A Survey on Cognitive Radio Networks

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Abstract. The limitation of the spectrum bands is a major bottleneck for the development of next generation wireless networks. Cognitive Radio (CR) aims at improving the spectrum utilization by taking advantage of licensed but currently unused spectrum. CR has broad applications including dynamic spectrum access and interference management, which will largely impact the next generation of wireless devices and networks. In this paper, we conducted a survey on CR networks from various aspects such as waveform, spectrum management and sensing, testbeds, performance evaluations and etc.

Keywords: Cognitive Radio, Primary User, Secondary User, Waveform, Testbed.

1 Introduction

When spectrum has become a scarce resource, using of existing spectrum efficiently is critical. Cognitive Radio (CR), a software system, enables unlicensed users to utilize allocated spectrum for licensed users when the spectrum is temporarily unused. It should be noted that, CR has two most important characteristics [1]: 1) Cognitive ability: through constant interaction with the environment, CRs are able to figure out the portion of spectrums which are currently unused. Consequently, CRs can decide the best spectrum (spectrum selection) to utilize, hence share it with other CRs, and exploit this spectrum without interference on primary users; 2) Reconfigurability: CRs should transmit and receive on different frequency bands in order to choose the best spectrum band and most appropriate parameters. Further, CR networks can access unlicensed as well as licensed but currently abandoned spectrum, which can be concluded into two main processes of CR networks [1]:

1. Licensed band operation: Since licensed band are primarily used by Primary Users (PUs), the main job of CRs focus on the detection of reappearance of PUs. As soon as a reappearance of PU is detected, CR must evacuate this spectrum band and leave immediately This process is called channel mobility.

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2. Unlicensed band operation: For a certain free spectrum abandoned by PU, all CRs have the same rights to access it. Consequently, effective spectrum sharing algorithms are of primary importance for CR networks to develop.

The rest of this paper is organized as follows: new waveforms aimed at improving the transmitting efficiency and throughput are surveyed in section 2. Section 3 introduces new algorithms for spectrum sensing/ sharing, channel allocation/ selection. Cross-layer and Media Access Control (MAC) protocols are studied with the cooperative communication in section 4. Moreover, to test new algorithms or new CR systems, testbeds suitable for different environments are introduced in section 5. Further, security aspects of CR are discussed in section 6. Finally, we studied performance and reliability of CR in section 7.

2 Waveforms for Cognitive Radio

The most important job of the Cognitive Radio (CR) is to efficiently use spectrum hole which is assigned to a primary user (PU). In order to achieve this goal, CRs have to detect the reappearance of PU frequently. They should quit the spectrum immediately as soon as a PU is detected in order to minimize their reciprocal interference. This suggests that CR has to change its transmitting waveform and adapt to the spectrum environment. Therefore, the adaptive waveform [2] techniques have been investigated.

The term adaptive waveform stands for "a time domain pulse in the radio frequency (RF) range that has the desired frequency response" [2]. In this technique, CRs will periodically monitor the RF spectrum (spectrum sensing) and choose the best available spectrum (spectrum decision). On basis of the spectrum information obtained, CRs generate an adaptive carrier waveform which fits only the free band. As soon as the waveform is generated, digital data will be modulated using this waveform and transmitted. Figure 1 shows the process of the adaptive waveform generation.

Obviously, how to decide and select a waveform for transmitting based on environmental measures is one of the most important problems for CR. A new on adaptive carrier waveform scheme is proposed in [3] to adapt to any band without bringing about harmful interference. It is useful in accessing TV spectrum with high spectrum utilization efficiency. In addition, a pulse generation

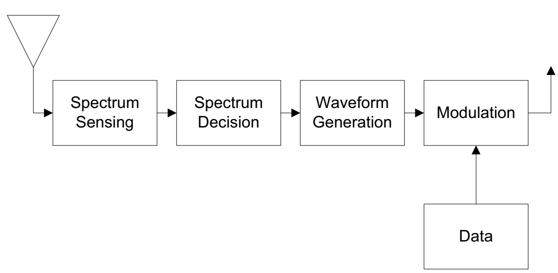

Fig. 1. Adaptive Waveform Generation [2]

method is introduced [4]. This time domain pulse is generated according to required frequency response using band pass filter. In [5], a hybrid overlay/underlay waveform generation is proposed to minimize the interference of secondary user on primary user. This method is aimed at exploiting both unused (white) and underused (gray) spectrum resources. In Ultra-wideband (UWB) systems there are two main kinds of waveforms: pulsed and chirp waveforms. A modified chirp waveform [6] is proposed to avoid the spectrum authorized to other existing systems.

Additionally, statistical knowledge of Primary User (PU) can be exploited in Spectrally Modulated, Spectrally Encoded (SMSE) waveform designs to maximize system throughput. Based on this knowledge, the authors in [7] proposed a SMSE algorithm using parametric variation in both waveform update latency and update rate. The benefit of this algorithm is apparent when using moderate value of latency and update rate. However, its performance will degrade when large latency value or high update rate are adopted. Further research of cognitive radio waveform will mainly focus on obtaining various carrier waveforms based on different pulses and developing the optimal design for adaptive transmissions.

3 Algorithms for Spectrum Management

The great challenges in CR networks are the interference issues due to CRs' coexistence with primary users. In addition, CR networks must provide seamless communication regardless of the reappearance of primary users [1]. These challenges can be addressed by spectrum management techniques, which mainly include four components: spectrum sensing, spectrum decision (spectrum allocation), spectrum sharing, and spectrum mobility. In this paper, we mainly investigate the process of spectrum sensing, spectrum decision and spectrum sharing. The applications of CRs in Multi-Input Multi-Output (MIMO) systems are introduced.

3.1 Spectrum Sensing

Particularly, as cognitive radio is designed to be sensitive to the changing environment, spectrum sensing becomes an important requirement for CRs. Generally speaking, spectrum sensing process includes obtaining the spectrum usage characteristics across multiple dimensions such as time, space, frequency, code, as well as determining what types of signals are occupying the spectrum [8]. Spectrum sensing techniques consist of primary transmitter detection, primary receiver detection and interference temperature management, which are illustrated in figure 2.

In [9], bandwidth problem of reporting channel during spectrum sensing is addressed. Contrasting to traditional sensing algorithms, this new method only allows cognitive users who have the highest performance to report in the absence of reliable cognitive user, which is proved to have better sensing performance.

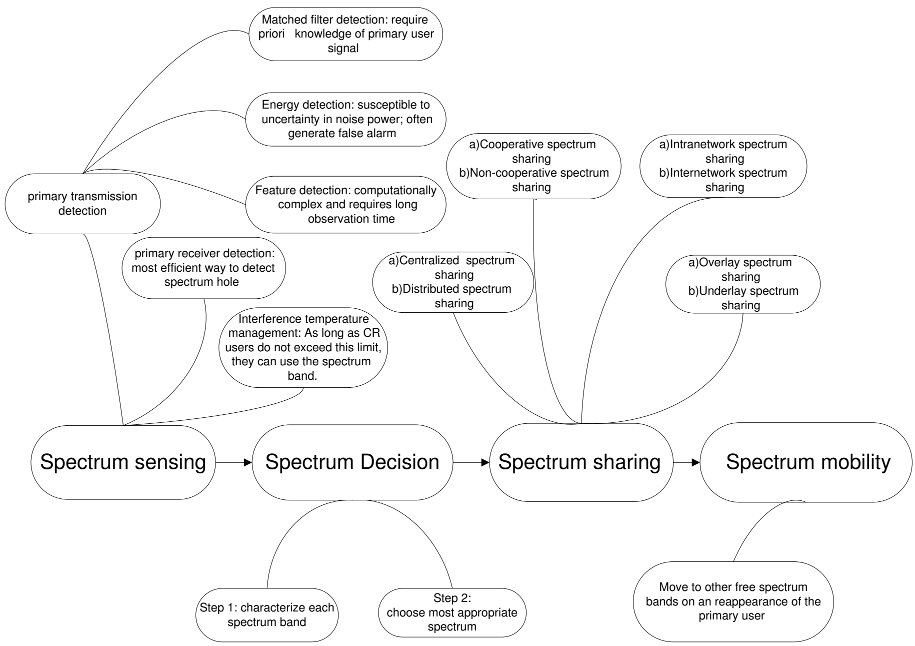

Fig. 2. Spectrum Management Process

3.2 Spectrum Decision and Spectrum Sharing

As shown in Figure 2, after sensing and choosing the best spectrum for CRs, the next step is to decide which CR should get the access right of this spectrum. The coexistence of primary users and secondary users makes the process of spectrum sharing more difficult. Recent research aiming at meeting this challenge can be classified by four aspects: the architecture, spectrum allocation behavior, spectrum access technique, and scope [1].

In cognitive radio networks, priority mechanism is adopted for CRs to share spectrum resource called channel allocation [11]. Many algorithms such as game theory and reinforcement learning are developed and proved to be effective for the channel allocation.

Game theory [12] is a mathematical tool that can help to solve the competitive situations among all the players and enable rational decision makers to choose their actions based on their interests. In [1], non-cooperative game theory is applied to address the waveform adaption . In [13] a game-theoretic based adaptive channel allocation scheme is proposed for cognitive radio networks. This scheme provides a natural framework for the design and analysis of noncooperative behavior.

Further, as allocated spectrum is not always occupied by licensed users, by predicting the leaving time and duration of licensed users from this spectrum [14], CRs can utilize this free spectrum and improve spectrum efficiency. In

[15], the authors introduces a novel predictive channel allocation scheme called Intelligent Channel Allocation (ICA), which is based on long term call statistics, instantaneous call statistics and event driven decisions for a fair utilization of spectrum. A reinforcement learning algorithm is proposed to learn the spectrum usage by interacting with the environment [16]. In [17], a Q-learning module is studied , in which CR users can choose their task through interacting with the environment and self-learning and consequently improve sensing efficiency. A improved algorithm is further studied in [18], in which a learning algorithm is combined with a reasoning engine to enable CRs to remember information learnt in the past and react quickly in the future.

In particular, secondary users need to get the position information of primary users for guidance. A robust distributed localization algorithm that enables secondary users to obtain the location information of primary users is proposed in [19]. However, traditional dynamic channel assignment algorithm cannot be directly used on CRs without modification. Thus in [11], the authors proposed methods of channel assignment and channel reallocation that are suitable for cognitive radio systems. In [10], both algorithms and spectrum access protocols are developed to control the dynamic allocation of spectrum resources between cooperating networks.

3.3 Application of CR in MIMO System

Recent research has emphasized on the utilization of cognitive radio on MIMO systems, in which each CR has Multiple-Input and Multiple-Output antennas. MIMO system has the advantages in sensing environment information because multiple antennas energy detector is more efficient when sensing primary users' signal. The selection mechanism of receiving antenna is proposed [2] to further reduce the computational and feedback complexity of the CR networks in a MIMO system. In addition, multiple antennas can be used to a) improve SNR, b) provide diversity, c) introduce an extra signaling dimension (i.e., spacial multiplexing), and d) mitigate interference [21].

4 Protocols for Cooperative Communication

In order to solve the problem of spectrum scarcity, new protocols are required to realize better spectrum access and high spectrum efficiency. The authors in [22] have done a survey on MAC protocols for cognitive radio, which mainly focuses on channel selection and channel sensing policies. Recently, new MAC protocols and cross-layer designed protocols have been studied by researchers to achieve better CR performance.

In [23], the authors propose a leasing oriented MAC protocol, in which secondary users are divided into several groups and each group bid for the right to use the spectrum occupied by a primary user who is going to leave it. This protocol can promise the fairness and dynamic allocation of spectrum resources. Moreover, in [24] the authors develope an adaptive MAC protocol which enhances the throughput of CR. The protocol allows cognitive channels to change

Table 1. Advantages of new CR protocols

New Protocols	Models Adopted	Merits of the proposed protocol
A Leasing Oriented MAC Protocol	Property-Rights Model	1. Maximizing the utilization of spectrum resources; 2. Achieving revenue maximization for primary users; 3. Allocating channels among groups fairly and evenly; 4. If a group is allocated channels, the group's minimum bandwidth requirement must be satisfied
A Decentralized Adaptive Medium Access Control (AMAC) Protocol	Cognitive Radio Networks (CRNs)	1. Has no dedicated global common control channel (CCC), Solve potential bottleneck problem(CCC); 2. Aggregated throughput is higher even in poor channel condition; 3. Solves the multichannel hidden terminal problem
Cognitive Radio-Enabled Multi-channel MAC (CREAM-MAC) Protocol	Wireless Ad Hoc Networks	1. Integrates the spectrum sensing at physical layer and packet scheduling at MAC layer; 2. Solve both the traditional and multi-channel hidden terminal problems by introducing the four-way handshakes of control packets over the control channel
Protocol That Combats The Hidden Incumbent Problem	Satellite Assisted Cognitive Radio Networks	1. Use of satellites in a cognitive radio setting is quite beneficial in addressing the yet unresolved problems in cognitive radio networks; 2. Avoids the hidden node problem while taking the mobility pattern into consideration

from transmitting mode to frame recovery mode when there is frame errors. It ultimately increases the throughput of the CR channels. Another method to improve the system throughput is proposed in [25]. This protocol decentralizes the system from dedicated common control channel (CCC) and every CR will have a table and index itself. In the method, the most stable channel will become CCC and thus available resource utilization is improved. Further, the challenges such as multichannel hidden terminal problem and timevarying channel availability are addressed by [26]. A cognitive radio-enabled multi-channel MAC (CREAM-MAC) Protocol is proposed to integrate spectrum sensing at physical layer and packet scheduling at MAC layer. The spectrum efficiency is improved by enabling each secondary user with a transceiver and a multiple channel sensor because it helps avoiding the collisions between primary users and secondary users as well as collisions among secondary users. In [27], the authors propose a handover protocol to address a hidden node problem and discover the mobility pattern of both primary and secondary users in satellite assisted cognitive radio networks. In [28], the author exploits a new direction for spectrum allocation called cooperative relay, in which the secondary user can performs as common channel to obtain information of free spectrum and assists transmission.

The reconfiguration of the radio is another challenge in cognitive radio networks. In [29], the author addressed this problem by proposing a radio-independent authentication protocol for CRs which used user-specific information, such as location information, as a key seed. This protocol is dependent of underlying radio protocols and could support EAP (Extensible Authentication Protocol) transport. In addition, a cognitive tree-based routing protocol for (CTBR) cognitive wireless access networks [30] is proposed to adapt the protocol to support multiple systems. This CTBR protocol is then proved to be more effective than the known TBR protocol. The comparison of these new protocols is shown in table 1.

5 Testbed Suitable for Different Environment

A testbed is a platform for evaluation of software, hardware and networking components in Cognitive Radio Networks. Most of existing wireless research uses simulations as its major validation technique. However, the simulations for cognitive radio techniques may not be convincing in some situations [31]. Accordingly, many different research testbeds for cognitive radio are proposed and developed.

In [32], the authors develop a cognitive UWB testbed, which generates an adaptive pulse applicable for different spectrum environment. Moreover, a new cooperative relay for resource allocation in cognitive radio networks [28] is studied based on this testbed.

A specific testbed is developed for ad-hoc cognitive radio network [33]. This testbed is designed for the crosslayer configuration and performance optimization which includes adaptive MAC layer and network layer as well as cross layer management interface. The testbed is developed for verification of new algorithms in Cognitive radio networks. In [34], the author provides a systematic testbed model to verify effectiveness of new algorithms such as Genetic Algorithm (GA) for channel selection. It demonstrated that primary and secondary users can coexist in a spectrum sharing manner.

It is worth noticing that cross-layer testbed design is addressed in [35] for spectrum sensing and interference analysis. This testbed is able to achieve the following three points: (a) cognitive radio system concept demonstration; (b) multi-resolution spectrum sensing (MRSS) receiver IC evaluation; (c) interference analysis for UWB coexistence with WiMax.

6 Security Consideration

The security concerns become critical in cognitive radio networks because a selfsh secondary user can modify its air interface to mimic a primary user for occupation of the spectrum and can mislead the spectrum sensing performed by primary users. Security threats and attacks against cognitive radio networks includes Denial of Service, selfish misbehaviours, licensed user emulation, attacks on spectrum managers and eavesdropping [36].

There are currently two major methods which address the security issues of cognitive radio. One is to identify an attacker by using position of the transmitter. The other one is to prevent secondary users from mimic of primary users [8] by using public key encryption based primary user identification. In the latter method, primary users are required to transmit encrypted values (signatures) along with their information. This legitimate primary user is then recognized by this signature. However, a disadvantage is that this approach requires all the CRs to have the mechanism of encrypting and decoding system.

Further, a new concept concerning the security of cognitive radio is proposed in [36] to allow two cognitive radio nodes to authenticate each other before conducting any confidential channel communication.

7 Study on Performance and Reliability of the Cognitive Radio

As CR will change its objective spectrum according to the change of primary users' status, it is difficult to obtain a firm understanding of the relationship between the primary and secondary users. In [38], the author suggests that the performance metrics of CRs should include spectrum utilization, impact to other SU nodes or incumbent ratios, power efficiency, communication cost for end users, as well as link reliability. Recently, many researches address the performance evaluation of cognitive radio networks. A study on the spectral efficiency of adaptive modulation is conducted in [39]. This study mainly focuses on a cross-layer combination of adaptive modulation and proves that cross-layer design could improve the performance of cognitive radio systems. A new algorithm is proposed for maximizing throughput of cognitive radio networks in [4], and it requires minimal interaction between primary and secondary users. Further, a queuing analytic framework is developed [41] in order to allocate available spectrum in a spectrum overlay scenario. The authors present a step-by-step procedure to derive key parameters for facilitating cross-layer design and improving QoS in CR networks. What's more, reliability of cognitive radio networks is addressed in [42], and effect of parameters (such as number of channels, radios, and simultaneous flows) on reliability of a CR is analyzed. This method can find optimal routes on basis of reliability and tune network parameters in order to improve performance.

To improve the performance of cognitive radio networks, two directions are promising. The first one is to increase the cooperative behavior of CR. With cooperative cognitive radio, information obtained from observation stage and knowledge benefited from a learning stage can be communicated and shared among CRs. The second is to conduct spectrum sensing, sharing and decision making processes from different layers. With the changed information and decision made among layers, better performance improvement can be obtained.

8 Conclusion

With the development of wireless network, spectrum resource is becoming more and more precious. Cognitive radio (CR) can largely improve the utilization of licensed spectrum.

In this paper, waveform designs which help obtain better spectrum utilization are introduced; New algorithms concerning spectrum sensing and channel allocation are investigated; Protocol designs which address cross-layer cooperation are given out; New designs of testbed for simulation and verification of new algorithms and CR designs are explained; Also, security of CR wireless network is given consideration and performance of CR systems is evaluated. CR is also facing cooperative and cross-layer communication challenges [10]. Since wireless communication is conducted in different layers, problems will arise from exclusion of information helpful for communication process. Consequently, both cross-layer design and cross-layer protocols are in urgent requirement.

The future research of CRs will include improving cooperation of different stages among different layers with a MIMO system to improve the performance and spectrum utilization of Cognitive Radio system. We anticipate that this article will provide better understanding of CRs and foster the research in the Cognitive research field.

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