Requirements, Design Challenges, and Review of Routing and MAC Protocols for CR-Based Smart Grid Systems

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The authors evaluate the requirements and key design challenges for routing and MAC protocols in the CR-based smart grid. The authors also provide a review of research carried out to date for routing and MAC protocols for the CR-based smart grid.

ABSTRACT

Cognitive radio technology can facilitate communication in smart grid applications through dynamic spectrum access. However, traditional routing and MAC protocols adopted for cognitive radio networks may not be beneficial in CR-based smart grid environments due to large data sizes and variable link quality among different functional blocks of smart grids. The interference and fading in wireless links necessitate efficient routing for reliable low-latency data delivery of smart grid applications. This low-latency data delivery must be achieved while protecting the legitimate primary users. Besides efficient routing, MAC layer protocols should be enhanced to achieve successful data delivery with simultaneous spectrum sensing and duty cycling for energy-efficient operation. In this article, we evaluate the requirements and key design challenges for routing and MAC protocols in the CR-based smart grid. We also provide a review of research carried out to date for routing and MAC protocols for the CR-based smart grid.

INTRODUCTION

Smart grids (SGs) are envisioned as future power grids to enhance the functionality of traditional power grids. The communication technologies in power grids suffer from connectivity problems due to dynamic topology changes, fading, and interference. A variety of communication technologies have been suggested to overcome these problems, and the cognitive radio network (CRN) is recognized as one promising solution. CRNs employ dynamic spectrum access (DSA) to search for available channels in both licensed and unlicensed bands. Hence, CRNs may not only counter the problems of traditional communication networks, but may also serve as a bidirectional communication paradigm between consumers and utilities in the smart grid [1].

CR communication in SGs must comply with the regulatory constraints for the various communication technologies. A detailed review of these regulatory constraints is outside the scope of this article, which focuses on routing and medium access control (MAC) protocols within the context of cognitive radio (CR)-based SGs. For one example of a communications technology with strict regulatory constraints, we point to IEEE 802.22 wireless regional area network (WRAN) communication, which is being considered for so-called smart utility networks (SUNs) that communicate over TV white space (TVWS) [2]. In the United States, CR communication by unlicensed SUN TV band devices has to comply with Federal Communications Commission (FCC) regulations. FCC regulations require TVWS devices to include a geolocation capability and the capability to access a database of protected radio services. Devices must check the geolocation database before transmission and must recheck the geolocation database periodically [3]. We also note that the growing interest in CR communication in SGs has spurred extensive standardization efforts. We refer the reader to [4] for an overview of these standardization efforts.

Smart grids have a multi-tiered architecture consisting of home area network (HAN), neighborhood area metwork (NAN), and wide area network (WAN), as shown in Fig. 1. The HAN encompasses the communication within a home, which is relayed via a HAN cognitive gateway to the NAN. The NAN interconnects the HANs in a neighborhood area with each other and with a NAN cognitive gateway. The NAN cognitive gateway relays the NAN communication to the WAN, which interconnects the NANs with the power utility facilities and control units. Besides this three-tiered architecture, hybrid architectures, such as the advanced metering infrastructure (AMI), are also present. The SG performance strongly depends on reliable, successful, and timely end-to-end message delivery among these architectural tiers (blocks). Multipath propagation, fading, interference, and noise phenomena vary greatly in both space and time, and so does the resulting link status. Multichannel communication and proper routing solutions can improve network capacity with interference-free transmissions over multiple channels.

TRAFFIC TYPES AND DELIVERY REQUIREMENTS

SG applications generate a wide range of traffic types. The traffic types have diversified requirements for quality of service (QoS), for example, in terms of reliability, delay, and throughput. The SG traffic types have been classified in the literature [4, 5] depending on SG application areas and architectural layers. One example classifica-

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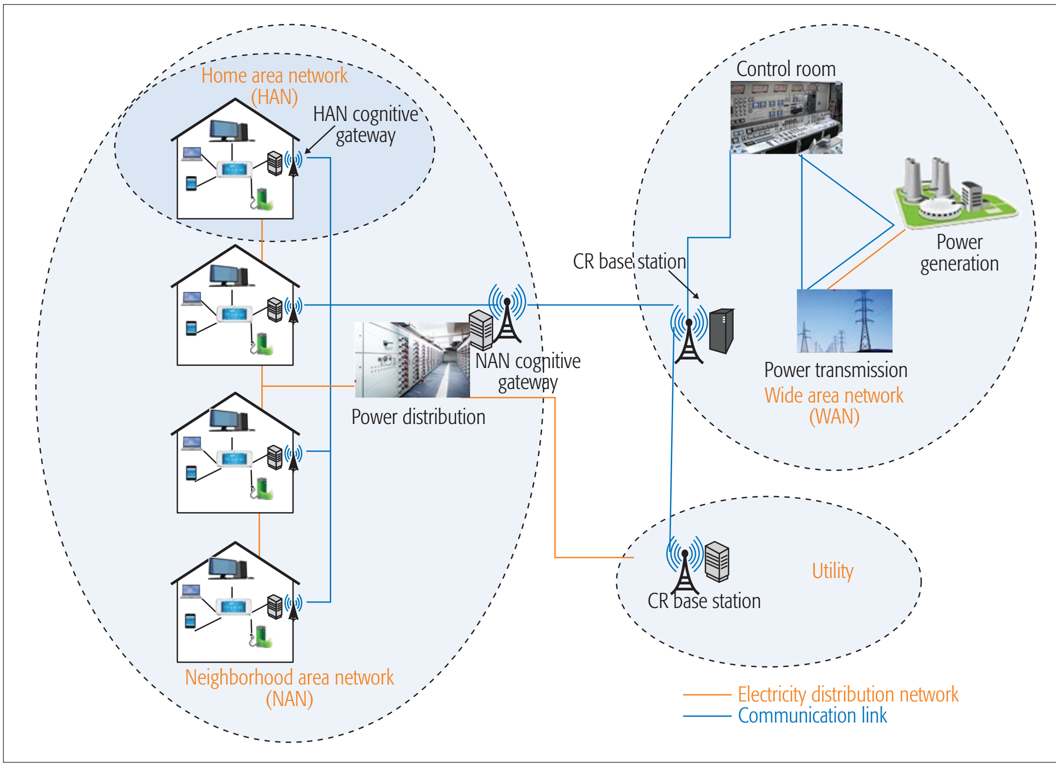

Figure 1. Conceptual CR-based SG architecture: A CRN is incorporated into the architecture to coordinate among three functional blocks (layers) of the SG: the HAN, NAN, and WAN.

CRNs have to search opportunistically for spectrum access in order to successfully transfer information. In particular, the physical layer should provide statistical information related to channel conditions to the upper layers.

tion defines three traffic types: multipoint-to-point (from devices to base station), point-to-multipoint (from base station to devices), and point-to-point (from device to device). Another classification in the literature defines data traffic according to priorities: highest priority vital messages are used for control, protection, and management; second highest priority messages convey system monitoring information; and third highest priority is for meter reading. SG data traffic types with payloads and delay in data delivery define network requirements. In Table 1, we summarize the different SG applications with typical data sizes as well as requirements for bandwidth, reliability, and latency.

Medium Access Control and Routing in Cognitive-Radio-Based Smart Grid

CRNs have to search opportunistically for spectrum access in order to successfully transfer information. In particular, the physical layer should provide statistical information related to channel conditions to the upper layers. The physical layer is responsible for providing opportunities to detect white space or primary user (PU) activity in time and frequency, while the network layer specifies their location dimension [6, 7]. The MAC layer should perform channel management functions, such as spectrum sensing, spectrum decision, spectrum sharing, and spectrum management. All these processes are power consuming; therefore they should be completed within a short time so as to maximize energy-saving sleep phases. In addition, it is very important that the CR MAC processes and transmission do not affect the legitimate PUs [1]. The design of novel MAC protocols for the CR-based SG requires the provisioning of low-overhead spectrum access. Moreover, the trade-off between spectral efficiency and energy efficiency should be balanced through optimal control of the duty cycle. The duty cycle is defined as the ratio of the duration of the listening time to the duration of the full listen-sleep period. CR nodes should be periodically turned off for as long as possible to minimize the duty cycle, thereby avoiding idle listening and reducing energy consumption. An adaptive duty-cycling mechanism may be a good strategy to keep the energy consumption low, in the sense that energy consumption does not necessarily affect the spectral efficiency. An efficient MAC protocol should not only strive for these simultaneous objectives, but also guarantee reliable operation in challenging smart grid wireless environments [8].

Minimum communication delays, which may be achieved through efficient multihop multicast routing algorithms, generally help to meet the objectives of SG applications. Multicast routing is especially promising for applications that need to reach multiple distributed grid components within a prescribed time period [9]. The routing protocols may be on-demand, table-driven, and QoS-aware [9], and should provide high packet delivery ratios, short end-to-end delays, and high energy efficiencies in different SG wireless environments [9]. The routing protocols attempt to deliver data after calculating a routing path with minimum cost. This minimum cost may correspond to either a minimum number of hops or a minimum total edge weight.

The overall satisfactory operation of the CR-based SG depends on the proper optimization of the MAC and routing protocols. These protocols should be designed to achieve necessary objectives while satisfying certain requirements. To date there has only been limited research on

SG application	SG architecture layer	Data size (bytes)	Bandwidth	Latency	Reliability (%)
Home automation	HAN	10–100	–	Seconds	>98
Building automation	HAN	>100	–	Seconds	>98
On-demand meter reading from meters to utility	NAN	100	10–100 kb/s/node, 500 kb/s for backhaul	<15 s	>98
Scheduled meter reading from meters to AMI	NAN	1600–2400	10--100 kb/s/node, 500 kb/s for backhaul	<4 h	>98
Bulk transfer of meter reading from AMI to utility	NAN	MBs (depending on the number of devices)	10–100 kb/s/node, 500 kb/s for backhaul	<1 h	>99.5
Pricing in terms of time of use (TOU) from utility to meters	NAN	100	–	<1 min	>98
Real-time pricing from utility to meters	NAN	100	–	<1 min	>98
Critical peak pricing from utility to meters	NAN	100	–	<1 min	>98
Demand response	NAN, WAN	100	14–100 kb/s per node/device	500 ms to several minutes	>99.5
Service switch operation	NAN	25	–	<1 min	>98
Distribution automation	NAN	25–1000	9.6–100 kb/s	<4 s to <5 s	>99.5
Outage and restoration management	NAN	25	–	<20 s	>98
Electric transportation	NAN	100–255	9.6–56 kb/s, 100 kb/s is a good target	<15 s	>98
Firmware updates	NAN	400–2000 k	–	<2 min to 7 days	>98
Customer information and messaging	NAN	50–200	–	<15 s	>99
Wide area situational awareness	WAN	>52	600–1500 kb/s	20–200 ms	>99.99

Table 1. SG applications with typical data sizes, as well as requirements for bandwidth, reliability, and latency.

such MAC and routing protocols. We summarize in this article these prior research studies in order to highlight the open design challenges. Our present work is different from previous overview articles such as [1, 4]. Reference [1] provided the motivations for employing CR-based communications in the SG. The general survey in [4] gave a broad overview of a wide range of aspects of the CR-based SG ranging from architectures, interference mitigation schemes, spectrum sensing mechanisms, as well as routing and MAC protocols to security, and also power and energy related schemes. In this article, we focus our attention on the routing and MAC protocols for the CR-based SG. More precisely, for both the routing and MAC protocols in the CR-based SG, we present in detail the requirements, comparisons of existing approaches, and challenges. In addition, we present in detail cross-layer protocols covering MAC and routing in the CR-based SG.

Outline of the Article

This article is organized as follows. The section on MAC protocols in the CR-based SG covers their requirements, surveys existing approaches, and outlines open challenges. We then cover the routing in the CR-based SG, detailing requirements, existing approaches, and main open challenges. Finally, we cover the cross-layer protocols presented in the literature. We summarize the existing work and outline possible future trends.

MAC Protocols in the CR-Based Smart Grid

The MAC layer in CRNs employs DSA to search for available spectrum without causing interference to legitimate primary users (PUs). CR users identify spectrum holes, that is, locally available channels that are not used by PUs. Alternatively, CR users can obtain up-to-date information about these spectrum holes from a geolocation database. CRs can change transmission/reception parameters according to spectrum availability on a range of channels [1].

The spectrum sensing process gathers information about the available channels and the presence of PUs. Spectrum sensing can require significant power in CR-based SG communication networks. Therefore, suitable approaches are necessary, such as minimizing hardware (e.g., using a single radio) and minimizing the sensing durations to an optimum level without compromising sensing accuracy. Besides achieving energy efficiency, the sensing process should account for multipath propagation, fading, and environmental noise. Moreover, the sensing process should avoid false alarms (i.e., should not detect PUs even if there

Requirements	Description
Accuracy in cognitive behavior	Accurate performance of the cognitive cycle (i.e., spectrum sensing, spectrum analysis, and spectrum decision) in terms of spectrum management functionalities is required [10]. Spectrum sensing thresholds should be set carefully, as a low threshold results in higher probability of detection at the expense of higher probability of false alarm. Spectrum sensing may cause harmful interference to PUs, may detect false presence of PUs, or may miss the detection of PUs [1]. Any wrong decision at the sensing stage further complicates other spectrum-related functions. In CR-based systems, PU protection is a very strict requirement, whereas CR communication performance may be compromised. Therefore, a high PU detection probability is a top priority for MAC protocol design, whereas a low false alarm probability is a secondary priority [8]. In [8, 11], the detection probability threshold is set to 0.9 and the probability of false alarm is set to 0.1.
Power optimization	Advanced solutions with power optimization capabilities should be designed. Sensing durations should be minimized to achieve power efficiency; however, sensing accuracy should remain high and data should be continuously delivered within limited time periods [1]. Sensing and data transmissions require power; therefore, energy-efficient mechanisms should be designed. Joint operation of event estimation, spectrum sensing, and channel identification can determine sleep schedules that achieve good CR data delivery performance while reducing energy consumption [6]. Experimental studies [8] found: Power drained in transmit mode = 66.2 mW, power drained in receive mode = 70.7 mW, and power drained in spectrum sensing = 65.8 mW. Large power savings can be achieved through sleep states whose power consumption levels are orders of magnitude lower than the listed power drain values for active states.
Efficiency	MAC protocol designs should consider channel interference and capacity. Data traffic from CRs may be sorted with respect to sensitivity and prioritized according to contention window sizes [10, 12]. The data should be forwarded to the node that provides the highest margin for delay budget [8]. During sensing, CR nodes do not forward data packets, thereby compromising network performance in terms of end-to-end throughput, latency, and packet loss ratio. Hence, there is a need to adopt suitable MAC protocols with optimum sensing durations [8].
Contention resolution	If a CR fails to access the channel in a time slot, it may attempt to access the channel in the next time slot. If there are many CRs trying to access the channel, an efficient contention resolution scheme is required; otherwise, packet loss increases. An increase of the timeout (backoff) duration may be a good option, which will increase the chances of channel access among CRs. Another possibility is to use receiver-based MAC protocols with suitable elective schemes in which receivers compete and the winner transmits instead of sender-based MAC protocols [8].
Single radio vs. multiple radio behavior	Single radio or low-complexity processors provide cost-effective solutions [8]. Contrary to this, multiple radios may result in long delays due to channel switching but may produce higher throughput [1]. The use of multiple radios may degrade the MAC protocol performance in case of dense CR node deployments [6].
Scalability	The SG consists of numerous users with a multitude of applications, utilizing many communication techniques, giving rise to scalability challenges. Scalability issues are often related to installation and maintenance costs of communication infrastructure. Wireless techniques reduce cost, but have limited coverage areas. To cover large areas, routers and access points have to be added, which typically increases the overall cost. The long range of IEEE 802.22 WRANs provides large coverage areas; however, availability of spectrum bands is an issue when moving between HANs, NANs, and WANs. A scalable SG system requires seamless connectivity with mobility and QoS support [1].

Table 2. Design requirements for MAC protocols in CR-based smart grid.

are none). False alarms can result in low spectrum utilization [1, 6].

In this section, we discuss MAC protocols for CR-based SG systems. We first discuss design requirements for MAC protocols in CR-based SG. We then analyze existing MAC approaches in the CR-based SG and present potential challenges for MAC protocols.

Requirements of MAC Protocols in CR-Based SG

Design requirements for an efficient MAC protocol in CR-based SG are summarized in Table 2.

Existing Approaches of MAC in CR-Based SG

In this section, we give an overview of the two main existing proposals, cognitive receiver-based MAC (CRB-MAC) and packet reservation multiple access (PRMA). Notable features of the existing approaches are summarized in Table 3. Please ignore the columns for carrier sense multiple access with collision avoidance (CSMA/CA) with distributed control algorithm (DCA) and suboptimal DCA for now; these two cross-layer approaches are covered later.

CRB-MAC: In the CRB-MAC protocol, nodes employ an optimal transmission time by starting a timer. The timer setting is subject to an interference constraint to improve overall network performance and to ensure PU protection [8]. Nodes can have a relatively short sensing time if they are in a region of low PU activity, thereby experiencing a low number of channel changes over time. CRB-MAC mitigates the performance degradation due to spectrum sensing by reducing the spectrum sensing time. To achieve this, the sensing time is initially set to a maximum value for a prescribed missed detection probability. Then the PU activity is followed, and based on the PU activity information, the sensing time may be decreased over time. In case of successive missed detection events, the node increases the sensing time [8].

CRB-MAC achieves energy efficiency and reliability through preamble sampling and opportunistic forwarding techniques. With preamble sampling, which is also referred to as asynchronous low-power listening, each node selects its sleep/wakeup schedule independent of the other nodes. Nodes sleep most of the time and sense the channels only briefly once during a so-called checking interval. Sending nodes prepend data packet transmissions with a preamble that has the same length as the checking interval to ensure that all receiving nodes sense the preamble and receive the data packet. Besides supporting sleep/wakeup modes without synchronization overheads for individual nodes, preamble sampling avoids idle listening, that is, time periods when secondary users (SUs) with CRs only listen to the channels and do not transmit data. Opportunistic forwarding benefits from the broadcast nature of wireless transmissions and employs multiple receivers. With opportunistic forwarding, a sender node transmits its data to all the neighbors in its communication range, without defining a particular node as a receiver. The transceiver can be tuned to any channel with multiple PU transmitters that have known locations and known maximum coverage ranges [8].

PRMA: In cognitive machine-to-machine (M2M) communications for the smart grid, a centralized MAC protocol may be tailored utilizing PRMA [11]. PRMA is a combination of slotted ALOHA, TDMA, and a reservation scheme. The protocol has a master-slave operation. Specifically, a powerful central network controller senses the spectrum for machine-type devices without spectrum sensing capabilities. This design aims to achieve low cost, low complexity, and low

Reference	CRB-MAC [8]	PRMA-based cognitive MAC [11]	CSMA/CA with DCA [10]	Suboptimal DCA [12]
Network type	CRSN	Cognitive M2M	CRSN	CRSN
Simulator used	Matlab	Matlab	NS-2	NS-2
PU transmitter stationary	Yes	–	–	–
Nodes stationary	Yes	–	Yes	–
Licensed/unlicensed operation	Licensed	Both	–	–
Single/multi-channel	Multi	Multi	Multi	Multi
Single/multihop	Multi	–	Multi	Multi
Energy consumption considered	Yes	Yes	No	No
Advantages	Few retransmissions; low delay; low energy consumption in good channels; high reliability; high packet delivery ratio	Diverse QoS support; low data rate optimization; periodic traffic patterns optimization; good scalability; low overhead dynamic spectrum access	Application-specific QoS requirements; low delay; good reliability; good throughput	QoS support; data scheduling; on-demand routing; low delay; good reliability; good throughput
Disadvantages	High energy consumption in poor channel conditions	Low throughput for low device density	Poor delay performance with increasing number of channels	No performance improvement with increasing number of channels; high contention on common control channel
Other features	Two state independent and identically distributed (i.i.d.) random process activity model; receiver-based; detection probability; low false alarm probability	Optimal reservation cycle; optimized throughput; two state i.i.d. random process traffic model; two state Markov chain for power demand	Joint optimization of routing; MAC and physical layer functions	Use of DSA to mitigate channel impairments; define multi-attribute priority classes; design distributed control algorithm for data delivery that maximizes network utility under QoS constraints
Performance metrics	Probability of channel switching; energy consumption; delay; reliability	Channel switching probs.; backoff; average access delay; throughput; duty cycle; interference ratio	Average delay; throughput; reliability	Reliability; packet latency; data rate
Objective	MAC protocol design for CRSNs in smart grid	Optimal frame structure for PU protection as well as high throughput and energy efficiency	Maximize weighted service of traffic flows belonging to different classes	Maximize weighted service of traffic flows belonging to different classes
Support for delay-sensitive apps.	Yes	Yes	Yes	Yes
Spectrum sensing technique	Energy	Energy	–	–
Architecture	HAN, NAN, WAN	HAN, NAN, WAN	HAN, NAN	HAN, NAN, WAN, AMI
Focused parameter	Energy	Energy	QoS	QoS
Number of PUs	4	–	6	4
PU (transmitter) activity model	Two state i.i.d. random process	Two state ii.i.d. random process	–	–

Table 3. Attributes of existing MAC protocols for CR-based smart grid; the DCA-based cross-layer approaches are reviewed in the section "Cross-Layer Protocols in CR-Based SG."

energy consumption. The underlying available cognitive channel has a number of fixed length time slots, each able to carry a single packet. A frame is formed by grouping a fixed number of time slots, in turn a fixed number of frames constitute a multi-frame. Uplink (UL) and downlink (DL) operate with time-division duplex on the same carrier. For high traffic levels in the UL, the ratio of DL to UL time slots is kept small, whereby only few time slots are reserved for DL communication and acknowledgments (ACKs). The DL time slots also carry broadcast status updates of UL time slots.

Challenges of MAC Protocols in CR-Based SG

The design requirements in Table 2 imply challenges faced by MAC protocols in the CR-based smart grid. However, there are additional challenges for efficient MAC protocols, which we outline next:

Dynamic Operation in Licensed and Unlicensed Bands: CRNs operate on both licensed and unlicensed bands. Channel switching probabilities in MAC protocols should be optimized to operate on these two bands. Moreover, channel switching to licensed bands may be affected by PUs, and operation in unlicensed bands may suffer from significant interference [8, 11]. In the existing studies, CRB-MAC operates in the licensed band, while PRMA can operate in both licensed and unlicensed bands.

Channel Access Delay: Average access delay (i.e., the average time a device has to wait before obtaining a reservation for the channel) is an important performance indicator of MAC protocols. Average access delay strongly depends on the presence of PUs, collisions among CRs, and the backoff schemes [11]. This average access delay has been examined in PRMA-based cognitive MAC [11].

Duty Cycle and Control Overhead: The optimization of the duty cycling has been an important challenge in all wireless networks, and MAC protocols in CR-based SGs may suffer from inefficient duty cycling. The availability of suitable duty cycles in energy-deficient devices remains a significant challenge [11]. Balancing the trade-off between energy efficiency and spectrum efficiency requires joint consideration of spectrum sensing and duty cycling. Moreover, MAC protocol reliability and effectiveness come at the cost of control overhead [6]. In dynamic radio environments, control overhead occurs in terms of channel switching overhead (i.e., when transmission changes from one channel to another channel) [11].

Error Correction: The continuously varying channel conditions may prevent packet recovery, impair packet forwarding, and cause congestion. Traditional fixed forward error correction (FEC) may not be sufficient for every channel. Therefore, the design of adaptive FEC schemes or hybrid automatic repeat request (HARQ) mechanisms remains a great challenge [6].

Routing in CR-Based Smart Grid

Routing layer protocols have to account for the link qualities of the wireless links, in terms of both individual links as well as the entire end-to-end path in dynamically changing environments.

Requirements of Routing Protocols in CR-Based SG

The design of an efficient routing protocol for the CR-based SG should address the requirements summarized in Table 4.

Existing Approaches of Routing in CR-Based SG

Notable features of existing routing protocols are summarized in Table 5.

QoS/Energy-Based Approach for HAN: Adaptations of the Routing Protocol for Low power and lossy networks (RPL) for HANs were presented in [7]. RPL maintains network state information using one or more directed acyclic graphs (DAGs) in which all edges are oriented to avoid cycles. Basic RPL has four steps: expected transmission time (ETX) calculation, rank calculation, directed acyclic graph (DAG) formation and maintenance, and destination list (DL) update. The ETX is defined in [7] to correspond to the (physical layer) link quality between two nodes, and is commonly based on the signal strength (signal-to-noise ratio) of the received packet. The rank to each node in the DAG is computed on the basis of an objective function. To construct the DAG, the gateway broadcasts a control message called DAG information object (DIO) containing relevant network information. Each node updates its DL through a device announcement message, that is, source IP and the next hop node ID are recorded until the message reaches the coordinator. The features of this approach are realized through selective routing as battery powered devices do not participate in spectrum sensing.

An 802.15.4 radio in the ZigBee pro stack with high receiver sensitivity is considered to cover licensed bands. The dual-radio architecture is employed to independently update the channel backup list without quiet periods. After joining the network, a node is considered a non-spectrum sensing node if it listens to any DIO from spectrum sensor devices or the coordinator. If it fails to do so, it is a spectrum sensing node [7].

QoS-Based Approaches for HAN, NAN, WAN, and AMI: Solutions to routing problems in CR-enabled AMI networks and CR-enabled M2M networks were examined in [13, 14]. Cognitive and Opportunistic RPL (CORPL) protects PUs and satisfies the utility requirements of CRs, that is, requirements for end-to-end throughput, latency, and packet loss ratio under spectrum sensing. CORPL modifies the basic RPL, but retains its DAG-based approach. CORPL has two important steps: selection of a forwarder set and unique forwarder selection. Each network node selects multiple next-hop neighbors as its forwarder set. With unique forwarder selection, the best receiver of each packet forwards the packet. To select the best receiver, the protocol employs a simple overhearing-based coordination scheme based on acknowledgment (ACK) frames. To select a forwarder set, CORPL utilizes the parent structure of RPL. This structure requires at least one backup parent besides the default parent. To maintain the forwarder set, each node opportunistically selects the next hop neighbors. Nodes are dynamically prioritized by a cost function approach in the forwarder set, whereas a simple overhearing-based coordination scheme performs a unique forwarder selection [13, 14].

The routing class decides the cost function to

The continuously varying channel conditions may prevent packet recovery, impair packet forwarding, and cause congestion. Traditional fixed forward error correction may not be sufficient for every channel. Therefore, the design of adaptive FEC schemes or hybrid automatic repeat request (HARQ) mechanisms remains a great challenge.

Requirements	Description
Reliability	The SG consists of a large number of smart meters and access points interconnected with a mesh network. A reliable routing path should be established to achieve reliable demand response, demand supply, dynamic power pricing, and other benefits [1, 13].
Packet delivery ratio (PDR)	The PDR is affected by certain factors, such as packet size and network load. The PDR gives an indication of the protocol performance for given packet loss ratios, whereby high PDRs indicate a well-performing routing protocol [9, 13].
Multihop and multicast design	In case of link failure or node failure, multihop and multicast designs are suitable options for reliable and secure information transfer. The routing algorithms should be able to select the best forwarding paths and the best neighbors set for high-speed and easy-to-deploy wireless backbone systems [6, 9, 13]. An opportunistic "store-carry-and-forward" scheme may be a good alternative to a basic "store-and-forward" scheme [9].
PU protection	PU protection is the utmost requirement. Routing protocols should select paths for CR nodes with minimum interference to PUs. Optimal transmission times for CRs must be selected for PU protection [7, 13].
Throughput	Throughput is the measure of the average rate (bits per second) of payload data delivered to the ultimate destination over a long time horizon. For continuously sending data sources, a high throughput multicast tree may help ensure that all receivers receive all the data.
Quality of service	The latency requirements of certain normal SG applications, such as demand response management, range from about 500 ms to several minutes. Real-time applications (e.g., wide area situational awareness) may need high bandwidth resources (600–1500 kb/s) and low latency (20–200 ms). Low delay can be achieved with complex and updated infrastructures, thus requiring expensive deployment of communication networks, while larger delay may jeopardize SG system stability and reliability. Efficient QoS-specific routing algorithms are needed to support the normal and time-critical operations of the smart devices without compromising other metrics. Routing protocols should also use multicast trees with high transmission rates and small hop counts. Asymmetry in networks due to varying node behaviors should not violate QoS provisioning [7]
Energy consumption	Energy consumption in the network is the averaged and aggregated value of the energy consumed at each node. Cooperative routing protocols, such as diffusion-based cooperative routing protocols, can be developed to increase the energy efficiency of packet forwarding [6, 9].
Path determination	The most commonly used metric to determine the route from the source to a destination in multihop wireless networks is the hop count. However, the hop count cannot reflect the varying link quality in SGs. Hence, traditional multihop routing protocols of mobile ad hoc networks (MANETs) cannot perform satisfactorily by utilizing only the hop count routing metric; additionally, the link loss ratio and the interference among links of a path should be considered in SGs [9]. Routing protocols should also consider the topology changes due to joining/leaving nodes [7].

Table 4. Design requirements for routing protocols in CR-based smart grid.

prioritize the nodes in the forwarder set. There are two different routing classes in CORPL: class A supports PU receiver protection, whereas class B satisfies the end-to-end latency for high-priority delay-sensitive alarms. The routes selected for the secondary network should pass through regions of minimum coverage overlap with the PU transmission coverage. This reduces interference to PU receivers. Class B supports delay-sensitive alarms by selecting the next-hop that ensures the deadline. The packet will be dropped if the deadline has elapsed [13, 14].

Challenges of Routing Protocols in CR-Based SG

Smart grid communication faces a number of challenges, including secure connectivity among different parts of the system. Connectivity may be lost as nodes drop out either permanently or temporarily. Disasters and security breaches are other main causes of connectivity losses. Dynamic environmental conditions, such as multipath, fading, noise, attenuation, and varied channel availability, which may be exacerbated near high-power electrical grid installations, result in unstable and inconsistent link connectivity in wireless SG environments. These connectivity problems also arise in CR-based SG systems, making routing challenging [4]. This section covers the challenges faced by routing protocols for the CR-based SG.

Latency: Latency represents the end-to-end delay components from source to destination [9]. In addition to the transmission delays, a packet may experience processing delay and queuing delay in the nodes, and then propagation delay on the medium. In CR-based SG systems, queuing delay may arise due to waiting for channel access. Although smart meters and smart devices are generally static in the smart grid, the wireless links among these devices and meters may be unstable due to interference and fading effects. For large numbers of smart devices and dynamic link quality, long data delivery delays may be unavoidable. If long delays occur, SG applications that strongly rely on fast data-related actions, such as demand response, dynamic pricing, and wide area situational awareness, may act incorrectly.

Complexity: Routing protocols often suffer from dynamic wireless link changes. Successful operation of CR-based SG networks cannot be achieved with traditional simple routing protocols alone; additional support for channel awareness and interference is needed, increasing complexity and costs [7].

Operation under Spectrum Sensing State: Nodes periodically enter the spectrum sensing state to monitor the channel for PU activity. Nodes in the spectrum sensing state do not forward data packets. The operation of routing algorithms becomes challenging when nodes are in the spectrum sensing state. The spectrum sensing state may degrade the routing protocol performance, especially in SG systems with many nodes or large geographic areas [6, 13]. With large node numbers, many SUs may attempt to simultaneously access the spectrum, whereby each SU may have to establish a reliable link. In addition, SGs covering large geographic areas may frequently experience widely varying wireless channel conditions.

Trade-off between PU and CR Operation: The routing layer needs to protect PUs, and should provide QoS for CRs. The trade-off between these

Reference	[6]	CORPL [13]	CORPL [14]	RPL modifications [7]	CSMA/CA with DCA [10]	Suboptimal DCA [12]
Network type	CRSN	CRN	Cognitive M2M	CRSN	CRSN	CRSN
Simulator type	–	Matlab	Matlab	Matlab	NS-2	NS-2
PU transm. stationary	–	Yes	Yes	–	–	–
Nodes stationary	–	Yes	Yes	–	Yes	–
Licensed/unlicensed operation	–	Licensed	Licensed	Both	–	–
Single/multi channel	Multi	Multi	Multi	Multi	Multi	Multi
Single/multi-hop	Multi	Multi	Multi	Multi	Multi	Multi
Energy consumption considered	No	No	No	Yes	No	No
Advantages	Reliability support	Good PDR; min. PU collisions; improved performance in spectrum sensing state	Good PDR; min. PU collisions; improved performance in spectrum sensing state	Minimum network traffic through channel load balancing; optimization of the protocol stack	Application-specific QoS requirements; low delay; good reliability; good throughput	QoS support; data scheduling; on-demand routing; low delay; good reliability; good throughput
Disadvantages	No performance evaluation besides reliability	High DAG convergence time for low node density; duplicate packet forwarding	High DAG convergence time for low node density; duplicate packet forwarding	Complexity and cost involved in designing CR hardware and software; inter personal area network interference	Poor delay performance with increasing number of channels	No performance improvement with increasing number of channels; high contention on common control channel
Other features	Protocol design principles; study of applications areas and energy harvesting techniques	Two state i.i.d. random process activity model; opportunistic forwarding; minimum harmful interference to PUs	Two state i.i.d. random process activity model; opportunistic forwarding; minimum harmful interference to PUs	Adaptation of RPL to asymmetric networks	Joint optimization of routing; MAC and physical layer functions	DSA mitigates channel impairm.; multi-attribute priority classes; distr. control alg. for data delivery to max. network utility under QoS constraints
Performance metrics	Reliability	Reliability; delay, collision risk	Reliability; delay; collision risk	Total effective links; number of packets	Avg. delay; throughput; reliability	Reliability; packet latency; data rate
Objective	Study the potential of sensor networks for SG apps.	Enhance RPL for CR enabled AMI networks	Enhance RPL for cognitive M2M networks	Modifications of RPL for user requirements (joining procedure; asymmetry)	Maximize weighted service of traffic flows belonging to different classes	Maximize weighted service of traffic flows belonging to different classes
Support for delay sensitive applications	No	Yes	Yes	No	Yes	Yes
Spectrum sensing technique	–	Energy	Energy	Feature	–	–
Architecture	HAN, NAN, WAN	AMI	HAN, NAN, WAN	HAN	HAN, NAN	HAN, NAN, WAN, AMI
Focused parameter	QoS	QoS	QoS	QoS/energy	QoS	QoS
Number of PUs	–	9	9	–	6	4
PU (transmitter) activity model	–	Two state independent and identically distributed (i.i.d.) random process	Two state independent and identically distributed (i.i.d.) random process	—	-	
Routing method	–	Multi root DAG	Multi root DAG	Multi root DAG	–	
Routing metric	–	ETX	ETX	ETX	–	Latency, data rate
Route maintenance	–	Proactive	Proactive	Proactive	–	Proactive

Table 5. Attributes of existing routing protocols for CR-based smart grid; the DCA-based cross-layer approaches are reviewed the section "Cross-Layer Protocols in CR-Based SG."

Although link scheduling is traditionally considered in conjunction with the link layer and MAC protocols, the joint consideration of routing and link scheduling can achieve significantly enhanced performance in CR-based SGs. Specifically, routing protocols can incorporate schedules with information about active links in each slot so as to minimize transmission conflicts.

two behaviors remains a significant challenge for routing protocols [13].

Link Scheduling: Although link scheduling is traditionally considered in conjunction with the link layer and MAC protocols, the joint consideration of routing and link scheduling can achieve significantly enhanced performance in CR-based SGs. Specifically, routing protocols can incorporate schedules with information about active links in each slot so as to minimize transmission conflicts. This approach is highly challenging as all schedules may have different delays, even for a single tree, making it difficult to select suitable link schedules.

Dynamic Route Discovery: Routing protocols start route discovery in case of a new event or addition/rejection of nodes. Dynamic applications in HANs and wide area SG monitoring pose challenges for successful and reliable route discovery [10].

Cross-Layer Protocols in CR-Based Smart Grid

In this section, we discuss cross-layer approaches for CR-based SG systems. The MAC and routing protocol aspects of the two main existing cross-layer approaches, which are based on a DCA, are summarized in Tables 3 and 5.

QoS-Based Approaches for HAN and NAN

Besides specifically focusing on QoS MAC protocol designs for the CR-based SG, cross-layer designs may be employed to meet the application-level QoS requirements. The DCA-based approaches in [10, 12] differentiate the traffic with heterogeneous QoS requirements into a set of priority service classes with different data rate, latency, and reliability levels. The weighted network utility maximization (WNUM) scheme is used to maximize the weighted sum of the flow service. A cross-layer heuristic solution is then employed to solve the utility optimization problem. The routing protocol interacts with the MAC and physical layers to select a suitable channel, and prioritizes transmissions by setting the MAC contention window size according to the class priority [10].

A CSMA/CA-based MAC protocol with DSA functionality is studied in [10]. An on-demand distributed routing protocol with lower route update frequency compared to ad hoc on-demand routing protocols is used to select a channel with sufficient capacity and constrained bit error rate. The operations of the routing, MAC, and physical layers are controlled through a routing frame period structure. Time is divided into routing frames to deliver data, whereby each routing frame has three periods: a fixed spectrum sensing period as well as variable control and data transmission periods. When the spectrum sensing period initializes, the routing agent switches the control to the physical layer and triggers spectrum sensing. After the sensing period, nodes switch to the common control channel in the control period and transmit their periodic hello beacons, contention frames, and broadcast messages. Route discovery is performed in the case of a new event or a new flow. Route discovery starts by broadcasting a route request message on the control channel during the control period of the routing frame [10].

QoS-Based Approach for HAN, NAN, WAN, and AMI

The cross-layer framework may be formulated as a Lyapunov drift optimization and a suboptimal DCA to support channel control, flow control, scheduling, and routing decisions [12]. The DCA selects the channel dynamically on the basis of the perceived signal interference and the resulting estimated channel capacity. It has been observed that the flows of higher priority classes are largely unaffected by an increase in the number of lower priority flows. At the same time, each class does not cause performance changes under limited number of channels with large PU footprints. In this strategy, the routing algorithm provides channel control by selecting the forwarding node and minimizes saturation to avoid interference. In addition, the routing algorithm initially attempts to provide a shortest routing path from source to destination, and utilizes load balancing to avoid congestion if there are many feasible paths.

Concluding Remarks and Future Trends

From the comprehensive review of existing approaches for MAC and routing protocols, we conclude that the design of routing and MAC protocols for CR-based SG networks is largely an unexplored area. Existing research has developed some initial novel MAC protocol designs for the CR-based SG, while routing protocol research has been limited to modifications of RPL.

More specifically, the novel CRB-MAC protocol has many attractive features but has high energy consumption in poor channel conditions since CRB-MAC requires reception by several next-hop receivers. Increasing the number of receivers to ensure a sufficiently large next-hop receiver set may not be a viable cost-effective solution. With the PRMA-based MAC approach, a device itself does not have spectrum sensing capabilities. Instead, a gateway senses the spectrum. This approach can reduce energy consumption, but delay-sensitive applications may suffer.

With timely reliable channel access and data transmissions, all SG applications can contribute to smooth SG operation. Delay-sensitive applications should receive priority; however, a fairness scheme should be maintained among all applications. Fairness can be ensured through backoff mechanisms in MAC protocols that are designed to support QoS requirements. Critical SG applications can prioritize channel access through a short backoff. However, sudden changes in dynamic CR-based SGs can trigger emergency alarms. If the applications with these alarms have low priority, they have to wait for a long backoff interval [8, 11]. A geolocation database, similar to the database used in IEEE 802.11af, could store the spectrum usage characteristics with number of channels and durations, and may be accessed on demand by SG applications. The database can shorten channel access delays and may be a good option for dynamic operation in licensed and unlicensed bands.

Existing routing studies on the CR-based SG have examined modifications to RPL that add complexity and cost for CR hardware and software. Furthermore, these modified routing protocols have not yet been widely studied in dynamic power systems where interference dominates the channel. As most of the routing protocols studied for CR-based SG systems so far have been based on modifications of RPL, a future research direction is to examine alternate routing strategies, such as the LOADng routing protocol, which is also designed for low-power, lossy networks [15]. Support for more general traffic patterns, flexible packet formats, and avoidance of control packet fragmentation make LOADng a promising alternate to RPL. Alternatively, for reliable data transfer in lossy channel conditions, sending multiple copies of the message concurrently over independent paths may be a good strategy. Retransmissions may be an alternative to account for packets that are dropped due to lost link connectivity. An important overarching future research direction is to develop and validate a common performance evaluation framework for MAC and routing protocols in CR-based SG systems.

Retransmissions may be an alternative to account for packets that are dropped due to lost link connectivity. An important overarching future research direction is to develop and validate a common performance evaluation framework for MAC and routing protocols in CR-based SG systems.

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