtocells perform energy-efficient allocation or change their subband access according to the interference price offered by the MBS [187]. A similar power allocation approach for the setting of only one SU and one PU is considered in [220].

2) On-Demand Spectrum Sensing in HAN and General Architecture: A biform game-based CR communication model for developing adaptive CR spectrum sensing and sharing algorithms for SG environments has been examined in [213]. The presented scheme operates on unlicensed bands and supports large data traffic amounts. Initially, the SUs estimate the current network condition and adaptively form clusters (according to a non-cooperative game model) for the cooperative spectrum sensing in a small portion of the multiband. The next phase involves the sharing of the detected idle spectrum based on a cooperative bargaining model. In each cluster, every user independently senses the spectrum and relays this information to the cognitive base station (CBS). The CBS is the decision-making authority controlling the usage of the CR spectrum. The proposed scheme enhances spectrum efficiency while ensuring fair sharing. SUs compete or coordinate with each other in a dynamically changing network environment to maximize their payoffs [213]. To resolve the overload control problem due to large data amounts in smart meters, on-demand spectrum sensing is applied [213]. Specifically, a dynamic radio resource allocation (DRRA) algorithm of the group paging mechanism is adopted in smart meters for 3GPP LTE networks [216].

3) Hybrid Periodic and On-Demand Spectrum Sensing in HAN and NAN: The HAN Cognitive Gateway (HGW) proposed in [3], [172] autonomously adapts to different radio technologies and opportunistically accesses the spectrum by combining both periodic and on-demand sensing. The HGW is connected to external networks, such as a NAN, utility, or the Internet. The HGW strives to provide an optimal data rate with low interference over the license-free spectrum bands. Hybrid dynamic spectrum access can improve spectrum efficiency in a NAN. Some licensed spectrum bands are leased/bought from a telecommunication operator and a NAN gateway (NGW) distributes these licensed bands to the HGWs according to the transmission demand. As licensed spectrum bands may be insufficient to meet the SG data requirements, HGWs may also need unlicensed access.

Each NAN shares its information with the utility control center through the WAN. Each NAN Cognitive Gateway (NGW) is no longer an access point; rather the NGW behaves as a cognitive node capable of communicating with the control center through unused frequency spaces. Several CR base stations may be connected to the control center. A spectrum broker enables the coexistence of multiple NANs by sharing the spectrum resources among the different NANs and managing communications among them. The spectrum broker has to respond quickly to meet the real-time changes in the network. In case of a large geographical area, base stations may not cover several NGWs.

Therefore, NGWs have to set up an ad hoc communication mode for sharing unoccupied spectrum bands. Both licensed and unlicensed band access are employed in a WAN and several NANs may share the same spectrum bands in a large service area without causing interference to each other [3].

Cost-driven spectrum leasing and quality of service (QoS)-driven spectrum management are two main challenges in the SG. A solution to these two optimization problems is formulated and evaluated for CR-based SG networks in [214]. The hybrid spectrum access (HSA) mechanism in [214] uses both licensed and unlicensed spectrum bands. The impact of the spectrum sensing error on the performance of HAS is analyzed with a multidimensional Markov chain. The spectrum sensing error may degrade the spectrum utilization causing high interference between the primary and SG services. The impact of spectrum sensing on the HSA mechanism is examined for two sensing types, namely periodic sensing and on-demand sensing. Periodic sensing detects the occurrence of the PUs with a fine sensing technique that requires high sensing accuracy. On-demand sensing quickly identifies available spectrum bands for new services through a fast sensing technique with moderate sensing accuracy. On-demand sensing does not sense all the channels as compared to periodic sensing. The proposed periodic sensing has negligible sensing error, but on-demand sensing can cause significant sensing errors [214]. The QoS-driven spectrum management problem is evaluated in terms of dropping probability, blocking probability, interference probability, and required number of licensed channels for different SG service loads and demonstrates good performance.

4) Collaborative Spectrum Sensing in NAN: An access network connecting smart meters to the concentrator with a wireless mesh NAN has been examined in [155]. The examined smart metering network architecture is based on communication through TVWS spectrum. A Radio Environment Maps (REMs) model in conjunction with a geo-location database manages the channel usage by the concentrator. The REM model is an integrated database that describes a radio environment consisting of multi-domain information, e.g., spectrum availability, geographical features, regulations, radio equipment profile, and past experiences. The REM information may be utilized to ensure cognitive functionalities, such as situation awareness and dynamic spectrum access. It may also be used to study the effects of the PU arrival interval on the network re-configuration latency and packet delivery ratio. Each node and a dedicated sensor network in the physical proximity of the node can provide local current sensing information of the white spaces to the REM [155].

5) Miscellaneous Spectrum Sensing Studies: To overcome varying spectrum characteristics and harsh environmental conditions for SG applications in WSNs (see Section VI-B5), spectrum-aware and cognitive sensor networks (SCSNs) are discussed in [158]. The distributed spectrum-aware sensor nodes monitor critical SG equipment. The sensed data is dynamically sent over available spectrum bands in a multihop fashion to meet the application-specific requirements [158].

The spectrum utilization in the UHF/VHF, cellular (GSM 900, GSM 1800, and 3G), WiMAX, ISM, and LTE bands has been studied in [215]. The study found that the TV spectrum band has low utilization making it suitable for the CR-based WAN infrastructure in the SG. The study [215] also observed that the cellular band is potentially available for the cognitive NAN in the SG.

E. Summary

Our comprehensive survey of the existing spectrum sensing mechanisms for CR-based SG systems followed the classification in Fig. 7. Based on this survey, we conclude that energy detection protocols have been extensively researched. This is primarily because energy detection protocols are simple to implement and give optimal sensing time while ensuring the necessary protection of the licensed channel. Energy detection has low computational complexities and can detect the signal even if the PU signal statistics are unknown. The main drawbacks of energy detection spectrum sensing are the poor performance in low SNR environments and the inability to distinguish between signal, noise, and interference.

Spectrum sensing with the feature detection strategy has been examined in relatively few studies to date. Feature detection enables CR users to detect licensed signals with a particular modulation type against a background of noise and other modulated signals. Channel effects are included in feature detection. Also, the feature detection strategy avoids the noise uncertainty problem and works well at low SNR. Feature detection requires relatively long, complex signal processing as well as a priori statistical knowledge of the PU or SU signals for satisfactory performance. The long computation time can be reduced through the use of cooperative detection at the expense of increased overhead and control for the CRN.

In comparison to the energy and feature detection strategies, matched filter detection has received very little research attention to date. Matched filter detection is attractive as it has relatively short detection time. However, feature detection is only applicable if SUs have a priori knowledge of the PU signal statistics. Moreover, optimal detection results are only obtained when stationary signals are detected in the presence of Gaussian noise.

Overall, we conclude from the comprehensive survey of existing spectrum sensing studies for CR-based SG systems that the research to date has exposed the basic trade-offs of the individual spectrum sensing strategies based on energy, feature, and matched filter detection in the SG context. Future research needs to build on these basic tradeoffs to develop and refine spectrum sensing protocols for CR-based SG systems that meet a good combination of the following goals: First, they ensure necessary PU protection while satisfying the QoS requirements of SG applications. Second, the detection process should terminate within a short detection time while having low complexity. Third, the process should be reliable, i.e., the signal detected from the PU should be distinguished from noise or interference. One promising direction for future research on spectrum sensing in CR-based SG systems may be to explore hybrid schemes that combine aspects of the three main sensing strategies energy, feature, and matched filter detection that so far have been examined in isolation. Moreover, adaptively selecting and combining the three main sensing strategies according to environmental conditions may be beneficial for CRs supporting SG

TABLE V
MAC PROTOCOLS FOR CR-BASED SMART GRID CLASSIFIED ACCORDING TO TYPE OF COMMUNICATION TECHNOLOGY

Reference	Contribution	Simulation Tool	Metrics Evaluated	PR Activity Model
CSMA/CA with DSA [193]	Cross-layer design for QoS	NS-2	Delay, Throughput, Reliability	Not considered
Suboptimal Distributed Control Algorithm [194]	Cross-layer design for QoS	NS-2	Packet Delivery Ratio, Channel Usage, Delay, Packet Deadline Miss-ratio, Throughput	Not considered
CRB-MAC [221]	Energy efficiency with improved delay	MATLAB	Energy Consumption, Delay, Reliability	Energy-based detection
PRMA-based MAC [22]	Co-existence and tradeoff of cognitive M2M network with primary network	MATLAB	Throughput, Duty cycle, Average access delay, Effect of reservation cycle	SNR detection

applications and should be examined. Furthermore, the sharing of sensed information among multiple CR users, which may be achieved by performing neighbor discovery, may help CRs differentiate between transmissions of PUs and other SUs. The optimal combination of continuous sensing and on-demand sensing is also an important future research direction, particularly for delay-sensitive SG applications.

VIII. CR-BASED MAC PROTOCOLS FOR SMART GRID

The data link layer functionalities include medium access control (MAC) and error control. CR-based communication architectures should have energy-efficient MAC protocols that take the dynamic CR spectrum management into consideration. Moreover, resource limitations, dense deployment, application-specific QoS requirements, spectrum sensing, and channel identification requirements should be considered in an efficient MAC protocol design for CR-based SG networks. The research on MAC protocols for CR-based SG networks to date is summarized in Table V. The table indicates the main contributions of each study along with the simulation tools used to evaluate performance metrics. An important aspect of a MAC protocol study is whether the study did or did not consider a PU activity model [104].

A cross-layer CR-communication approach for the SG based on a CSMA/CA MAC protocol has been presented in [193]. This cross-layer approach integrates the CSMA/CA MAC protocol with dynamic spectrum access (DSA), which evaluates the list of available channels. The other protocol layers (e.g., the routing layer reviewed in Section IX-B) set the contention window size of the MAC protocol to control the overall cross-layer system. The MAC protocol prioritizes transmissions through different backoff intervals. The CR communication cross-layer framework [193] is applied to a QoS scheme in [194]. More specifically, a suboptimal distributed control algorithm based on the CSMA MAC protocol has been developed to support efficient QoS through a combination of dynamic spectrum access channel selection decisions, flow control decisions, and packet dropping [194]. The proposed channel control algorithm has a frame with three periods for spectrum sensing, control, and data transmission.

An important step for the integration of CR-equipped sensor networks into the SG is to optimize the MAC layer to achieve low-overhead spectrum access, joint spectrum sensing and duty cycling to balance the trade-off between spectral efficiency and energy efficiency, as well as reliable operation in heterogeneous wireless environments. To support these attributes, an energy-efficient and reliable CR-based MAC (CRB-MAC) protocol design has been proposed for CR-equipped sensor networks in the SG in [221]. It is assumed that each node is equipped with a single radio transceiver that can be tuned to any channel in the licensed spectrum. CRB-MAC is a receiver-based MAC protocol and uses preamble sampling and opportunistic forwarding techniques with multiple receiving nodes for each data transmission. “Preamble sampling” (also referred to as asynchronous low power listening) involves idle listening and supports sleep/wakeup modes without synchronization overhead. Each node independently selects its sleep/wakeup schedules and senses the spectrum within a prescribed time duration to detect any PU activity. In case of PU presence, the sender node goes to sleep mode and the sensing operation is repeated after a checking interval has expired. Now, if no PU is detected, the node starts transmitting the preamble followed by the data. The neighbors of the sender wake up, receive the data, and set a timer before forwarding the data to the next hop. The closest node to the sink has the shortest timer and forwards the data towards the sink. Right after the timer expires, each neighbor senses the channel and for PUs. The sender node retransmits only if none of the participating nodes in the contention window duration successfully forwards the data packet. This operation is repeated in case of multiple hops until the data is received by the sink.

Due to the receiver-based nature of CRB-MAC, data from a sender is transmitted without defining a particular receiver node. All the neighboring nodes within the communication range of the sender node receive the data packet, ensuring reliability in the harsh SG environment. The received preamble information enables nodes to decide whether or not to forward the data packet. The receiver which takes the lead in an elective process forwards the data to the next hop towards the gateway/sink. Nodes do not forward data packets during sensing. PU protection is guaranteed as nodes employ an optimal transmission time under an interference constraint. Results in lossy wireless environments indicate that CRB-MAC has few retransmissions, thereby reducing overall energy consumption and delay. The multiple receivers contribute to the high reliability [221].

A MAC protocol is designed in [22] to meet the needs of M2M devices in SG communication systems. The centralized MAC protocol is based on Packet Reservation Multiple Access

(PRMA) with an optimized frame structure to support the coexistence of the cognitive M2M network (secondary network) with the primary network. The underlying available channel of the PRMA-based MAC protocol has a number of fixed length time slots, each for a single packet. A frame is formed by grouping a prescribed number of time slots, and a prescribed number of frames constitute a multiframe. Each multiframe is initialized with a channel detection period followed by a preamble or a multiframe control header to broadcast an enabling signal carrying channel availability information. Time Division Duplex (TDD) is used for channel utilization and slotted ALOHA is used for slot contention. Contention resolution in case of a collision is done by a backoff procedure. Fairness is ensured by limiting the reservation for a definite amount of time among devices. Performance metrics are investigated through analytical models for AMI networks in dynamic power systems.

A. Summary

Our comprehensive survey of MAC protocols for CR-based SG networks has revealed that only cross-layer frameworks (that include some consideration of MAC) for the general CR-based SG communication architecture and MAC protocols for CR-WSNs-based SG networks have been examined to date. On the other hand, there have been no studies to date with a focus on MAC protocols for the general CR-based SG communication architecture. Thus, research on efficient MAC protocol designs for general CR-based SG networks remains a great challenge and is urgently needed.

More specifically, the studies [193], [194] have focused on cross-layer design frameworks based on underlying MAC protocols. MAC-focused studies have only been conducted in [22], [221]. However, the design in [221] focuses only on a receiver-based MAC protocol. All the nodes in the sender's range receive the data and may forward it towards the destination node. If there are a large number of nodes in the SG network, then this scheme may result in high delays and security threats. Moreover, CRB-MAC [221] has high energy consumption in poor channel conditions due to multiple receivers. Future research should seek to optimize the number of receivers needed to achieve prescribed reliability levels while keeping delays and energy consumption low. In the MAC protocol designs proposed to date, only one radio is considered. Future research needs to develop protocols that operate efficiently in multi-radio scenarios. Moreover, the MAC frame structure has usually a sensing slot and a transmission slot; research on optimal frame structures that achieve good sensing and data transmission performance is needed.

IX. CR-Based Routing Protocols for Smart Grid

The SG is a continuously evolving network featuring new and improved smart devices supporting a wide range of applications. The SG is designed to provide quality of service (QoS) requirements, which becomes challenging with the dynamically evolving nature of the communication technologies. Many new problems in the area of routing arise due to the unique SG environment [222]. The complex network topology has many nodes generating large variable-sized data sets, which have to be collected and transmitted over the network under delay constraints [223]. Routing protocols may be differentiated according to the layered SG architecture. In HANs, routing protocols should have low energy consumption, while preserving the security and privacy of the consumers. Routing protocols in NANs and WANs should satisfy strict QoS requirements for large data volumes [224]. Hence, a careful design of routing protocols is required for efficient CR-based SG communications.

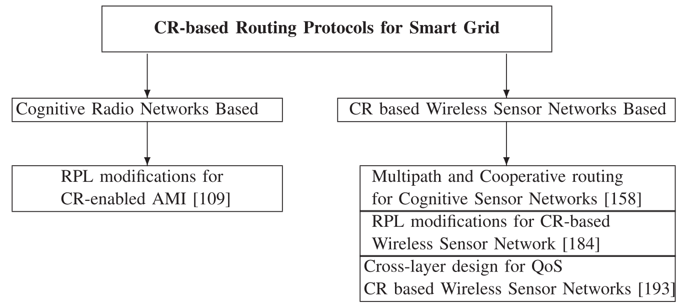

Fig. 8. CR-based routing protocols for the SG classified according to the type of the underlying communication technology: Cognitive Radio Network (CRN) or Cognitive Radio-based Wireless Sensor Network (CR-WSN).

Dynamically changing communication conditions, such as varying background noise, attenuation, available channels sets, and wireless propagation phenomena, lead to volatile links and intermittent connectivity in CR networks. The combined challenges of dynamically evolving SG communications and the volatility in CR link connectivity make routing in CR-based SG systems highly challenging. The goal of routing research has been to develop efficient and appropriate routing protocol designs that include several components, e.g., a path determination scheme and a packet forwarding scheme [10], [225].

We classify the routing protocols for CR-based SGs according to two major types of underlying communication technologies, i.e., routing protocols for general cognitive radio networks (CRNs) and routing protocols for CR-based wireless sensor networks (CR-WSNs), as illustrated in Fig. 8.

A. Routing Protocols for Cognitive Radio Networks (CRNs)

Routing protocols for low power and lossy networks (RPL) are expected to be the standard routing protocol for the majority of SG applications, including advanced metering infrastructure (AMI) networks [109]. RPL is a distance-vector and source routing protocol, which employs one or more Directed Acyclic Graphs (DAGs) to maintain network state information. A root node in each DAG behaves as a gateway. Each client node is assigned a rank based of an objective function. The rank represents the node's virtual position with respect to the DAG root, whereby the DAG root has the lowest rank. The DAG construction starts by broadcasting a control message called DAG Information Object (DIO) from the gateway. Each DIO contains relevant network information, including the DAGID to identify the DAG and the rank information. If a node wants to join the DAG, it adds the DIO sender to its parent list. Then, the joining node computes its own rank according to the objective function and forwards the DIO message with the updated rank information [226], [227].

In CRNs, PUs must be protected. This PU protection strongly depends on the accurate detection of PU activity. Therefore, the network layer of CR users should avoid regions occupied by PU users. This may result in a performance tradeoff for the secondary network. Moreover, CR nodes are not involved in forwarding data packets while sensing the channel. To overcome these challenges, the concept of cognitive and opportunistic RPL (CORPL) has been introduced in [109], [226], [227] to meet the requirements of the secondary network. CORPL is specifically designed for the AMI network by supporting reliable, low latency data delivery for delay-sensitive SG applications. CORPL retains the DAG-based approach of RPL and introduces novel modifications for CR environments. Two key steps in CORPL are different from traditional RPL: selection of a forwarder set and unique forwarder selection [109].

For forwarder set selection, each network node selects multiple next hop neighbors in an opportunistic manner and maintains a forwarder set. CORPL is based on the existing parent structure of RPL that requires at least one backup parent besides the default parent. Modifications at the MAC layer are made to add the addresses of the nodes in the forwarder list to the MAC header of the frame. The receiving nodes extract the address information by decoding the MAC header. In the forwarder selection scheme, a simple overhearing based coordination scheme is employed to ensure that only the best receiver of each packet forwards the packet. A cost function approach and a simple overhearing-based coordination scheme dynamically prioritize the nodes in the forwarder set and identify the best receiver for forwarding. The overhearing-based coordination scheme is based on acknowledgement (ACK) frames. In CORPL, the performance degradation due to spectrum sensing is mitigated through gathering sensing schedule information of the neighboring nodes and by decreasing the spectrum sensing time.

A system-level performance evaluation [109] has indicated that CORPL is a viable solution for practical cognitive AMI networks. High-priority delay sensitive alarms are supported and PU transmitter protection is ensured through an optimal transmission time for the secondary network under an interference constraint. The performance evaluation revealed that CORPL improves the reliability of the network while reducing harmful interference to PUs up to 50%. CORPL also reduces the deadline violation probability for delay-sensitive traffic [109].

B. Routing Protocols for Cognitive Radio Based Wireless Sensor Networks (CR-WSNs)

General routing design goals for CR-based SG WSN architectures (see Section VI-B5) have been formulated in [158]. The CR-based SG WSNs benefit from multipath routing as diverse path options can mitigate interference. Cooperative routing schemes may also be adopted to make packet forwarding more energy efficient. Spectrum-aware multichannel routing algorithms should be designed to improve the efficiency of spectrum usage with minimum event-to-sink delays. Furthermore, spectrum decisions should be made after investigating the tradeoff between spectrum handoff and adaptation of the routing layer [158].

Multi-layered energy- and spectrum-efficient routing protocols for CR-based Wireless Sensor Networks (CR-WSN) operating primarily in SG HANs have been proposed and examined for both licensed and unlicensed bands in [184]. To take advantage of energy savings in CR-based SG applications, the proposed protocols for CR-WSNs build again on RPL. The RPL-based design takes asymmetry, i.e., data packets flow through different routes in different directions and the different capabilities of the network nodes into consideration to achieve reliable and low-latency routing support for large-scale cognitive SG networks. Selective routing is performed, whereby battery-powered devices are spared from spectrum sensing and a minimum number of routes is maintained.

The different QoS requirements for control and monitoring applications have been addressed in a cross-layer routing protocol design for SG networks based on CR-WSNs in [193]. A set of priority classes is defined to represent the traffic heterogeneity of SG applications according to their data rates as well as latency and reliability requirements. The problem is modeled as a weighted network utility maximization (WNUM). The objective is to maximize the weighted sum of provided flow service of the different priority classes. Joint routing, dynamic spectrum allocation, and medium access control (MAC) are performed according to a cross-layer to solve the utility optimization problem [193].

Further, an on-demand distributed algorithm in [193] interacts with the MAC and physical layers. With lower route update frequency as compared to other routing protocols in the literature, the proposed protocol defines a routing frame period structure to control the operations of the routing, MAC, and physical layers. This cross-layer interaction is performed for a suitable channel selection having sufficient capacity and constrained bit error rate, and meeting the flow requirements in terms of channel interference. Essentially, a routing frame period structure is defined to jointly optimize the operations of routing, MAC, and physical layer. The results indicate that the numbers of flows of each class are maintained according to their weight fraction considering their respective data rates as well as SG application latency and reliability requirements [193].

C. Summary

Our comprehensive survey of the existing routing protocols for CR-based SG networks indicates that the area of CR-based routing protocols has so far only received relatively limited attention. Mainly, modifications to existing routing protocols have been examined or cross-layer designs have been explored. For the area of routing in general cognitive radio networks (CRNs) for the SG, only modifications of RPL for the specific use case of AMI networks have been investigated. Hence, there is an urgent need to design routing protocols for general CRNs for the SG. While routing in CR-based wireless sensor network (CR-WSN) in the SG has received somewhat more attention so far than the routing in general CRNs, there are still relatively few routing studies for CR-WSN SG networks available.

Overall, new routing protocol designs should consider QoS requirements and should support cross-layer operation for

TABLE VI
INTERFERENCE MITIGATION SCHEMES FOR CR-BASED SG

Reference	Type of Network	Proposed Approach
[197]	IEEE 802.22 WRAN CR-based cloud computing smart grid	Beamforming based on Minimum Mean Squared Error (MMSE) method
[187]	Femto cell cognitive heterogeneous mobile networks in the smart grid environment	Stackelberg game
[190]	Zigbee-WLAN Coexistence	Cognitive beamforming algorithm
[217]	WiMAX Extension	Periodical sensing

increased efficiency. Dynamic network topologies in all layers of CR-based SG infrastructure (see Fig. 2) should be considered. Moreover, adaptive routing protocols with respect to network topology and applications are required. We also recommend that the behaviors of multipath and cooperative routing protocols should be studied in detailed for the CR-based SG environment since the multipath/cooperative routing strategies may improve the throughput-delay performance and the reliability in the face of individually unreliable CR links.

X. Interference Mitigation Schemes for CR-Based Smart Grid

Heterogeneous and un-coordinated CR-enabled smart devices can create and then suffer from excessive interference or congestion, which in turn increase delays and make communication unreliable. The CR-based SG infrastructure should not exclusively depend on dynamic spectrum access, but should also incorporate self-coexistence schemes to coordinate spectrum usage. The IEEE 802.19.1 standard [149] provides guidelines for wireless coexistence in the TVWS. These guidelines may help in mitigating interference among CR-based AMI/FANs [107]. Generally, spectrum access may be prioritized according to SG traffic requirements, such as real-time versus non-real-time requirements or emergency report versus demand response, when striving to mitigate interference. We have summarized the existing approaches for interference mitigation in CR-enabled SG networks in Table VI.

A. IEEE 802.22

One approach for interference mitigation is beamforming with the minimum mean squared error (MMSE) method in smart meter systems [197]. As discussed in detail in Sections VI-B8 and IV-D2, this scheme requires accurate channel and noise-plus-interference power estimations for effective mitigation of self-interference. The focus is on the efficient exploitation of the preamble feature of the IEEE 802.22 WRAN for channel and noise-plus-interference power estimation. A cloud computing-based SG infrastructure is considered that runs the IEEE 802.22 WRAN CR standard. A pervasive bi-directional AMI communication method based on a CR protocol is developed. The selected CR channel may be a primary channel or a back-up channel in emergency scenarios. The BS towers employ antenna arrays to suppress the self-interference effects in the uplink channel of the CR-based SG. Results in [197] indicate that the MMSE beamformer requires no additional coordination among cells of different service providers to effectively mitigate the self-interference effects in the uplink channel.

B. CR-Based Mobile Networks With Femto Cells

In cognitive heterogeneous mobile networks, joint radio spectrum and SG environment sensing is examined in [187] for power control and interference management. A three-level Stackelberg game is applied to solve electricity price decision, energy-efficient power allocation, and interference management problems. The Stackelberg game is analyzed through a backward induction method. Every MBS protects itself by charging the femtocell users to mitigate the cross-tier interference between femtocells and macrocells, as discussed in detail in Section VI-B2.

C. WLANs

In [190], cognitive beamforming and energy-efficient rate adaptation algorithms are proposed to manage the interference between the WLAN and the SG network and to save transmit power. The algorithm not only ensures negligible interference to the WLAN but also satisfies a required rate for smart metering. A major advantage of this cognitive beamforming is the spectrum sharing by the SG with the WLAN (cf. Section VI-B2 for more details). The QoS of the SG network can be guaranteed even if the traffic of the WLAN increases significantly at the expense of the increased cost and complexity of installing multiple antennas [190]. This cognitive beamforming is beneficial even if WLAN traffic significantly increases due to the installation of additional antennas. The electricity usage is then reported and feedback of the interference power from the smart meter to the home appliance is provided [190].

D. WiMAX

The in-band interference in a cognitive WIMAX setting is analyzed through a mechanism for a "WIMAX-Extension" (WIMAX-EXT) system in [217] (see Section VII-A1). This system shares the spectrum with SCADA systems, operating between 223–235 MHz. A detector employing a periodical sensing (PS) process is used during the normal wireless communication to gather real-time interference data. The PS process also defines the cross-layer messages between the PHY and MAC layers to deliver the interference information to the downlink and uplink. The time and frequency domain PS data is analyzed to classify received interference into several types. This interference classification aids interference minimization schemes.

E. Summary

The existing interference mitigation schemes mainly consider a given communication network environment. However,

TABLE VII
SECURITY APPROACHES AGAINST CERTAIN THREATS FOR CR-BASED SMART GRID

Reference	Type of Threat	Proposed Approach
[135]	Grid Failure	Priority-Based Traffic Scheduling and Utility Optimization
[131]	Unauthorized Users	Reconfigurable FPGAs
[131]	Malicious Data Attacks	Generalized Likelihood Ratio Test Detector
[210]	Intrusion	FPGA-based Fuzzy Logic
[210]	Distributed Attacks	Trusted Neighbors
[229]	Jamming Attacks	Combined Online Optimization and Linear Programming

CR-based SG infrastructures may span large geographical areas and encompass many different communication technologies. Future research needs to address interference mitigation across a variety of communication technologies so that interference can be mitigated globally in the SG.

XI. SECURITY AND PRIVACY FOR CR-BASED SMART GRID

As the SG communicates personal power consumption and billing data, ensuring the security and privacy of SG communications are key requirements for CR-based SG communication. Security and privacy issues arising from SG applications need to be studied and their impact on the overall system needs to be evaluated. Security issues in the general SG have been surveyed in [96]–[98], while privacy-aware metering is considered in [99]. Security threats and countermeasures for general CR networks have been surveyed in [61]–[63]. We focus on surveying the literature on security and privacy specifically for the CR-based SG in this section.

A. Security Considerations in CR-Based Smart Grid

In [228], it is suggested that depending only on legacy systems for SG communication may result in vulnerability. From the communication point of view, traditional communication technologies are the legacy systems in SGs. Therefore, employing CR communication techniques instead of legacy communication systems may prevent some vulnerabilities. With CR technology, the communications infrastructure can potentially utilize all available spectrum resources. This increase in SG communication efficiency may aid in making the communication more secure and reliable [228]. However, CR-based SGs may introduce entirely new areas of security threats, including download of malicious software, licensed user emulation, and selfish misbehaviors [59]. Smart grid network elements can be widely dispersed making them easily accessible from any location and prone to cyberspace threats [228]. Cognitive capabilities and reconfigurability may also result in new security threats. For example, an attack may be initiated by an adversary node that pretends to be a PU transmitter, which may result in false spectrum sensing observations, i.e., undermine the cognitive capability. Attackers may exploit the reconfigurability, for instance, by executing malicious code in CRs [61], [62]. The wide range of security threats for CR-based systems [63] necessitate a thorough security analysis of CR-based SG systems.

Security considerations in the SG need to encompass the information flow as well as the power flow. The security considerations for the information flow data include data confidentiality, data authenticity, data integrity, data freshness, and data privacy, as well as attack detection and attack survivability. The security considerations for the power flow are commonly focused on autonomous recovery [131].

Unpredictable faults, e.g., faults resulting from environmental disasters, cyber attacks, or mechanical failures, should be detected as quickly as possible. A graph-theoretic approach may be used to analyze the cyber attack impact on the SG. The system should monitor data to maintain the optimal operation mode, or to recover to the correct working condition. In addition, the system should have prediction capabilities to continuously search for latent dangers. Arising problems should ideally be addressed autonomously [131].

B. Suggested Counter-Measures

In this section, we provide a comprehensive survey of the existing mechanisms for countering security threats in CR-based SG systems. Table VII gives an overview of security threats for CR-based SG systems with suggested counter-measuring approaches.

In [131], a microgrid testbed supporting power and information flows with various distributed energy resources, different power loads (appliances), and control modules is presented. A network testbed consisting of multiple nodes is also introduced. The network testbed has two security features: First, the data sent out by the nodes is encrypted to prevent unauthorized users from intercepting the data over the air. Second, the reconfigurable FPGAs are protected against invasion or tampering.

A detector of malicious data attacks based on the generalized likelihood ratio test (GLRT) is introduced in [131]. Two basic approaches for optimization in the face of uncertainty are proposed: Robust optimization with deterministic and set-based uncertainty modeling, and stochastic optimization with random uncertainty modeling. Robust optimization ensures stable performance with bounded errors, while stochastic optimization gives the average performance with known or partially known probability distribution information.

In [210], FPGA-based fuzzy logic intrusion detection is proposed for the SG. In this approach, different variables that influence the inference of an attack are analyzed and then combined to make security decision. Additionally, this approach exploits alerts from trusted neighbors. The alerts generated by these neighbors can be used to adjust local variables or parameters to better cope with distributed attacks and more accurately detect their presence [210].

The availability of the CR communication services for the SG in the presence of jamming attacks is studied in [229]. The presented model has a CR link for the SG with n orthogonal channels. Two SUs are considered, one for the sender and one for the receiver. There is no central controller to perform any coordination and no channel statistics are available. There are four types of jammers: static jammer, random jammer, myopic jammer, and multi-armed bandit (MAB) jammer. The static jammer continuously jams the same set of channels while the random jammer randomly picks channels to jam in each time slot. The myopic jammer employs a myopic algorithm to learn the channel occupancy pattern of the PUs. The MAB jammer employs a machine learning algorithm to predict the joint behavior of the SUs and the PU. A combined online optimization and linear program are utilized to mitigate the effects of jamming. This anti-jamming dynamic spectrum access scheme employs a time-slotted system with each time slot containing sensing and ACK components. This allows the SUs to learn about the channel availabilities. An MAB-based algorithm is applied to enable the secondary sender and receiver to approximate their optimal channel selection strategy, thus resulting in resistance to jamming attacks, even to a cognitive attacker employing myopic or MAB-based jamming.

C. Summary

Our comprehensive survey of the security protocols for the CR-based SG indicates that very limited research has been conducted so far on the security aspects of CR-based SG systems (cf. Table VII). A recent survey of general SG security issues [96] outlined a wide range of security vulnerabilities of SG systems. However, very few of these general SG security vulnerabilities have been addressed to date. CR-based communication gives rise to specific security threats [61]–[63]. CR-based communications in SG systems thus may open critical electrical power systems to new types of attacks that exploit CR features, e.g., reconfigurability.

For instance, a CR-based SG may allow a so-called primary user emulation (PUE) attack to disrupt electrical power services. In a PUE attack, a malicious node attains the PU characteristics; thus, causing the CR nodes to perceive the malicious node as a PU [230], [231]. The malicious node may force the CR node to vacate the occupied channel or the malicious node may jam the CR user's spectrum sensing process. The malicious node may thus disrupt the SG communication for critical electrical power services. One way to counter such PUE attacks is random channel switching by the CR node. However, this switching may result in a tradeoff between countering the attack and switching away from a good channel. This tradeoff is referred to as *dogfight in spectrum* [232]. However, such types of attacks and their countermeasures have not yet been investigated in detail for CR-based SG systems.

It is also not yet established that a particular security mechanism will work in all architectural layers of CR-based SG systems, i.e., in HAN, NAN, WAN, and AMI. The isolation of security-breached areas from secure areas without affecting seamless operation remains an open issue. Similarly, the effective recovery or security breached area requires extensive research. We recommend that security and privacy protocols for the CR-based SG should be designed for the specific SG communication architecture. More specifically, future security protocol research for CR-based SG should consider the security issues and needs of HANs, NANs, WANs, and AMIs. For instance, the security requirements and security attacks for a HAN controlling a smart home are different from the security requirements and attacks for WANs.

XII. Power and Energy Related Schemes for CR-Based Smart Grid

The communication technologies and protocols in the SG have to help satisfy the energy consumption needs of the consumers. Considerable work has been done to achieve this in general SG systems (that do not employ CR), e.g., through a four-way handshake protocol and a token-based energy forwarding network model based on the store-and-forward principle of delay-tolerant packet networks [233]. Moreover, the communication protocols in the SG should be energy-efficient. In HANs, for instance, a WiFi Direct technique simultaneously provides power saving and reliable communication for the SG [234]. Furthermore, the overall SG should operate in an energy-efficient manner. An example for energy-efficient SG operation has been examined for a VANET-enhanced SG in [235]. The mobility of electric vehicles (EVs) is incorporated into the EV charging strategy to improve energy utilization and to reduce the EV travel cost while avoiding power system overload [235]. The use of renewable energy sources, such as utilizing wind farms, has been suggested in [236].

Similar energy-related issues arise in CR-based SG architectures that transmit energy-related data. If the CR transmission introduces errors in the energy-related data, then severe problems can result. For instance, incorrect information about surplus electricity in the CR-based SG, can lead to consumers using more energy while paying lower electricity rates. Therefore, accurate and reliable transmission of information about energy is required for real-time pricing and DRM.

A multi-layered architecture for CR-based SGs consisting of cognitive HANs, cognitive NANs, and cognitive WANs can support energy- and spectrum-efficient designs [172]. At the same time, a CR-based Wireless Sensor and Actuator Network (WSAN) (see Section VI-B5) may be a good energy distribution model for SG automation [191]. In the following subsections, we comprehensively survey power- and energy-related solutions in CR-based SG architectures and technologies. We classify these approaches according to the underlying CR-based SG architectures and technologies.

A. CM2M for Smart Grid

An energy-efficiency driven spectrum discovery scheme is studied for a cognitive machine-to-machine (CM2M) network in [132]. The general spectrum sensing mechanisms of this CM2M network are reviewed in Section VII-A1b. We focus on the energy-saving features of the spectrum sensing scheme in this section. A CM2M network is motivated by a green requirement as a machine is a low-cost, low-power device, designed to work for several years without battery replacement. This requires energy saving, which can be achieved by optimizing the sensing and processing of the M2M nodes. The M2M coordination and cooperation in the renewable energy FANs architecture (see Section VI-B1) in [132] reduces energy consumption in the spectrum discovery phase. Through M2M coordination, nodes cooperate to gain knowledge about the discovered spectrum. Specifically, [132] consider a scenario of wind farm FANs in which distributed renewable energy sources, such as wind and solar power, are integrated into the power grid.

Similarly, several HAN gateways (HGWs) in the NANs may cooperate to efficiently detect unused frequency bands in the primary network. A Time-Division Energy-Efficient (TDEE) sensing scheme has been proposed in [132] to save energy. TDEE sensing divides the sensing period of each gateway into two equal time slots. In the first time slot, the first HGW senses the first channel and the second HGW senses the second channel. In the next time slot, the operation is reversed, i.e., the first HGW is tuned to sense the second channel, and the second HGW searches the first channel. The HGWs then forward the sensing results to an SG concatenator for a final decision. TDEE sensing does not require HGWs to acknowledge a successful cooperation, resulting in substantial energy savings without compromising sensing accuracy. TDEE sensing has been found to be more energy-efficient than both cooperative and non-cooperative sensing schemes [132].

B. Mobile Multimedia Applications for Smart Grid

Mobile multimedia applications can generate high data rates and therefore greatly increase energy consumption. A green cognitive mobile network with small cells may be employed to meet the high data rate requirements in the SG and to improve the energy efficiency of mobile multimedia communications [185]. Joint spectrum and SG environment sensing, as described in detail in Section VII-D1, is performed to allocate power and manage interference for multimedia communications. The electricity price decision, energy-efficient power allocation, and interference management problems are formulated as a three-stage Stackelberg game, as discussed in Section VI-B2 and [187]. The price decisions by retailers are modeled through a homogeneous Bertrand game with asymmetric costs. Real-time pricing for demand side management is achieved by providing real-time electricity prices by retailers to heterogonous mobile networks [237]. Both MBS and SCBSs sense the SG environment in order to adjust the amount of electricity consumption by performing energy-efficient resource allocation. The results in [237] indicate that this is a good cost-effective scheme in terms of operational expenditure and CO_2 emissions.

C. WLANs and Smart Grid

The coexistence of WLAN and the SG network may be achieved by using a cognitive beamforming technique [190]. In this scheme, electricity-related information from the home appliances is transmitted to the smart meter simultaneously with the WLAN transmission on the same spectrum. An energy-efficient rate adaptation algorithm slows down the transmission rate in the cognitive SG network. The rate-adaptation algorithm employing multiple antennas with beamforming reduces the energy consumption for smart metering compared to conventional transmission.

D. TVWS and Smart Grid

A trade-off between power efficiency and spectrum efficiency may be achieved by employing CR functions in TV band devices (TVBD) based on multi-objective genetic algorithms [189]. The functions serve as an effective wireless technique for the communications between a smart meter and its remote-area power management (RAPM) server.

E. CR-WSNs for Smart Grid

A multi-layered approach can be utilized for energy- and spectrum-efficient designs in HANs of CR-Based Wireless Sensor Networks (CR-WSNs) at the SG utility. This can be done by making suitable modifications of RPL [184], as discussed in detail in Section IX-B. Mainly, the battery powered devices are spared from spectrum sensing operation [184].

An energy-efficient scheme for cognitive sensor networks based on CRB-MAC [221] has been discussed in detail in Section VIII. Designed for SG applications, CRB-MAC uses preamble sampling and opportunistic forwarding techniques. The preamble sampling approach tackles idle listening and supports sleep/wakeup modes without synchronization overheads thereby improving energy-efficiency.

F. Summary

The comprehensive review of power and energy-related schemes for CR-based SG systems in this section indicates that only few research efforts that have been scattered across different network types have been undertaken so far. Future research should explore energy-efficient network designs with joint consideration of the power allocation and spectrum efficiency trade-off. In particular, the designs need to trade off the energy consumed when CR-based smart devices continuously sense the spectrum versus transmission opportunities that are missed when devices are in a power-saving idle (non-sensing) mode.

XIII. Open Issues, Challenges, and Future Research Directions

CR-based communication architectures for the SG face many challenges, due to the dynamic nature of the network environment. Spectrum efficiency and energy efficiency are important problems together with reliability and security. In this section, we discuss open issues and challenges as well as future research directions for CR-based SG environments.

A. Spectrum Related Research Directions

1) Spectrum Sensing: Efficient spectrum sensing is required which not only considers network resource limitations but is also aware of dynamic spectrum challenges. There may be high numbers of sensor nodes in large-scale SG systems. However, incorporation of multiple radios and complex processors on each sensor node may be costly and consume high power. In dense SG environments, sophisticated spectrum sensing algorithms that operate on an individual single-radio node are not recommended due to their high sensing time and power needs [158]. Rather, cooperative energy-efficient sensing schemes should be developed for dense SG environments.

2) Spectrum Sharing: CR-based SG communication employs dynamic spectrum access to utilize unoccupied or underutilized spectrum for SG applications. CR tries to obtain the best available spectrum through cognitive capability and reconfigurability. Since, most of the spectrum is already assigned, the sharing of the licensed spectrum without interfering with the PU transmissions remains a key challenge [6]. Coordinated spectrum sharing prevents packet collisions and multiuser collisions in the crowded SG radio spectrum environments. The co-existence of different communication technologies also requires QoS spectrum sharing schemes in order to meet reliability and latency requirements. To achieve these objectives, joint temporal and spatial reuse of spectrum appears beneficial [158] and should be examined in detail in future research.

3) Spectrum Mobility: In a CR environment, an SU transmits as long as no PU is detected. When a PU returns to the licensed channel, the SU has to leave the channel and switch to the next-best available channel. This spectrum mobility (spectrum handoff) can interrupt ongoing communication, e.g., increase delays or cause losses. Due to the large geographical area covered by an SG, spectrum mobility may result in the selection of heterogeneous links and thus adapting to different spectrum regulations becomes critical [158].

B. Quality of Service (QoS)

The CR-based SG operates in a dynamically changing environment with resource constraints, e.g., limited data transmission and storage capacities. Subject to these constraints, SG application-specific QoS requirements, e.g., in terms of data rate, latency, and reliability, should be satisfied. QoS-aware communication protocol designs are needed that meet the requirements of SG application while scaling to large SG networks and many users. Based on the SG application requirements, CR spectrum management functions should be developed to adapt data transmission parameters, such as data rate, acceptable error rate, delay bound, transmission mode, and transmission bandwidth [25].

Meeting SG QoS requirements becomes particularly challenging when there is a high density of secondary CR users. A high number secondary of users may degrade QoS, particularly during peak traffic hours. At the same time, the statistical behaviors of PUs affect the available resources for CR to a high extent [128], [238]. Future research needs to examine the achievement of QoS requirements for the full range of PU and SU traffic and density dynamics.

1) SG Monitoring and Control Applications: Monitoring and control SG applications can be severely affected by PU arrivals during an ongoing SU transmission. Transmission interruption resulting from PU arrivals may cause losses or delays of sensed data/control commands/alarms. Future research should examine how packet losses or delays may be mitigated by sending message replicas from multiple transceivers and investigate the resulting costs. One specific SG control application is automatic generation control (AGC), which adjusts the generated output power of distributed power plants. Randomly switched on-off power system schemes may be good strategy for addressing AGC issues [112], [239]. However, detailed practical design considerations for such control schemes need to be thoroughly examined for CR-based SG systems.

2) Emergency/Time-Critical SG Applications: Real-time monitoring of power systems is an important SG application. Alarm messages about power system misbehaviors or failures, such as a power outage in a particular area, should immediately be relayed to the control center. The timely delivery of such alarm messages and corresponding control instructions is necessary for a smooth SG operation. CR-based SG communication networks can generally fulfill this requirement. However, suppose CRs are transmitting normal data when an emergency arises. In such a situation, the CRs need to arbitrate between interrupting the regular transmissions and communicating the alarms/control actions. Future CR-based SG systems should employ adaptive algorithms to resolve such situations. SG data may be prioritized according to QoS-aware differentiation into vital messages comprising of alarms/control actions with the highest priority, system monitoring data with moderate priority, and meter readings with the lowest priority. If the SG system is not properly dimensioned, then the transmission of prioritized commands may disrupt ongoing transmissions, e.g., continuous DRM updates and result in irregular DRM. Hence, strategies for properly dimensioning SG network capacity need to be developed. The dimensioning strategies should incorporate CR-based resource utilization decisions based on QoS-aware prioritized data [135], [240], [241].

3) Support for SG Data Management: Smart meters will frequently generate large data amounts, thus requiring a Meter Data Management Systems (MDMS) for data storage and analysis. Data can be combined to obtain context-related information about consumers or the SG network. At the same time, a communication framework will be needed to transfer contextual information from the MDMS to control centers. As the smooth and secure SG operation depends on the continuous bidirectional transfer of such contextual information, CR-based SG systems should be designed to meet these data management demands [242].

C. Evaluation for Full Range of SG Operating Conditions

1) Electromagnetic Effects From Power Components in SG: As outlined in Section II-C, CR-based communications mechanisms for the SG should achieve good QoS for a wide range of network densities and traffic rates under harsh wireless communications conditions. As surveyed in the core sections of this article, the CR-based SG communications mechanisms developed to date have been evaluated for some of the challenging SG operation conditions. However, a systematic evaluation and validation of the CR-based SG communications mechanisms for the full range of SG operating conditions has been missing. Future research needs to rigorously examine and validate the performance of CR-based SG communications mechanisms for the full range of SG operating conditions, including the harsh conditions near electrical power equipment.

2) Interference Management: The presence of multiple communication technologies, continuously varying environments, and electricity flows can result in severe interference in CR-based SG networks. Therefore, interference avoidance schemes should be applied. The spectrum management and coexistence solutions should be employed in addition to coordination between base stations. One strategy for avoiding RF interference is the development of new adaptive power allocation and dynamic spectrum access schemes [25], [243].

A potential future research area for mitigating the electromagnetic effects from electrical power components on CR-based SG systems is the development of methods to predict areas of potential effects and to adopt preventive or self-healing measures. A related future research area is to develop methods for selecting optimal locations for CR nodes, where the communication is not degraded by electromagnetic effects. One possible strategy is that CR nodes near high-power components send their data to intermediate CR nodes located at suitable distances, rather than sending directly to control centers. The intermediate nodes may not only relay the data, but may be capable of analyzing the data to detect any abnormal changes. These intermediate CR nodes could also serve as backup nodes to their neighbors.

3) CR Transmission Parameter Selection: The CR nodes can change their transmission parameters in order to communicate on the best available channel while sharing spectrum resources with multiple users. In multi-user scenarios, the dynamic nature of the SG requires optimal parameter selection among nodes, such as transmission power, predictive capacity, delay, energy-efficiency, and error rate [158]. Thus, there is a need to investigate the parameter selection problem as well as algorithms and protocols for optimal parameter selection for future CR-based SG applications. Due to presence of multiple communication techniques, different radio propagation models have to be integrated into performance analysis schemes to study link budget and network capacity for the expected SG traffic [14], [120].

D. Communication Technologies and Protocols

1) Cognitive Radio (CR) Communications versus Other Communication Paradigms: Most studies on the CR-based SG to date have focused on designing or improving a particular CR-based communication mechanism for SG applications, e.g., spectrum sensing or medium access control as surveyed in Sections VII and VIII. These studies often evaluate the investigated CR-based communications mechanism for the SG through comparisons with other variations of CR-based communications. However, in order to identify the communication technology best suited for the SG, it will be important to conduct comprehensive comparative evaluations of CR-based communication mechanisms against alternate communication technologies for the range of SG applications. Such comparisons could, for instance, consider the communication technologies outlined in Section II-E and should encompass the wide range of SG operating conditions noted in Section XIII-C.

Future research should also thoroughly examine cooperations between CR-based communications mechanisms and other communication technologies in the SG. Some architecture studies have already considered combining CR communication with other communication technology, e.g., some architecture studies surveyed in Section VI. Such hybrid "cross-technology" studies combining CR-based communication with other communication technologies should be further pursued in future research and examined in the context of the full SG operating conditions (see Section XIII-C). Similarly, the integration of the CR communication paradigm into alternate communication technologies, e.g., CR-based transmissions in 4G wireless systems (see Section II-E2, and e.g., specifically study [4]) should be extensively investigated in future research for optimally serving the SG communication needs.

2) Interoperability: A SG consists of many devices, each using advanced communication protocols. Hence, there may be several communication technologies using different standards to meet the specific QoS requirements. CR-based communication architectures should contribute to the overall coordination among SG devices. Interoperability among all communication protocols, including the protocols for CR communication, is needed to smoothly and efficiently operate the complex SG communication infrastructure [25].

3) Specific Protocol Layer Issues: There are numerous directions for future research to address specific open problems in individual or a cross-layer combination of protocol layers in the CR-based SG. For instance, a configurable physical layer should be designed for selection of operating frequency, modulation, channel coding, transmission power, and spectrum sensing duration. At the data link layer, MAC and error control should be improved. For densely deployed CR-based SG environments, application-specific QoS parameters are required to adapt to varying channel conditions. A joint optimization of event estimation, spectrum sensing, duty cycling, and channel identification may be considered to reduce network energy consumption.

Improved designs of the routing layer are required for optimal route selection that minimizes interference. Cooperative routing schemes should strive to increase the energy efficiency of packet forwarding. A proactive congestion control algorithm and schemes with minimized control packet exchanges should be investigated to help energy harvesting [158]. The routing algorithm should explicitly account for the spectrum sensing state of different CR nodes [109]. The reliability and speed of data gathering and information broadcasting could be improved by robust and tunable network coding protocols in SGs [223].

E. Security and Reliability

CR-based communication architectures face a multitude of security and reliability threats, e.g., jamming of the channel, malicious/selfish node behavior, and internal failure of a CR node. For instance, jamming attacks can degrading the DRM performance of the SG [244]. As the SG has to reliably transmit critical data, the security and reliability issues need to be thoroughly adopted in future research [161]. One way to achieve security and reliability is to monitor the SG with sensor nodes with cognitive capabilities. Based on the monitored data, cryptographic SG surveillance programs with privacy preservation and disaster recovery management operations should be employed along with reactive and/or preventive measures [147].

XIV. Conclusion

The smart grid (SG) is the future development of the traditional electrical power grid. By leveraging the tight integration of communications and information technologies with electrical power systems, the SG provides advanced features, such as adaptive control for dynamic demand response management (DRM) and wide area monitoring. These advanced features can improve the efficiency and reliability of the electrical power service. Wireless communications can effectively support many of the SG applications that require flexible communication over diverse terrain. In this paper, we have presented a comprehensive survey of research on employing cognitive radio (CR), which bypasses the fixed spectrum assignment in conventional wireless networks in the SG. We have surveyed CR-based SG architectures along with their applications. We have observed that adopting CR technology for communication in the SG can be helpful at the generation, transmission, and distribution stages of the power grid. We surveyed in detail spectrum sensing approaches as well as routing and MAC layer protocols for the CR-based SG. Moreover, we covered security and privacy related issues as well as power and energy related issues in the CR-based SG. We concluded the survey by outlining open issues and challenges as well as future research directions for the CR-based SG.

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