Shah *et al. Complex Adapt Syst Model (2016) 4:18*
DOI 10.1186/s40294-016-0030-y

Complex Adaptive Systems Modeling

REVIEW **Open Access**

A survey on MAC protocols for complex self-organizing cognitive radio networks

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Abstract

Complex self-organizing cognitive radio (CR) networks serve as a framework for accessing the spectrum allocation dynamically where the vacant channels can be used by CR nodes opportunistically. CR devices must be capable of exploiting spectrum opportunities and exchanging control information over a control channel. Moreover, CR nodes should intelligently coordinate their access between different cognitive radios to avoid collisions on the available spectrum channels and to vacate the channel for the licensed user in timely manner. Since inception of CR technology, several MAC protocols have been designed and developed. This paper surveys the state of the art on tools, technologies and taxonomy of complex self-organizing CR networks. A detailed analysis on CR MAC protocols form part of this paper. We group existing approaches for development of CR MAC protocols and classify them into different categories and provide performance analysis and comparison of different protocols. With our categorization, an easy and concise view of underlying models for development of a CR MAC protocol is provided.

Keywords: Cognitive radio, MAC protocols, Control channel, Control information, Spectrum sensing, Spectrum access

Background

As modern large-scale wireless networks grow in size, complexity and variety, the change in networks is not just terms of scale but also in the emergence of newer types of communication networks such as cognitive radio (CR) networks, ad-hoc, peer-to-peer (P2P), multiagent, wireless sensors, internet of Things (IoT), social and cloud-based networks. An intelligent cognitive radio network has the capability to self-organize, self-learn and self-configure to utilize an unoccupied band and to transmit based on the available spectrum resources. Various inherent nonlinearities in network operations can lead to an increase in complex communications, which can have unpredictable effects on different aspects of networks such as communication costs, traffic congestion and so on (Niazi and Hussain 2013a). Due to the intrinsic nonlinearity, modern networks can be modelled and simulated in a better way by treating them as artificial Complex Adaptive Systems (CAS), or generalizing as Complex Adaptive COmmunicatiOn NetworkS and environments (CACOONS) (Niazi and Hussain 2013b). Complex Adaptive Systems (CAS) or complex systems are characterized by the interactions between their numerous elements often leading to emergent phenomena whose effects are often untraceable to individual network components (Gershenson and Niazi 2013). Recent research work has demonstrated the effectiveness of Agent-based modelling (ABM) and complex networks–based modelling (CN) in simulation and modelling modern large-scale, wireless communication networks (Niazi and Laghari 2012; Niazi 2013; Batool and Niazi 2015).

Cognitive radio (CR) network is an intelligent wireless network where nodes are able to sense the environment for vacant spectrum and then seize the opportunity to transmit ensuring that the licensed user will not suffer. This process of scanning the spectrum (*S*), exchanging the control information (*E*), agreeing on an unused spectrum (*A*) and then transmitting data (*T*) with other CR nodes in the network is repeated continuously in a cycle called *SEAT* cycle. The phenomenon of this SEAT cycle complex self-organizing CR network is presented in Fig. 1a.

The CR is considered to be an emerging technology which can efficiently address the spectrum scarcity issues. Switching of TV channels from analog to digital in UK and other countries has vacated some portion of spectrum which can be used in a CR. Other applications can include free mobile calls with better link quality, public safety and disaster management, license free wireless applications etc. However, there are certain challenges associated with the CR and most challenging task is how will CR nodes converge on a control channel and how will they form a CR network. The paper mainly focusses on addressing these challenges in a CR environment.

CR is always dependent on the licensed user and its spectrum. A CR node cannot establish a communication link until there is a vacant spectrum. Furthermore, CR nodes must have to ensure that if they are using the licensed user spectrum, there must not be any kind of interference or inconvenience to the licensed users in any case. The dependence on other wireless nodes, agreeing with other CR nodes for communication on a vacant channel, seizing the opportunity to transmit, regulatory issues, sensing abilities, security concerns etc. add more and more complexity to the existing CR technology.

A CR node can learn from its own network or it can coexist with other existing wireless networks. Due to its ability to coexist with other wireless networks, a CR network structure is heterogeneous. A cognitive radio (CR) network can adapt one of the following three different network architectures.

Infrastructure CR networks

This type of CR network has a base station which usually governs the cognitive functions in the network. Like other Infrastructure wireless networks, the base station is responsible for providing information about available spectrum, security management and cooperation amongst CR nodes in the infrastructure network (Fig. 1b). Cordeiro et al. (2005) has presented the first worldwide wireless standard IEEE 802.22 for cognitive radios. The applicability and market of IEEE 802.22 is restricted to remote and rural areas and the TV channel bandwidths of 6, 7 and 8 MHz have been specified as the most appropriate spectrum band for unlicensed users to transmit. Further enhancements on IEEE 802.22 has been presented by Carl et al. (Stevenson et al. 2009). Their article presents a high-level overview of the IEEE 802.22 standard for cognitive wireless regional area networks (WRANs) that is under development in the IEEE 802 LAN/MAN Standards Committee. A dynamic spectrum access (DSA) protocol (DSAP) has been presented in (Brik et al. 2005) which makes use of DSAP server and DSAP relay

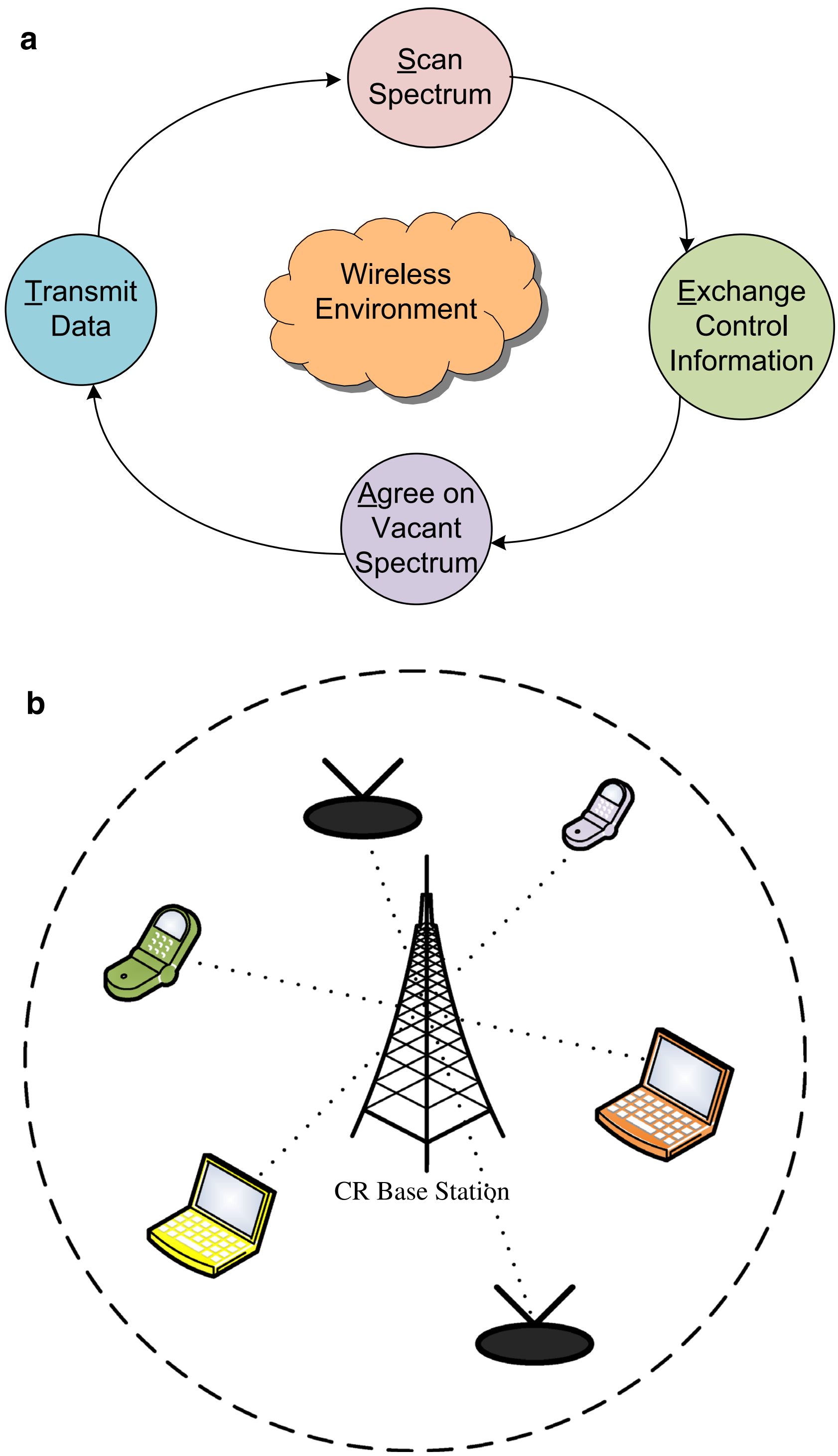

Fig. 1 **a** The SEAT cycle in complex self-organizing cognitive radios. **b** An infrastructure-based CR network

which are centralized entities that coordinate spectrum access requests and allow multi-hop communication between DSAP clients. The server accepts spectrum lease requests from clients and assigns the spectrum resources with certain constraints such as a time for lease. Like the dynamic host configuration protocol (DHCP), DSAP also makes use of a channel-discover request which is responded to by a channel offer message and a channel request message. Both these messages contain the channel details and lease criteria. A channel acknowledgement (ACK) is sent by the DSAP server to either accept or decline clients' requests for lease. In the case that there is primary user (PU) occupancy, a channel reclaim message is sent to the client, forcing it to terminate or reassign clients' lease. In spite of the dedicated central entity that is in DSAP, the exchange of five control frames as control information, prior to any data transmission, imposes a high computational cost and pre-transmission overheads.

We suggest that the channel-discover, channel-offer and channel-request messages could be replaced by channel broadcast message containing the FCL. DSAP clients can receive a channel broadcast message and can start their data transmission with other DSAP clients.

Bolivar et al. (2010) present an infrastructure-based cognitive radio network and use frequency-division multiplexing to divide the spectrum into predetermined frequency slots in which SUs communicate. The time-division multiplexing scheme is additionally used to determine if a PU has accessed the channel. This scheme also exchanges multiple control frames that consume network bandwidth. Like DSAP (Brik et al. 2005), no specification has been made on which spectrum band will be used by the server and clients to dialogue control information. Islam et al. (2010) proposed another infrastructure based CR network which utilizes point-to-multipoint CR network and shares some of the primary channels from the network. A base station is responsible for controlling and supporting a set of fixed-location wireless subscribers. In order to minimize the required cooperation between cognitive and primary devices, two phased mixed control algorithms (distributed/centralized) are developed. In the first phase, the coverage of the cognitive network is maximized while maintaining the constrained signal-to-interference-plus-noise ratio of primary transmissions.

Thilina et al. (2016) presents a dynamic CCC-based MAC protocol for centralized cellular CR networks. The CCC is dynamically selected by a fix number of SUs which participates in the CCC selection process. The four main phases involved in this protocol are as follows: spectrum sensing, CCC selection, data transmission, and beaconing. Their proposed protocol eliminates the GCCC which minimizes the overheads of contention and backing off and the use of support-vector-machine efficiently finds a CCC, however, the authors have not clearly specified the concept of cellular structure in a CR environment. Furthermore, it is hard to identify the difference of this cell-based CR MAC protocol with other classical CR MAC protocols.

Ad hoc CR networks

Unlike infrastructure-based CR networks, the CR nodes in the ad-hoc network are responsible for all cognitive operations and functionality. CR nodes can communicate directly with other CR nodes without involvement of a central entity like the base station (see Fig. 2). Nodes can join and leave the network at any time, and exchanging control information amongst CR nodes without the presence of a centralized station is a key challenge in CR ad-hoc networks. Extensive research has been carried out for this category and different protocols have been presented for ad-hoc CR networks which address

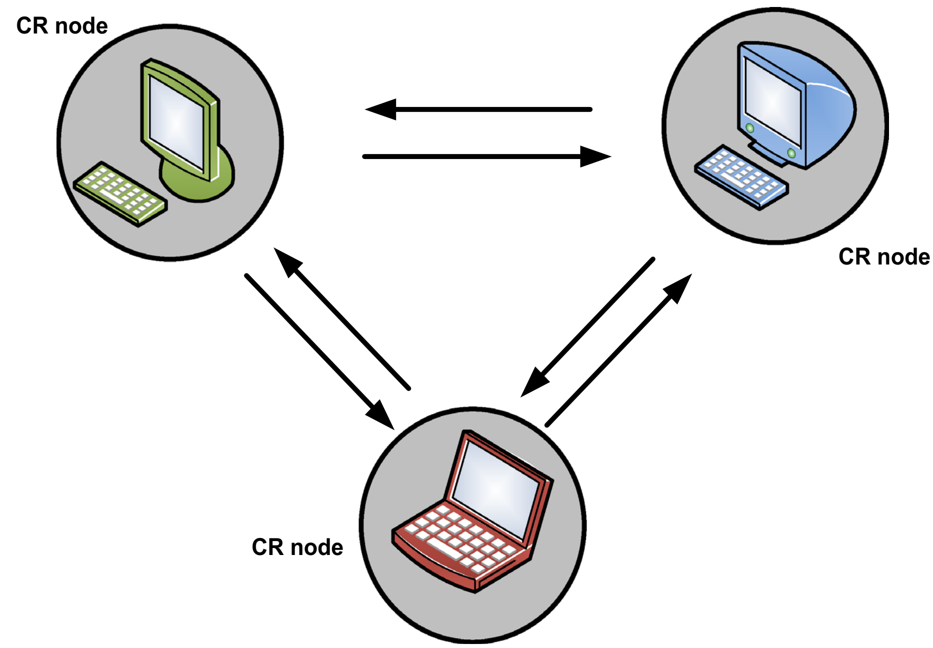

Fig. 2 An infrastructure-less CR network

issues such as synchronization of nodes, authentication mechanisms for new nodes to join the network, and access mechanisms to dialogue control information on the common control channel. Ad hoc CR networks are further categorized based on whether they use the ISM band global common control channel (GCCC) or not. Our research is based on infrastructure-less CR networks and is a hybrid between GCCC and non GCCC. More details about GCCC and non-GCCC will be provided in the next section.

Mesh CR networks

Mesh networks for cognitive radio merge the architectures of infrastructure CR networks and ad-hoc CR networks into one. It uses the mesh topology where different base stations are connected to form a single backbone (Fig. 3). The challenge for route selection and spectrum decision could be efficiently addressed by mesh CR networks (Zhu et al. 2008; Akyildiz et al. 2009). Figures 2, 3 shows the topological design for Mesh CR network.

The medium access control plays an important role in various cognitive radio functions namely spectrum mobility, spectrum sharing, resource allocation, and channel sensing (Akyildiz et al. 2006; Ghasemi and Sousa 2008; Yucek and Arslan 2009). When a primary user is detected, spectrum mobility allows a secondary user to leave its channel, and to access an idle band where it can re-establish the communication link. Channel sensing allows a cognitive user to gather spectrum usage information, and to maintain a record of available channels dynamically. As per the QoS requests, available channels are opportunistically assigned to cognitive users through resource allocation. In order to avoid any harmful interference, spectrum access is utilized which deals with contentions between heterogeneous primary and secondary users. Multi-channel MAC protocols for ad-hoc wireless networks is the first step in the development of MAC protocols for

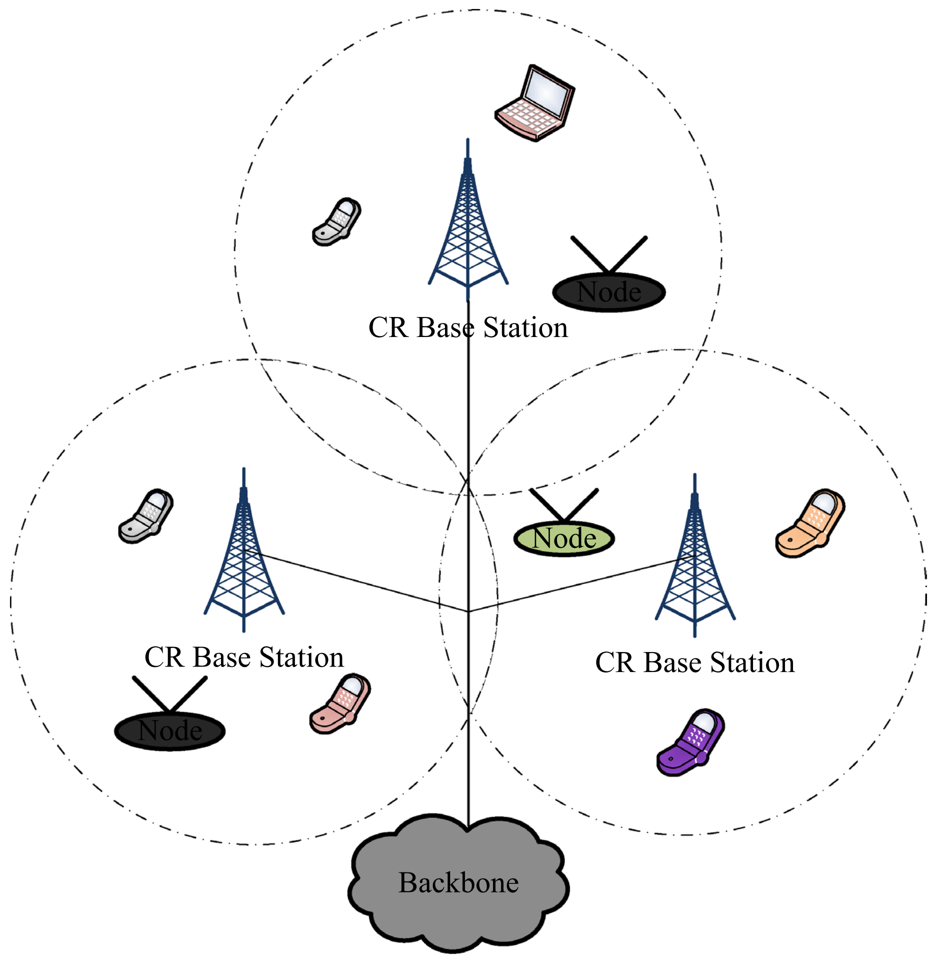

Fig. 3 Mesh CR network architecture

cognitive radio in unlicensed scenarios. These protocols address similar issues; operating in a multichannel context and facing the multiple channel hidden terminal (So and Vaidya 2004). However, a cognitive radio may utilize increased sophisticated sensing functionalities that protect licensed transmissions and differentiate between primary users and secondary users. Unlike multi-channel network where number of channels available to each user is fixed, in a cognitive network it changes with space and time. Moreover, the time-scales for cognitive radio and ad-hoc radio are very different from each other. In case of cognitive radio, periodical sensing must be utilized by secondary users to be aware of the wireless environment evolution and users must change their behaviour rapidly to comply with interference constraints.

To help understand the CR taxonomy and more specifically how the control information is exchanged amongst CR nodes, we review different types of MAC protocols for Complex Self-Organizing CR networks. We survey the literature over the period 2004–2013. In particular, we emphasize on the MAC protocols for decentralized CR networks.

The rest of the paper is organized as follows. "Types of common control channel" section describes types of common control channel. "Medium access control mechanism in CR networks" section reviews medium access control mechanisms used in complex self-organizing CR networks. We present design constraints for channel accessing in "Design constraints of channel accessing for CR users" section. The CR MAC protocol classification is discussed in "CR MAC protocols classification process" section. It analyses the different methodologies used in designing a CR MAC protocol. In "Summary and findings" section, we present our findings about the CR protocols before the paper is concluded in "Discussions" section.

Types of common control channel

A common control channel is a free channel required by cognitive devices to exchange a free channel list (FCL) and to initialize communication among co-operating cognitive nodes. Before sending and receiving actual data, a pair of SUs has to coordinate and decide about the chosen white space(s) for subsequent transmission. A common control channel (CCC) is required by infrastructure-less CR nodes only where they dialogue control information.

GCCC, non-GCCC and assumed CCC

The selection criteria for the CCC could be *static* or *dynamic* under the static case, SUs use the ISM band provided by the FCC for exchange of control information. CCC in this case would be called a global/universal common control channel. We denote this global CCC as 'GCCC'. In the dynamic case, the control channel is one of the empty spaces from the list of unoccupied spectrum bands or a channel from the free channel list (FCL). This type of control channel is also called local control channel and is denoted as non-GCCC. Synchronization amongst CR nodes using a non-GCCC is one of the most challenging tasks as nodes are not aware of other nodes in the vicinity initially and nodes may have disparity in deciding a channel in FCL as non-GCCC. There also exists some of the CR MAC protocols that are hybrid between GCCC and non-GCCC families of CR MAC protocols, e.g., (Shah et al. 2011b). More details about assumed CCCC are provided in "Hybrid access MAC" section. Using GCCC for control information has advantages and disadvantages (Kondareddy and Agrawal 2008; Joshi et al. 2009; Safdar and O'Neill 2009).

Medium access control mechanism in CR networks

In order for CR nodes to communicate with each other, they must exchange the control information and spectrum information through a common control channel. This CCC must be known and available to all CR nodes for subsequent transmission to take place. The medium access control (MAC) protocols help CR nodes to access the CCC and to access available white spaces without interfering with the licensed users. MAC protocols also help CR nodes with addressing and channel access control mechanisms that make it possible for nodes in the CR network to communicate within a multiple access network that employs a shared medium. MAC protocols for complex self-organizing CR networks are especially designed to enable reconfiguration and adaptation based on spectrum sensing functions. CR MAC protocols could be classified on the basis of channel access mechanism, use of GCCC or non-GCCC, in-band or out-of-band CCC, overlay and underlay, synchronous and asynchronous CRN, direct access based and dynamic spectrum allocation based, centralized and decentralized CR networks, and whether they are based on cooperative or non-cooperative CR MAC protocols. A single CR MAC protocol can belong to different categories at the same time. For example, a MAC protocol presented in (Shah et al. 2011b) is non-GCCC, decentralized, overlay and cooperative at the same time. More detail about each category will be provided in the oncoming sections of this chapter.

Design constraints of channel accessing for CR users

To borrow unoccupied channels, CR users must be capable enough to identify a channel's characteristics and its availabilities. Since PUs may come back to use the spectrum anytime, CR users must be able to timely sense the presence of PUs and vacate the occupied bands immediately to avoid or restrict the interference to PUs. Therefore, spectrum sensing and spectrum accessing/vacating are two crucial tasks to realize this technique. Spectrum sensing enables CR users to collect information about the spectrum usage and the presence of PUs. Mostly physical layer performs such task. For spectrum accessing and vacating CR users have to transmit data packets on unoccupied channels and release these channels to PUs as quickly as possible. We examine the design constraints of channel access for CR users, including the efficiency of control channel, the efficiency of data channel and the efficiency of vacating a channel.

Efficiency of control channel

Efficiency of control channel depends upon the time required for CR nodes to discover a common control channel. Subsequent communication amongst CR nodes could not occur until CR nodes are aware of a channel that is available for all CR nodes. The control channel efficiency is linked with the selection criteria for the control channel. The control channel may be either a well-known and publicly available channel, commonly called the GCCC or it could be one of the most reliable and available white spaces (non-GCCC). The former category has some drawbacks such as saturation of the GCCC, no traffic differentiation (QoS unaware) and security attacks like denial-of-service (DoS). The latter though exhibits worse searching efficiency, but once the control channel is found by all CR nodes in the vicinity, nodes takes less time in exchanging control information and quickly respond to transmit data.

Efficiency of data channel

Data channel efficiency is termed as the time needed for two CR nodes to conclude transmission on a data channel. In high traffic loads of PUs, CR users transmit only one data frame before they vacate the channel. However, in case of less chance of PUs interferences if CR nodes still have data to send, more than one data frame can also be transmitted in one transaction. The data channel efficiency may be enhanced by using more than one data channel simultaneously (Hsu et al. 2007; Joshi et al. 2009). On the other hand, determining the length of a spectrum hole would also help increase data channel efficiency.

Efficiency of vacating a channel

CR users should vacate the occupied channel when the PU claims it to minimize the interference. Most of the CR MAC protocols found in the literature assume that nodes are automatically aware of the existence of PUs (Cabric et al. 2006; Jia and Zhang 2007;

So and Walrand 2008; Su and Zhang 2008a; Akyildiz 2008; DaSilva and Guerreiro 2008; Jiang et al. 2009; Rashid et al. 2009). However, the unrealistic assumption is criticized because CR nodes cannot sense the PU presence when transmitting and PUs cannot generate interruptive signals to SUs on occupied channels. The performance of both PUs and SUs largely depends on whether or not the PU activity can be sensed timely. Equipping CR nodes with sensors in conjunction with transceivers could help alleviate the assumption and is less costly than transceivers (Zhang and Su 2011).

CR MAC protocols classification process

As previously discussed, MAC protocols for complex self-organizing CR networks are especially designed to enable reconfiguration and adaptation due to their dependence on spectrum sensing functions. Numerous protocols for CR networks have been designed and developed. A thorough review has enabled us to classify CR MAC protocols as presented in Fig. 4.

Classification based on access mechanisms

Due to the classical wireless nature of cognitive radio, existing channel access mechanisms (e.g. random, time slotted and hybrid, a combination of random and time slotted) could be applied. The classification of CR MAC protocols based on different channel access mechanisms is further described below.

Time-slotted CR MAC protocols

The MAC protocols in this category divide the control channel into time slots of fixed length. Each time slot represents one CR node, and nodes can only communicate in their respective time slots. Each time slot has a listening period and a transceiving period. All CR nodes are synchronized in the listening period of each time slot. The time division multiple access (TDMA) algorithm is used to access the common control channel to exchange the FCL or to transmit data in data channels. The protocols presented in Cordeiro and Challapali (2007); Kondareddy and Agrawal (2008); Sha et al. (2009); Song-song and Wei (2009) logically divide the channel into slots, each of which, in turn, includes a slotted listening period where nodes exchange information, negotiate channel usage and get synchronized, and a transceiving period where the actual data transmission takes place (see Fig. 5). Each node transmits/receives a beacon in a listening period of its designated time slot, which helps deal with hidden nodes, medium reservations, and mobility. The limitation of this category of CR MAC protocols is that a centralized entity is required for the network-wide synchronization.

Random access CR MAC protocols

The main principle used by the CR MAC protocols in this category is carrier sense multiple access with collision avoidance (CSMA/CA). Each CR node contends for the medium to dialogue control information and then switches to a common channel in the FCL for subsequent data transmission. No time synchronization amongst CR nodes is required in this category but there is always starvation of the control channel. The protocols designed in Ma et al. (2005a); Adamis et al. (2007); Jia et al. (2008); Lien et al. (2008); Salameh et al. (2009) use traditional listen-before-transmission phenomenon.

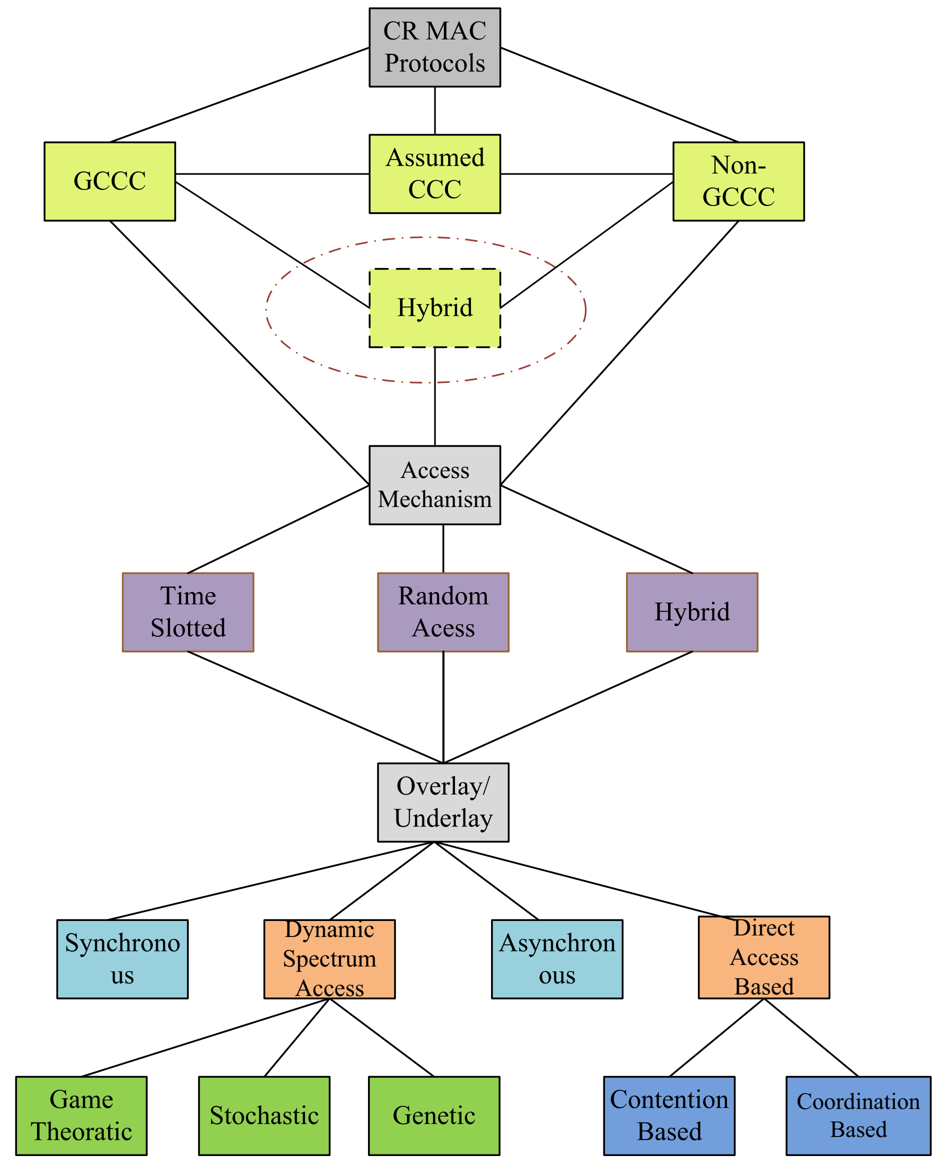

Fig. 4 Classification model for cognitive radio MAC protocols

Each node shall sense the carrier before transmission. If the channel is sensed idle, then the CR node that wants to transmit packets sends a RTS message on the common control channel. If the corresponding CTS message is received successfully, then both the sender and receiver switches to the data channel that was found as common during the initial RTS/CTS dialogue. Data packets can be transmitted on the data channel followed by an acknowledgement (ACK) message. This behaviour of CR nodes is provided in Fig. 6.

Hybrid access MAC

The protocols in this category make use of an approach lying between random access and time-slotted access mechanism. Control signals are synchronized amongst nodes in

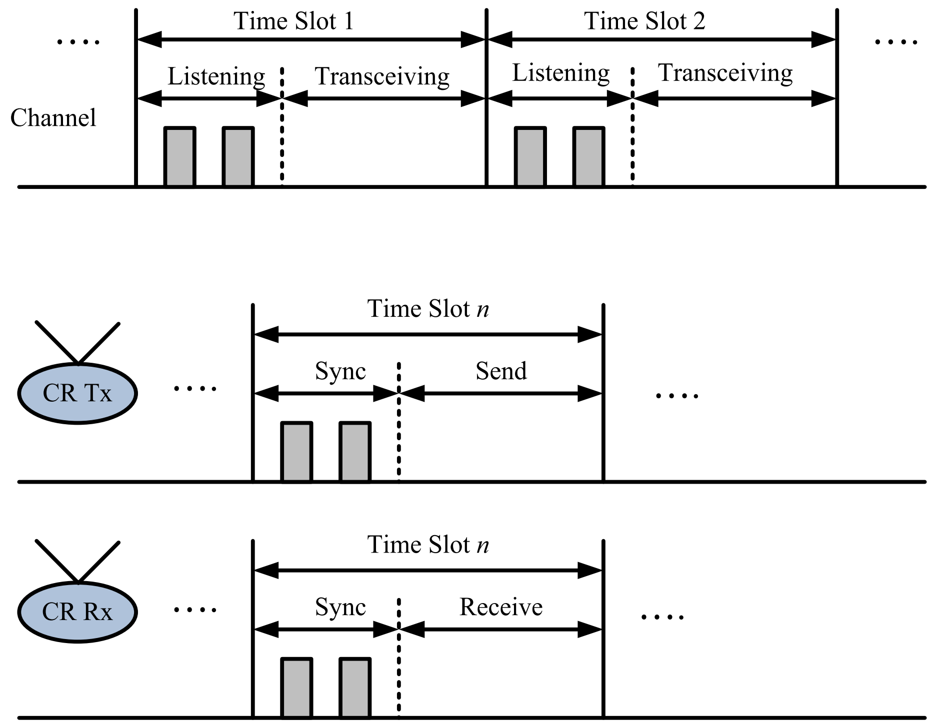

Fig. 5 Structure of time slotted CR MAC protocols (Shah et al. 2013a)

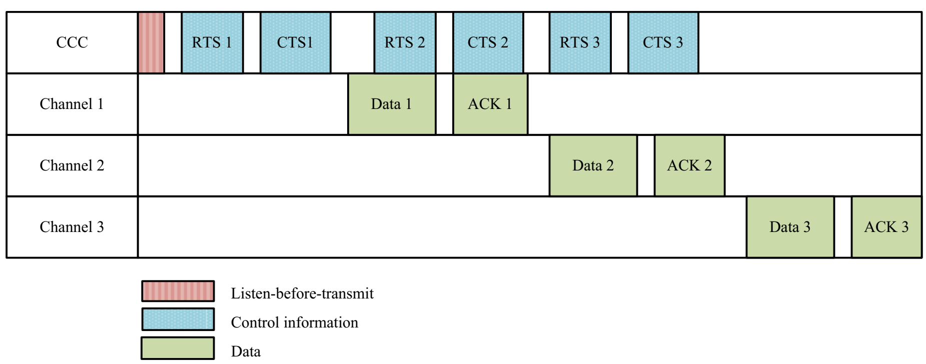

Fig. 6 The behaviour of random access CR MAC protocols

complex self-organizing CR network through time slots, and actual data transmission occurs following the random channel access mechanism. The OS-MAC protocol for cognitive wireless networks (Hamdaoui and Shin 2008) devotes one channel as a CCC, where inter-channel control traffic takes place. In OS-MAC, devices are needed to be equipped with a half-duplex transceiver only. OS-MAC balances the traffic load over all spectrum bands which improve the spectrum access efficiency significantly, and it treats all users fairly by assuring them to receive an equal throughput share or access time share. Synchronizing amongst nodes is established by locating and switching nodes to the best spectrum band (which is, less loaded, and less noisy). Another hybrid access CR MAC protocol which has been developed is the SYN-MAC protocol (Pan and Wu

2007), which divides the network time into frames. Every frame includes three intervals: the contention interval, the hidden-station elimination interval and the data interval. These intervals help achieve a shorter synchronization time, and nodes within one collision domain agree on a close-enough time point for transmission. The major design flaw in both the OS-MAC and SYN-MAC protocols is the fixed duration of time-slot. The length of time-slot should vary as more nodes join and leave the network.

Classification based on proactive and reactive approaches

In the proactive approaches, a CR user regularly searches for unoccupied channels, and record the properties of sensed channels in the form of table (such as channel occupancy and signal-to-noise ratio), even though it has no data to send immediately. A statistical channel allocation MAC protocol is proposed in Hsu et al. (2007), where all CR users regularly sense the spectrum and CR receivers determine the potential transmission opportunities. Unlike previous approach of devoting a channel for control message exchanges, the scheme presented in Kondareddy and Agrawal (2008) assumes that each CR user is equipped with two transceivers to perform channel sensing (named listening radio) and data transmission (named data radio). Listening radio of each CR user keeps sensing channels in a logical order. For sending data, a CR sender randomly selects a common channel to send control frames at a defined time slot. However, there is an implementation issue, i.e., global synchronization among CR users. A sequence-based rendezvous mechanism is presented in DaSilva and Guerreiro (2008) where two non-synchronized radios, looking for each other will eventually be searching on the same channel through the use of non-orthogonal channel hopping sequences. However, the paper doesn't explain how to detect the presence of PUs.

In the reactive approaches, a CR user searches for unoccupied channels only when it has data frames to transmit. In HC-MAC (Jia and Zhang 2007) time is divided into beacon intervals, and each beacon interval is further divided into three phases: *channel selection*, *sensing*, and *data transmission*. In the channel selection phase, a CR user notifies the intended receiver of the selected data channel. In the sensing phase, a CR pair senses the availability of the selected data channel and once the selected data channel is idle, the CR sender starts sending data packets. In the data transmission phase, CR users can transmit data packets on the control channel as well in addition to the data channels, thus providing CR users opportunities to send data even when all data channels are occupied by PUs. Similar to Niyato and Hossain (2009), the global synchronization among CR users is an important implementation issue. To overcome the limitations of sensing and transmission constraints, an optimal stopping problem was formulated in Su and Zhang (2008a), where a potential CR sender can achieve its optimal expected throughput with the help of derived sensing time. CR nodes which hear a cognitive-ready to send (C-RTS) or cognitive-clear-to-send (C-CTS) on the control channel are not allowed to send data. Consequently, only one CR pair can transmit at a time which decreases the overall throughput of the CRN.

A channel-hopping based cognitive radio MAC mechanism, called CH-MAC is presented in Su and Zhang (2008a). In CH-MAC, each CR user maintains its own channel hopping sequence determined by a unique ID (e.g., MAC address). Since all CR users employ a same hopping-sequence generation function, a potential CR sender can easily obtain the hopping sequence of intended CR receiver. For negotiation and data transmission a CR sender follows its receiver's hopping sequence and doesn't need a dedicated control channel. However, the paper didn't describe that how a potential CR sender meets its intended CR receiver on a particular channel efficiently. The sensing scheme presented in DaSilva and Guerreiro (2008) attempts to explore the channel hopping sequence to guarantee rendezvous. To do so, each CR user has a pre-defined channel hopping sequence constructed in such a way that CR senders rendezvous with their intended CR receivers when they are not synchronized. However, the derived expected time-to-rendezvous a CR pair, and sensing conflict have not been addressed in the paper. In Jiang et al. (2009), considering multi-channel cognitive medium access control, the problem of optimal channel sensing order is formulated and then a dynamic programming technique is proposed as a solution. In addition, some special cases are presented to support the claim that the optimal solution does exist. Nevertheless, there are some limitations; the computation complexity is high when some channels cannot be used by CR users, and the channel vacating issue has not been addressed.

Classification based on common control channel

CR MAC protocols exchange control information on a well-defined and well-known control channel. Based on the selection criteria of the control channel, CR MAC protocols could be broadly categorized as: GCCC CR MAC protocols, non-GCCC CR MAC protocols and Assumed CCC CR MAC protocols:

GCCC MAC protocols

Protocols in this category use GCCC in either the ISM band e.g., 2.4 GHz, or any other unlicensed band. A decentralized GCCC-based CR MAC protocol is presented in Hsu et al. (2007) which use the statistical channel allocation for wireless ad-hoc networks (SCA-MAC). It can speed up the transmission by either using more than one channel for data transmission or can wait for some high bandwidth channel to become available. A hardware-constrained cognitive MAC (HC-MAC) is presented in Jia et al. (2008) for efficient spectrum management. It uses an unlicensed band as control channel and addresses the hardware issues to make CR more practical. A new MAC protocol with control channel auto-discovery for self-deployed cognitive radio networks (DUB-MAC) (Adamis et al. 2007) uses a different unlicensed spectrum band other than ISM. These protocols focus on data transmission and ignore the pre-transmission overheads, e.g., the time required to exchange initial configuration and to converge on the common control channel.

Non-GCCC CR MAC protocols

This category either use of one of the white spaces as the control channel or use a different band other than ISM to exchange control information before actually starting the communication. The synchronized MAC protocol for multi-hop cognitive radio networks (SYNC-MAC) (Kondareddy and Agrawal 2008) chooses one of the common channels with neighbours to exchange control signals while other channels are selected to send data. In the opportunistic-cognitive MAC (OC-MAC) (Hung et al. 2008), initially all nodes reside on a non-GCCC and to select a data channel from the FCL three-way handshake is performed followed by the acknowledgement of data transmission. In OC-MAC length of the spectrum hole is predicted by the CR nodes. We strongly criticize this because in order to calculate the length of available spectrum hole, first the exact time interval during which the PU is not utilizing the spectrum needs to be found, which is very difficult in case of an opportunistic network. The cognitive MAC protocol for multi-channel wireless networks (Cordeiro and Challapali 2007) selects the so-called R channel within the white spaces for a control channel and manages the communication on the R channel. However, the selection criteria for the control channel have not been clearly described. The paper also lacks the clarification about which node will set the control channel and how the other nodes will be synchronized.

A distributed cluster-based CR MAC protocol (DCP-MAC) for common control channel selection is proposed in Kim and Yoo (2009). The CR nodes in DCP-MAC searches for an existing common control channel by scanning all possible channels to receive a CC-BC (Common Channel Beacon) which is broadcasted periodically by a cluster head. Apparently, the network topology based on a cluster is formed by a group of neighbour nodes sharing the same common channels but DCP-MAC has ignored the overheads of exchanging four control frames and has not mentioned the time it will take for all CR nodes to complete the clustering forming process. There are real chances that the channel identified as control channel will be occupied by the time CR nodes in the network form the cluster.

F^2-MAC protocol (Chao et al. 2011) presents an efficient channel sensing and access scheme for an ad-hoc CRN. F^2-MAC employs a five-way handshake to exchange control information. Similar to traditional RTS and CTS frames, two types of control frames are delivered through a dedicated control channel. Three more control messages, data channel idle (DCI), DCIACK and ready-to-vacate (RTV), are delivered through data channels. However, five control frames and a certain waiting time before transmitting in the F^2-MAC protocol results in the highest overheads. The maximum number of frames exchanged as control information is four for many CR-MAC protocols. Exchanging five control frames will not only consume more mobile energy but also CR nodes may miss the rare opportunity to transmit. Energy-efficient communication via wireless interfaces optimization usually requires some collaborative mechanism between operating system, applications, and network infrastructure (Fatima and Shah 2015). Moreover, F^2-MAC does not specify whether the dedicated control channel is GCCC or non-GCCC.

A coexistence cognitive radio (CCR) MAC protocol is presented in Cheng et al. (2016). The proposed protocol is a decentralized solution which addresses the unfairness problems that are caused in coexistent heterogeneous CR networks where there are high chances of collisions with PUs. The CCR-MAC protocol enhances the SUs' ability by employing a probing function. The probing function is a MAC-layer approach that uses a jamming-based PU-detection mechanism without additional hardware support. CCR-MAC protocol enhances the PU-detection ability and the fairness feature. However, the SUs are busy in the probing function most of the time and their rare resources are being in used in activities other than the CR, hence, we believe that there is a degradation in data transmission and communication amongst SUs.

Assumed CCC CR MAC protocols

The protocols (Song and Lin 2009a, b; Zhang and Su 2011; Chao et al. 2011) in this category do not delve into a control channel setup mechanism and simply assume that a control channel has already been established prior to any data transmission. The cognitive radio-enabled multi-channel MAC (CREAM-MAC) (Zhang and Su 2011) is a decentralized CR MAC protocol that applies a four-way handshake with communicating nodes on the control channel under the assumption that the control channel is always available and reliable. CREAM-MAC assumes that a CCC has been found and agreed upon by all CR nodes in the neighbourhood before the CREAM-MAC starts its operation. Further to the assumed existence of a control channel, CREAM-MAC also assumes that the control channel is always reliable and PU-interference free. It is strongly believed that finding a common channel to exchange control information is the prime task of cognitive nodes and subsequent operations could not succeed unless the existence of a control channel has not been addressed. Hence, the assumption of an available control channel is unrealistic. Moreover, emphasis has been given to only data transmission while the overheads of determining and agreeing upon the control channel are completely ignored.

Song et al. (2009a) have proposed a CR MAC protocol under the property-right model, in which SUs are divided into several non-overlapping groups, and each group uses the proposed auction algorithm to bid for leasing the required channels from the auctioneer appointed by PUs. Though, the proposed MAC protocol claims for efficient spectrum usage but there are numerous pre-transmission overheads, e.g., those made by two different algorithms (an algorithm for joining/leaving the network and another algorithm for free channel allocation to the leaders in each SU group) which are executed prior to any CR transmission. The protocol also does not identify the process of FCL creation.

To avoid the interference with PU using match filtration technique, a new MAC protocol is presented in Oo et al. (2016). The idle spectrum is accessed jointly by the SUs. Using the Markov Chain Model, the authors have considered the ON–OFF alternating renewal process of PUs accessing the spectrum. After taking into account the last renewal of the PUs, the SUs transmit opportunistically. Though, in this paper, an extra dimension to the existing 2-D Markov chain is added to represent the dynamics of PU activities, the main SU activities have not been discussed much and most of the usual MAC operations remained unanswered, such as how have SUs agreed on a CCC; is the control channel a GCCC or an assumed one? We believe that any CR MAC protocol must have to address these primary issues of a CR environment first.

Hybrid CCC CR MAC protocols

A MAC protocol presented in Shah et al. (2011a), (2013) uses a hybrid approach for CCC. The protocol makes partial use of GCCC to launch a beacon frame in GCCC. The listening nodes read the information and switches to the non-GCCC for further exchange of control information.

To summarize, GCCC-based protocols (Hsu et al. 2007; Adamis et al. 2007; Jia et al. 2008) endure the drawbacks discussed previously, i.e., the saturation of GCCC (since it is widely available for anyone, imposing a high computational cost from backing off) and security vulnerabilities. The synchronization of CR nodes on the common control channel has not been clearly defined in non-GCCC MAC protocols. The assumption of presence of a control channel is too strong for subsequent data transmission that is heavily dependent on the control channel. Moreover, CR nodes must release the occupied spectrum to avoid interference with PUs. Above mentioned protocols assume that whenever a PU activity is detected, SUs will leave the spectrum. However, this assumption needs to be justified because SUs cannot detect any activity of PUs while transmitting data and PUs cannot generate signals on busy channels to CR users. CR nodes can only switch to actual data transmission once successful and secure FCL transactions have taken place. Thus, a clear methodology is needed for the selection of the control channel rather than on how data transmission amongst two CR nodes will take place.

MAC protocols based on direct access

Direct-access based MAC protocols are of two types: *contention based protocols* and *coordination based protocols*. In former category, the CR nodes perform a handshake. This handshake includes classical RTS and CTS frames followed by the FCL (see Fig. 7). After the exchange of FCL, nodes are able to identify the common white space which they both agree to select as data channel and the subsequent transmission is concluded on the agreed data channel.

Adaptive MAC (A-MAC) (Joshi et al. 2009) is a contention based non-GCCC CR MAC protocol. The A-MAC protocol is distributed in nature and can utilize the backup channel when higher throughput is required. A-MAC needs an always-available control channel to exchange control information amongst CR nodes. The important thing to note in A-MAC is the exchange of four control frames. A-MAC, being a contention-based protocol, gives to the contention winning node a chance to occupy the control channel for as long as required. This may cause severe delays to other nodes contending for the medium, especially when any of the control frames is lost and thus has to be retransmitted.

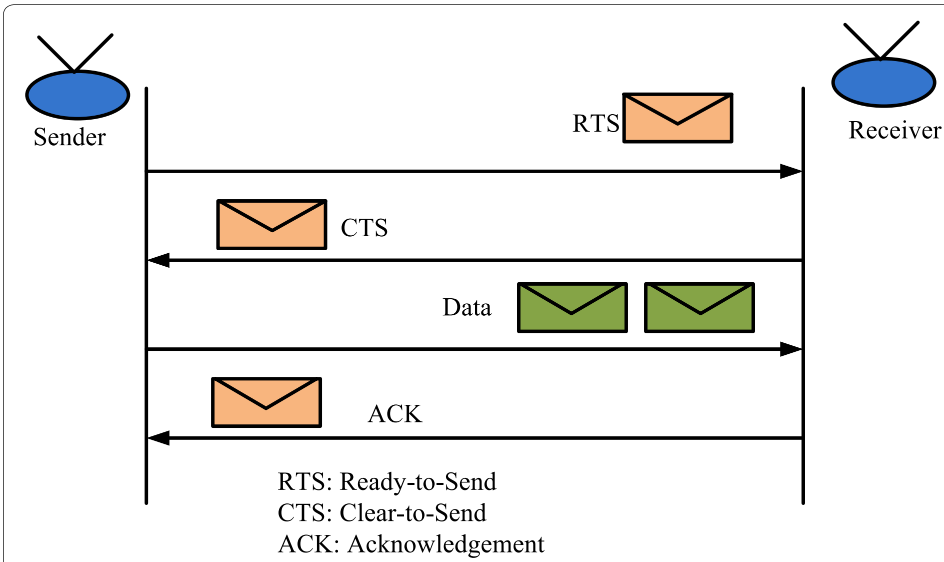

Fig. 7 Simple handshake process in direct-access based MAC protocols

Unlike previously discussed protocols, A-MAC makes use of a non-GCCC. However, the methodology used by CR nodes in the neighbourhood to converge on a non-GCCC is not defined. Nodes in the CR network need to be well aware of the control channel because no subsequent transmission could occur without first finding the control channel. Also, more control frames with a larger size for each control frame cause a higher pre-transmission time. As a result, CR nodes will struggle a lot in order to seize the rare opportunity to utilize the white spaces before a PU activity is sensed. In the coordination-based MAC protocols, each CR node establishes adjacency with its neighbours to improve sensing reliability and improve the system performance (Fig. 8). This also helps CR nodes to avoid the hidden terminal problem.

The Opportunistic Cognitive MAC (OC-MAC) (Hung et al. 2008) is a coordination-based MAC protocol that co-exists with a wireless local area network (WLAN). OC-MAC performs the three-way handshake by employing IEEE 802.11 DCF over the dedicated control channel [132] [133]. Each secondary user in the OC-MAC protocol maintains a list of all channels available for communication and creates a channel-state-table (CST). The physical layer is equipped with sensors. The sensors scan the spectrum and look for the free channels. The statistics for channel utilization and average time of use of channel by the PU are maintained in the CST.

The information contained in the CST is used to estimate the PU traffic and the system busy time. Nevertheless, in OC-MAC there are some critical design flaws which make it inappropriate for CR nodes. First, the OC-MAC employs a dedicated control channel which is used for exchange of RTS/CTS and CRTS, but no description of the dedicated control channel is provided. Secondly, in OC-MAC length of the spectrum hole is predicted by the CR nodes, but this prediction is strongly criticized. Because in order to calculate the length of available spectrum hole, first the exact time interval during which the PU is not utilizing the spectrum needs to be found, which is very difficult in case of an opportunistic network. Lastly, the protocol claims that CR nodes co-exist with a WLAN, however, the justification for this is neither clearly presented in the paper nor do we believe it, because WLANs use the ISM band (e.g., 2.4 GHz) that is already freely available for any user. In ISM band there is no need to seize the opportunity to transmit, and nodes only need to contend.

The SCA-MAC protocol (Hsu et al. 2007) senses the spectrum intelligently and accesses the unused or underutilized spectrum dynamically with minimum or no interference to PUs. *Operating range* and *channel aggregation* are the two basic control parameters for SCA-MAC and to achieve a higher spectrum utilization it employs

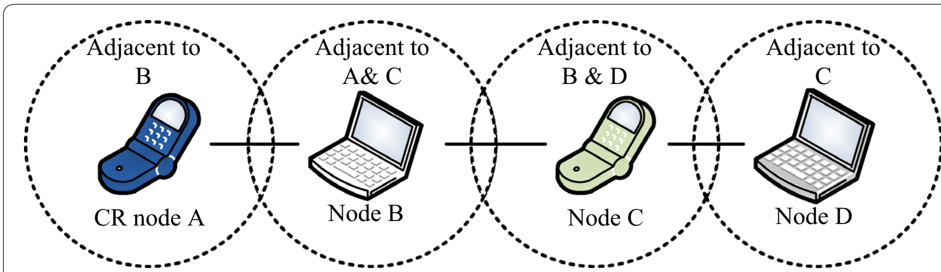

Fig. 8 Network architecture of a coordination based CR MAC protocol

CSMA/CA (Zuquete 2008) mechanism. For the continuous and rapid spectrum sensing, SCA-MAC uses a cyclostationery feature detection (Cabric et al. 2004; Kim and Shin 2008). This protocol can speed up the transmission by either using more than one channel for data transmission or can wait for some high bandwidth channel to become available. A global decentralized CR protocol SCA-MAC performs a two-way handshake by exchanging frames that contain the information of the best opportunity. SCA-MAC focuses on the data transmission but ignores the pre-transmission overheads. Of course, exchanging more frames as control information will not only delay for QoS aware data but it will also cause inefficient power consumption as nodes will have to wait longer before the actual transmission starts.

MAC protocols based on dynamic spectrum allocation (DSA)

The DSA-based MAC protocols make use of advanced algorithms to access the available spectrum opportunistically, intelligently, and fairly. In order to efficiently exploit the available resource, the SUs in DSA-based MAC protocols adapt their transmission parameters (i.e. modulation and coding, power transmission, and antenna configuration) to the changes of the wireless environment. Finding the best transmission opportunities in this category is the most challenging task that requires computational cost and complex calculations to fully understand and learn the status of the CR network. Hence, the MAC protocols in this category experience negotiation delay, low scalability and the complexity. To overcome the limitation of complexity in DSA-MAC protocols, several approaches have been considered to model network interactions e.g. the localized variation of the island genetic algorithm (El Nainay et al. 2008), graph colouring theory (Zheng and Peng 2005; Willkomm et al. 2008), game theory (Younis and Krunz 2006; Zou and Chigan 2008), stochastic theory Swami et al. (2005), genetic algorithms (Rondeau et al. 2004), and swarm intelligence algorithms (Atakan and Akan 2007).

MAC protocols for synchronous cognitive radio networks

The research community has proposed several spectrum sharing based MAC protocols for the synchronous cognitive radio networks. More precisely, Swami et al. (2005); Zhao et al. (2007) developed a cognitive-radio MAC protocol based on the partially observable Markov decision processes (POMDPs) framework. A decentralized cognitive MAC protocol has been proposed in Zhao et al. (2007). The protocol allows SUs to autonomously exploit spectrum opportunities without a central entity or a dedicated communication channel.

MAC protocols for asynchronous cognitive radio networks

Several asynchronous CR MAC protocols have been proposed that initialize the CR operation in the network after receiving certain signals at certain time intervals [144–153]. The performance evaluation for these CR MAC protocols is carried out based on several parameters such as the transmit duration of SUs based on the sensing results to balance the interference caused to PUs and the overall spectrum utilization efficiency, the coexistence with multiple parallel WLANs and providing an innovative solution to the hidden terminal problem by using three sets of radios (Ma et al. 2005a; Yuan et al.

2007; Xing et al. 2007; Niyato and Hossain 2007; Chou et al. 2007; Geirhofer et al. 2008; Huang et al. 2008; Huang et al. 2009a, b; Su and Zhang 2010).

Classification based on overlay and underlay

The CR MAC protocols can also be classified as overlay or underlay. Kim et al. (Hossain 2008), proposed an underlay spectrum sharing based CR MAC protocol and investigated the dynamic spectrum sharing problem among PUs and SUs. The protocol considered a scenario where PUs exhibited on–off behaviour and SUs dynamically assess the PU arrival patterns. They calculated the SUs' transmission probabilities and developed a framework to maximize the number of admitted SUs for the given fairness constraints.

Elezabi et al. (2009) proposed a scheme for the SUs in underlay cognitive radio networks, which aims to minimize the interference to the PUs. Wang et al. (2008) focused on the CDMA-based underlay cognitive radio systems where the PUs can increase transmission power to counter-balance the harmful interference caused by the SUs. Hoang et al. proposed a two-phase channel and power allocation scheme for the underlay-based multi-cell cognitive radio networks to improve the system throughput (Hoang and Liang 2006). Zhang et al.(2008) proposed a single input multiple output (SIMO) MAC scheme with joint beam forming and power allocation, which compares PUs' and SUs' power rates and lets the SUs transmit keeping in mind the PUs' power constraints.

Another CR MAC protocol which exploits the underlay approach is COMAC proposed in Salameh et al. (2009). COMAC allows SUs to transmit in PUs' spectrum band at low power rates to avoid interference to PUs. The protocol has a major design flaw, i.e., when multiple SUs simultaneously access the common control channel, it causes collisions and furthermore, the multichannel hidden terminal problem is not solved if neighbouring SUs are busy in transmission.

Numerous overlay CR MAC protocols have been proposed that consider unlicensed users (i.e. secondary users) opportunistically, exploiting the spectrum holes in licensed frequency bands. In overlay CR networks, secondary users can only transmit on channels if these channels are not being used by primary users. In Srinivasa and Jafar (2007) the overlay access paradigm is investigated and compared with the classical interweave access. The overlay model is based on the assumption that the secondary transmitter has a priori knowledge of the primary user's message. Furthermore, all channel gains are known to both transmitter and receiver. Simulation results showed how the underlay technique can potentially outperform the achievable secondary network. Nevertheless, the overlay performance gain is strongly affected by the distance, as the knowledge of the licensed user message can be available at the cognitive side only if the two transmitters are located in close proximity. Moreover, complicated pre-coding techniques must be available at the cognitive transmitter, and cooperation between primary and secondary systems is necessary to estimate channel gains between transmitters and receivers.

A MAC protocol for opportunistic spectrum access in cognitive radio networks (OSA-MAC) has been proposed in Le and Hossain (2008). The proposed OSA-MAC integrates both sensing and channel access functionalities and works in a multi-channel environment where each SU only accesses at most one channel at any time. The protocol also takes into account issues such as synchronized transmission, contention on the control channel, and the traditional hidden terminal problem. In addition, to avoid the possible collision with PUs, SUs perform sensing frequently besides doing the contention resolution as in a conventional MAC protocol. The protocol assumes that a dedicated control channel is always available for exchange of control information and thus suffers from all the drawbacks mention in "GCCC, non-GCCC and assumed CCC" section.

In Wang et al. (2007), a cognitive MAC protocol for QoS provisioning in overlay ad-hoc networks is proposed which establishes a neighbour list to help a CR node recognize the spectrum opportunities. The protocol is different from the legacy CSMA/CA by introducing an algorithm with an improved contention resolution mechanism, consisting of a gating mechanism, a linear back off algorithm and a stall-avoidance scheme. The proposed protocol maintains three different types of table: a PU information table (PIT), a reservation information table (RIT), and a contention information table. We believe that creating, populating, indexing and searching three different tables at each CR node will not only add processing complexities within the CR nodes but will also make it hardware dependent as nodes have to manage three different tables simultaneously.

Classification based on single radio and multiple radio

The cognitive radio MAC protocols could also be categorized based on the number of transceivers/radios used. Here a single radio is used for sending and receiving data with the constraint that when it transmits, it cannot receive and vice versa. Many single-radio based MAC protocols have been proposed (So and Vaidya 2004; Cordeiro and Challapali 2007; Ma et al. 2007; Shin 2008).

The single radio adaptive channel (SRAC) algorithm is proposed in Ma et al. (2007) and it adaptively combines spectrum bands based on the CR user requirement, called dynamic channelization. In addition, it uses a scheme like frequency division multiplexing (FDM), called cross-channel communication, in which a CR user may transmit packets on one spectrum band but receive messages on another spectrum band. Although, the hardware cost could be reduced by deploying a single radio but it could suffer the traditional hidden terminal problem. Also, the SRAC algorithm makes the strong assumption and claim to be already capable of detecting PU arrival of the licensed spectrum bands.

The cognitive MAC (C-MAC) protocol proposed in Cordeiro and Challapali (2007) operates over multiple channels. Logically each channel is divided into recurring super frames which in turn include a slotted beaconing period (BP), where nodes exchange information and negotiate channel usage. Each node transmits a beacon frame in a designated beacon slot during the BP, which helps in dealing with hidden nodes, medium reservations, and mobility. A rendezvous channel (RC) is utilized for coordination amongst nodes in different channels. The RC is decided dynamically and in a totally distributed fashion. The functionality and the operation of the C-MAC protocol are heavily dependent on the rendezvous channel (RC), which is one of the white spaces in the FCL. If the RC is occupied or reclaimed by the PU, there are no mechanisms for CR nodes in C-MAC to resume the cognitive functionality on some other RC.

Hyoli et al. (Shin 2008) propose a MAC-layer sensing scheme in cognitive radio networks. The proposed scheme tries to discover as many utilizable spectrum opportunities as possible and assumes every SU is equipped with a single identical antenna that can be tuned to any combination of consecutive licensed channels. However, equipping each SU with a single antenna will lead to the traditional hidden terminal problem and SUs would not be able to detect claims by PUs in a timely manner.

The task of designing a multi-channel MAC protocol is notably simplified, when multiple transceivers are in place. Thus, issues related to connectivity, hidden and exposed terminal problems, and channel switching can be overcome to great extent. The key to overcome aforementioned challenges is the assumption that nodes have multiple transceivers that are capable of tuning to and accessing different channels simultaneously. Here, the research focus is channel selection strategies. Dynamic private channel (DPC) protocol introduced in Hung et al. (2002) is based on the assumption that nodes are equipped with as many transceivers as the number of channels. Like other protocols, one particular channel is reserved as the default control channel for negotiation purposes. Provided that a transceiver is always associated with the control channel, the multi-channel hidden terminal problem is eliminated. In this protocol, special RTS and reply-to-RTS frames are utilized to select another channel for transmission of data.

The multi-channel MAC protocol proposed in Nasipuri et al. (1999) it is also assumed that each node has as many transceivers as the number of available channels, but here nodes are capable to listen to all these channels simultaneously. Whenever a node needs to send a packet, it selects an idle channel for transmission. If multiple idle channels are available, the preference is given to the one engaged in the last successful data transmission. This technique is known as "soft channel reservation". An improved channel selection strategy for this protocol has been proposed in Nasipuri and Das (2000), channel selection is based on the power level sensed at the transmitter. In contrast, channel selection in receiver-based channel selection (RBCS) scheme (Jain et al. 2001) is based on the signal-to-interference and noise ratio (SINR) at the receiver.

The dynamic channel assignment (DCA) protocol (Wu et al. 2000) operates similarly to RBCS. It employs a default control channel while other channels may be used for data transmission. A distinctive feature of DCA is that it requires exactly two transceivers, one of which is permanently tuned to the default control channel and the other of which is free to tune to any of the data channels.

The motivation behind power saving multi-channel MAC protocol (PSM-MMAC) (Wang et al. 2006) is the fact that some nodes are powered by battery. To do so, PSM-MMAC targets the power consumption under reduction of multi-channel operation. However, it mainly focuses on the one-hop case and it is not easy to apply it directly to the multi-hop case. Lastly, the common spectrum coordination channel (CSCC) protocol presented in Raychaudhuri (2003) is an extension of the DCA protocol, which enables different types of wireless devices to share the radio spectrum via negotiation through the CSCC.

Summary and findings

Numerous CR MAC protocols have been designed and developed by the research community. There exists different parameters and characteristics that are considered while designing a CR MAC protocol (see Fig. 4 for different types of CR MAC protocols). These design parameters include the type of infrastructure, the design of the common control channel, the access mechanism on the control channel and the access mechanism on data channels, the number of control frames exchanged as control information, the utilization of free spaces with and without coalition of a PU, the cooperation type, the number of transceivers and the selecting criteria for best channel. There are a few other parameters that are also taken into consideration during the development of a complex self-organizing CR network such as signalling methods, spectrum sensing techniques, and certain physical layer parameters. Not all the CR MAC protocols present a similar design. A broad classification of these CR MAC protocols is presented in Fig. 9.

Discussions

Complex self-organizing cognitive radio (CR) network has emerged as a promising technology to address spectrum scarcity and its inefficient utilizations. Extensive research is being carried out to make this technology more practical. However, there are number of potential issues and challenges that need to be addressed prior to deploy CR networks in wide-scale manner. These key issues and challenges could be related to regularization, timely coordination, complicated decision processing, security, software radio issues and hardware constraints etc.

One of the biggest challenges is lack of standardization and regularization which may cause security vulnerability, inconvenience and disruption in the services to the user. For instance, what would be the legal value for the usage if nodes in a CR network are to use the licensed spectrum? Similarly, if a CR network is to use the ISM band like 802.11, strong justification would be required for CR network to exist on the ISM band. There should be some widely acceptable regulations that could ensure proper and predictable operation of complex self-organizing CR networks.

In CR networks, signal detection and classification to extract signal information is a key challenging task. Additionally, presence of multiple licensed users with variety of signals in the same band imposes additional challenges. A CR network must be capable

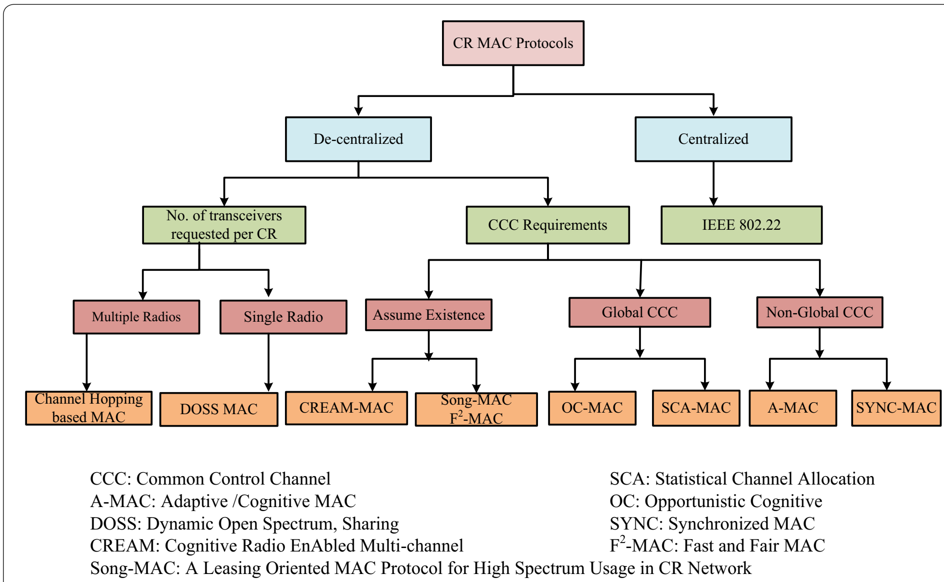

Fig. 9 Classification of CR MAC protocols (Shah et al. 2013b)

of detecting and classifying the signals in the vicinity to exploit spectrum opportunistically and to respond to the changes in environment in an efficient way. Even with the best sensing capabilities, there is a possibility of failing to find the active primary devices. Researchers have proposed different solutions to enhance the spectrum sensing capabilities of complex self-organizing cognitive radio (CR) networks which includes spectrum usage tables, network assisted detection, sharing spectrum occupancy information amongst cognitive radio devices, and using beacons when primary license devices become active. Moreover, the spectrum sensing range could be improved by the deployment of multiband antennas in cognitive radio devices.

The cognitive radio technology that consists of nodes, architecture and control strategies, has appeared to be an efficient solution for heterogeneous networks. However, this leads to security issues because same security standards could not be applied in all heterogeneous networks. The capability of complex self-organizing CR networks to intelligently reason about the environment is subject to the representation of the knowledge that the radio has about its environment. The need for such a knowledge representation is another key task. The striving and dependent nature of CR networks is also a concern which may negatively impact network performance.

Software radio issues like improving frequency flexibility and agility, enhancing data converter technologies and careful software architecting are also the issues for cognitive radio (CR) network as it's just an evolution of the software radio control processes. Hardware constraints is another challenge for complex self-organizing cognitive radio (CR) networks. For example, a cognitive radio (CR) network antenna capable of sensing and scanning unoccupied spectrum in 410 MHz would be different from the antenna designed for 2.4 GHz.

Conclusions

In this paper, we have discussed numerous MAC protocols for complex self-organizing cognitive radio (CR) networks and the parameters considered in their design and development process. We have summarized our review in the Tables 1 and 2 which thoroughly presents different features of CR MAC protocols. It is concluded that in order to develop a CR MAC protocol, there are certain parameters that a CR MAC protocol must address. In Table 2, we have selected 22 CR MAC protocols and have summarized their design parameters. It could be observed that each CR MAC protocol has certain distinct features and not all MAC protocols are suitable for every environment. The deployment of a particular CR MAC protocol is subject to a specific environment. In future, we aim to enhance our research by selecting few MAC protocols and simulate them for different parameters and for different environments. This will enable us to identify the design limitations and appropriateness of each CR MAC protocol.

Table 1 Comparative evaluation of CR MAC protocols

Features	CREAM	OC-MAC	SCA-MAC	A-MAC	F^2-MAC	DNG-MAC
Spectrum sensing (Akyildiz et al. 2008; Hossain 2009)	Energy detection	Not discussed	Cyclo- stationery	Not discussed	Not discussed	Energy detection
Acknowledgement after Tx	No	Yes	Yes	No	No	No
Avoidance of multi-channel hidden terminal (Adamis et al. 2007)	No	Not addressed	Not addressed	No	Yes	Yes
Control channel	Assumed	Dedicated	GCCC	Non-GCCC	Dedicated	Non-GCCC
Best channel criteria	Arbitrary	data rate	arbitrary	Channel rank	Not discussed	Arbitrary
Multi-channel MAC (Bolívar et al. 2010)	Yes	Yes	Yes	Yes	Yes	Yes
Physical layer parameters (Wang et al. 2008)	DSSS	Not discussed	Not discussed	DSSS	Not discussed	DSSS
Use of backup data channel	No	No	Yes	Yes	No	No
Spectrum access	802.11 DCF	802.11 DCF	CSMA/CA	802.11 DCF	CSMA/CA	CSMA/CA
Number of transceivers	Single	Single	Single	Single	Multiple	Single
Number of control frames	4	3	4	4	5	2

Table 2 Salient features of different CR MAC protocols

	Infrastructure/ architecture	Access mechanism	Direct access based	Single/multi transceivers	Number of control channels	Signalling	Quiet period
CREAM-MAC (Zhang and Su 2011)	Decentralized	IEEE802.11 DCF	Contention based	Single	1	Not addressed	No
DOSS-MAC (Ma et al. 2005b)	Decentralized	CSMA/CA	Contention based	Not addressed	none	Out-of-band	Not addressed
SYNC-MAC (Kondareddy and Agrawal 2008)	Decentralized	IEEE 802.11 DCF	Coordination based	2	1	In-band	No
OS-MAC (Hamdaoui and Shin 2008)	Distributed	CSMA/CA	Coordination based	Single	1	Out-of-band	Not addressed
C-MAC (Cordeiro and Chal-lapali 2007)	Distributed	Time slotted	Coordination based	Single	1	Out-of-band	Yes
HC-MAC (Jia et al. 2008)	Distributed	IEEE 802.11 DCF	Contention based	Single	1	Out-of-band	Yes
DUB-MAC (Adamis et al. 2007)	Decentralized	CSMA/CA	Contention based	Not addressed	1	Not addressed	No
CO-MAC (Salameh et al. 2009)	Distributed	Not addressed	Contention based	Not addressed	1	Out-of-band	No
OSA-MAC(Le and Hossain 2008)	Decentralized	IEEE 802.11 DCF	Contention based	Not addressed	1	Not addressed	No
CogMesh (Chen et al. 2007)	Distributed	TDMA	Coordination based	Single	1	Out-of-band	Yes
IEEE 802.22 (Stevenson et al. 2009)	Centralized	Random	Coordination based	Single	none	In-band	Yes
DC-MAC (Chen et al. 2006)	Decentralized	Random	Contention based	Single	1	Not addressed	No
DCCP-MAC (Bolívar et al. 2010)	Centralized	Not discussed	Coordination based	Not addressed	none	Out-of-band	No
CL-MAC (Su and Zhang 2008b)	Decentralized	CSMA/CA	Coordination based	2	1	Not addressed	Yes
OP-MAC (Xue et al. 2010)	Decentralized	IEEE 802.11 DCF	Contention based	1	1	Not addressed	No

Table 2 continued

	Infrastructure/ architecture	Access mechanism	Direct access based	Single/multi transceivers	Number of control channels	Signalling	Quiet period
DCP-MAC (Kim and Yoo 2009)	Decentralized	CSMA/CA	Coordination based	Not addressed	1	Not addressed	No
Sr.-MAC (Krishnamurthy et al. 2005)	Decentralized	IEEE 802.11a	Coordination based	2	1	Not addressed	No
Hu.-MAC (Song and Lin 2009b)	Decentralized	Not addressed	Coordination based	2	1	Not addressed	No
DH-MAC (Shih et al. 2010)	Decentralized	IEEE 802.11 DCF	Contention based	1	1	Out-of band	No
DDH-MAC (Shah et al. 2011a)	Hybrid	IEEE 802.11	Coordination	2	2	Out-of-band	Yes
DCCC-MAC (Thilina et al. 2016)	Centralized	SVM	Coordination based	1	1 (dynamic)	In-band	Yes
CCR-MAC (Cheng et al. 2016)	Decentralized	Not discussed	Coordination	Single	1	Not addressed	No

Abbreviations
CR: cognitive radio; P2P: peer-to-peer; IoT: internet of things; CAS: complex adaptive systems; CACOONS: complex adaptive communication networks; ABM: agent-based modelling; DAS: dynamic spectrum access; DASP: dynamic spectrum access protocol; DHCP: dynamic host configuration protocol; WRAN: wireless regional area networks; ACK: acknowledgement; PU: primary user; FCL: free Channel list; CCC: common control channel; GCCC: global common control channel; DoS: denial of services; TDMA: time division multiple access; CSMA/CA: carrier sense multiple access with collision avoidance; TDMA: time division multiple access; MAC: medium access control; CTS: clear-to-send; RTS: ready to send; C-CTS: cognitive-clear-to-send; RTV: ready-to-vacate; QoS: quality of services; CREAM-MAC: cognitive radio-enabled multichannel MAC; CCR-MAC: coexistence cognitive radio MAC; DCI: data channel idle; DCA: dynamic channel assignment; CH-MAC: channel hopping based MAC.

Authors' contributions
All authors contributed equally to the paper in terms writing compiling and proofreading. All authors read and approved the final manuscript.

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Acknowledgements
The authors would like to convey their sincere appreciation to the anonymous reviewers. Their insightful remarks and suggestions made us able to improve the quality of manuscript.

Competing interests
The authors declare that they have no competing interests.

Funding
This research is not funded by any national or international organization and none of the authors received any monetary support from any private or government organization for conducting this research.

Received: 4 May 2016 Accepted: 12 August 2016
Published online: 18 August 2016

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