Cognitive Radio Networking and Communications: An Overview

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***Abstract*—Cognitive radio (CR) is the enabling technology for supporting dynamic spectrum access: the policy that addresses the spectrum scarcity problem that is encountered in many countries. Thus, CR is widely regarded as one of the most promising technologies for future wireless communications. To make radios and wireless networks truly cognitive, however, is by no means a simple task, and it requires collaborative effort from various research communities, including communications theory, networking engineering, signal processing, game theory, software–hardware joint design, and reconfigurable antenna and radio-frequency design. In this paper, we provide a systematic overview on CR networking and communications by looking at the key functions of the physical (PHY), medium access control (MAC), and network layers involved in a CR design and how these layers are crossly related. In particular, for the PHY layer, we will address signal processing techniques for spectrum sensing, cooperative spectrum sensing, and transceiver design for cognitive spectrum access. For the MAC layer, we review sensing scheduling schemes, sensing-access tradeoff design, spectrum-aware access MAC, and CR MAC protocols. In the network layer, cognitive radio network (CRN) tomography, spectrum-aware routing, and quality-of-service (QoS) control will be addressed. Emerging CRNs that are actively developed by various standardization committees and spectrum-sharing economics will also be reviewed. Finally, we point out several open questions and challenges that are related to the CRN design.**

***Index Terms*—Cognitive radio (CR), cognitive radio networks (CRNs), dynamic resource management, dynamic spectrum access (DSA), spectrum sensing, spectrum sharing.**

I. Introduction

THE RADIO spectrum, which is needed for wireless communication systems, is a naturally limited resource. To support various wireless applications and services in a noninterfering basis, the *fixed spectrum access* (FSA) policy has traditionally been adopted by spectrum regulators, which assign each piece of spectrum with certain bandwidth to one or more dedicated users. By doing so, only the assigned (licensed) users have the right to exploit the allocated spectrum, and other users are not allowed to use it, regardless of whether the licensed users are using it. With the proliferation of wireless services in the last couple of decades, in several countries, most of the available spectrum has fully been allocated, which results in the spectrum scarcity problem. On the other hand, recent studies on the actual spectrum utilization measurements have revealed that a large portion of the licensed spectrum experiences low utilization [1]–[3]. These studies also indicate that it is the inefficient and inflexible spectrum allocation policy that strongly contributes to spectrum scarcity and, perhaps, even more than the physical shortage of the spectrum. To maintain sustainable development of the wireless communication industry, novel solutions should be developed to enhance the utilization efficiency of the radio spectrum.

Dynamic spectrum access (DSA) has been proposed as an alternative policy to allow the radio spectrum to more efficiently be used [4], [5]. In DSA, a piece of spectrum can be allocated to one or more users, which are called primary users (PUs); however, the use of that spectrum is not exclusively granted to these users, although they have higher priority in using it. Other users, which are referred to as secondary users (SUs), can also access the allocated spectrum as long as the PUs are not temporally using it or can share the spectrum with the PUs as long as the PUs' can properly be protected. By doing so, the radio spectrum can be reused in an opportunistic manner or shared all the time; thus, the spectrum utilization efficiency can significantly be improved.

To support DSA, SUs are required to capture or sense the radio environment, and a SU with such a capability is also called a *cognitive radio* (CR) [4], [5] or a CR user. There are different types of *cognitive capabilities* with which a CR may be equipped. For example, a CR may sense the ON/OFF status of the PUs [4], [6] or can predict the interference power level that is received at the primary receiver (Rx) [6]. In an extreme case, if a CR is a genie user, it may also acquire the messages that are transmitted by the primary Tx [7]. The process of acquiring the radio environment knowledge can be complex and expensive, because it may involve spectrum sensing, autonomous learning, user cooperation, modeling, and reasoning.

With different cognitive capabilities, a CR may access the radio spectrum in different ways. In the literature, the following

Manuscript received August 19, 2010; revised February 10, 2011 and April 24, 2011; accepted May 13, 2011. Date of publication June 7, 2011; date of current version September 19, 2011. The work of K.-C. Chen was supported in part by the National Science Council, the National Taiwan University, and Intel Corporation under Contracts NSC 99-2911-I-002-201 and 98-2221-E-002-065-MY3. The review of this paper was coordinated by Prof. R. Schober.

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Digital Object Identifier 10.1109/TVT.2011.2158673

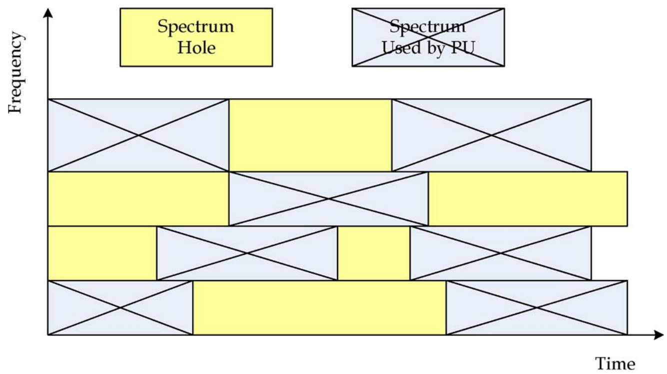

Fig. 1. OSA model: CR users opportunistically access the spectrum holes.

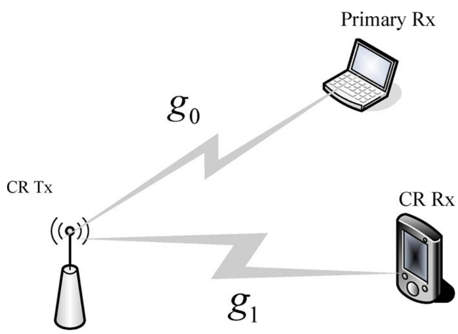

Fig. 2. CSA model: CR users coexist with active PUs under the interference power constraint.

two *cognitive spectrum access* models have received extensive attention: 1) The *opportunistic spectrum access* (OSA) model and 2) the *concurrent spectrum access* (CSA) model.

The OSA model is illustrated in Fig. 1. In this model, a CR user carries out spectrum sensing to detect spectrum holes [8], i.e., portions of spectrum allocated (licensed) to some PUs but left unused for a certain time. Upon detecting one or multiple spectrum holes, the CR user reconfigures its transmission parameters (e.g., carrier frequency, bandwidth, and modulation scheme) to operate in the identified spectrum holes. While doing so, the CR user needs to frequently monitor the spectrum on which it operates and quickly vacate it whenever the PUs become active. This approach of spectrum access was first proposed by Mitola in his pioneering work [4], [5], under the name *spectrum pooling*. The term *opportunistic spectrum access* was later introduced by Defense Advanced Research Projects Agency (DARPA) in its Next-Generation Communications (XG) Program. We note that some authors also refer to this model as *spectrum overlay* in [9] and [10] and interweave paradigm in [11].

The CSA model is shown in Fig. 2, where a CR user coexists with an active PU in a licensed band as long as the CR transmitter (Tx) refrains its transmit power such that the interference that is caused to the primary Rx is below a tolerable threshold. This model requires the CR Tx to predict the interference power level that is received at a particular location, and it is also referred to as *spectrum sharing* in [6] and *spectrum underlay* in [10].

A *cognitive radio network* (CRN) contains more than one CR node, and similarly to conventional wireless networks, it can

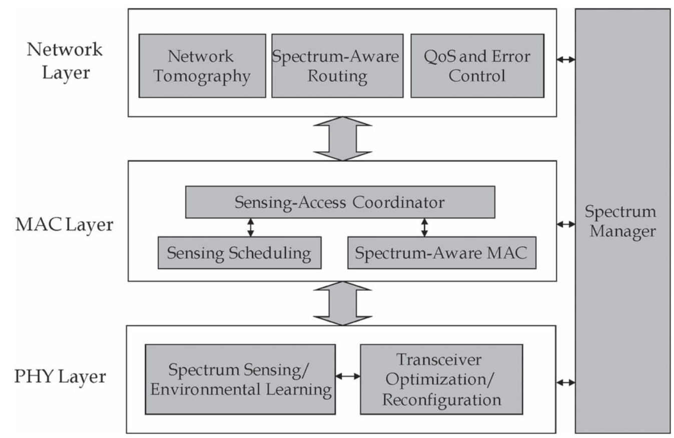

Fig. 3. Main functions of the PHY, MAC, and network layers in a CR.

be classified as either an infrastructure-based network or an ad hoc network [12]. In a CRN, each CR node may have the same or a different level of cognitive capability. In a more general sense, a CRN can be perceived as an intelligent overlay network that contains multiple coexisting networks, and each of the CR nodes may belong to different coexisting networks. In this case, the CR nodes are likely to have different levels of cognitive capability. Thus, building a fully functioning CRN can be a very challenging task. This case is due to the difficulties in designing multiple system components, including, but not limited to, physical (PHY)-layer signal processing, medium access control (MAC)-layer spectrum management, and network-layer routing and statistical control. Furthermore, these system components often interact in complex ways, the design of which may require cross-layer design and control frameworks.

Fig. 3 illustrates the key functions of the PHY, MAC, and network layers in a CR. In the PHY layer, spectrum sensing is the essential component that enables CR users to identify spectrum holes, whereas environmental learning supports the CR users to gain higher level of radio environment knowledge, such as the channel-state information or channel gain from the CR Tx to the primary Rx. Based on the outputs of these operations, cognitive spectrum access is carried out through transceiver optimization and reconfiguration. The specific tasks that the MAC layer of a CR must perform include sensing scheduling and spectrum-aware access control. The spectrum-sensing scheduler controls the sensing operations, whereas the spectrum-aware access control governs the spectrum access to the identified spectrum holes. The sensing-access coordinator controls the operations of these two functions in a time basis by taking care of the tradeoff between the sensing requirement and the spectrum access opportunity that the CR user may achieve. With regard to the network layer, three important functions are listed as follows: 1) network tomography; 2) quality of service (QoS) and error control; and 3) spectrum-aware routing [13]. Finally, the spectrum manager links the three layers and supports the access of available spectrum in a dynamic and efficient manner. We highlight here that the aforementioned architecture is by no means the only architecture that can be designed for CRs; instead, it serves as the functional architecture for this overview paper. For other architectures, see [12] and [13].

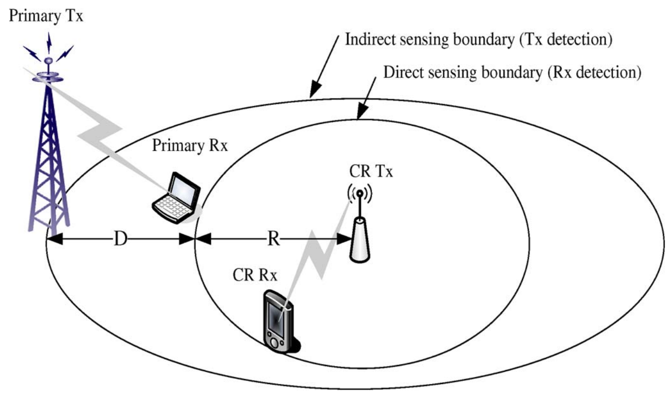

Fig. 4. Principle of spectrum sensing.

In this paper, our main objective is to provide readers a systematic overview on CR communications and networking. We review the key functions of the PHY, MAC, and network layers involved in the CR design and explain how these layers are crossly related. In particular, for the PHY layer, we address signal-processing techniques for spectrum sensing, cooperative spectrum sensing, and transceiver design for cognitive spectrum access. For the MAC layer, we review sensing scheduling schemes, sensing-access tradeoff design, spectrum-aware access MAC, and selected CR MAC protocols. In the network layer, CRN tomography, spectrum-aware routing, and QoS and error control will be covered. Emerging CRNs that are actively developed for various applications and spectrum-sharing economics and values will also be reviewed. Finally, we raise out some design challenges and open questions that are related to CR communications and networking.

II. Spectrum-Sensing Techniques

As aforementioned, a spectrum hole is a frequency band that is assigned to the PUs but is not utilized at a certain time and location [6], [8], [14]. In some portions of the spectrum such as the TV band, the TV program may be predetermined in some regions; thus, such spectrum hole information can be broadcast to the SUs using geolocation database solutions. When such information is not available to the SUs, spectrum sensing [15]–[18] enables CR users to identify the spectrum holes, thus protecting the PUs. Therefore, spectrum sensing is considered one of the critical elements in CRN design.

Fig. 4 shows the basic principle of how spectrum sensing can be used to protect the PUs. As shown in the figure, a primary Tx sends data to its intended Rx in a certain licensed spectrum band. A pair of CR users (CR Tx and CR Rx) intends to access the spectrum holes for secondary communication. To guarantee the protection of PUs, the CR Tx needs to perform spectrum sensing to find spectrum holes. In particular, the CR Tx is required to detect whether there is an active primary Rx inside the coverage of the CR Tx. If not, the CR Tx can safely transmit to the CR Rx using the identified spectrum hole. Otherwise, the CR users are not allowed to use the band. Therefore, detecting the nearby primary Rx's can directly identify the spectrum hole, which is called *direct spectrum sensing*.

It is well known that detecting a Rx is a challenging task, because the Rx does usually not transmit signals when it works. Thus, most of the existing spectrum-sensing schemes identify spectrum holes by detecting the primary Tx's [10], [13]. In Fig. 4, let D be the transmission range of the primary Tx and R be the interfering range of the CR Tx. Then, the CR Tx needs to detect the presence of an active primary Tx within a distance $D + R$. If the distance between the primary and the CR Tx's is larger than $D + R$, there will be no active primary Rx inside the interfering range of the CR Tx, and then, the CR Tx can safely access the spectrum bands. Otherwise, the primary Rx may be inside the interfering range of the CR Tx and be interfered by its transmission. Therefore, detecting surrounding primary Tx's can also identify the spectrum holes, but in an indirect way, which is called *indirect spectrum sensing*.

Compared with direct spectrum sensing, indirect spectrum sensing requires a larger detection range from R to $R + D$. Thus, indirect spectrum sensing needs to detect very weak primary signals, which makes spectrum sensing more challenging [18], [19]. Furthermore, when the signal-to-noise ratio (SNR) of the primary signal that is measured at the CR Tx is low enough, e.g., below the SNR wall [20], it is impossible for the CR Tx to detect the primary Tx, even when the infinity number of samples of the primary signals are used.

A. Direct Spectrum Sensing

The most effective way of spectrum sensing is to directly detect the primary Rx, because it is the Rx of a PU system that should be protected. In general, the PU systems can be divided into the following two categories: 1) one-way communication systems and 2) two-way communication systems. One-way communication systems have only one direction communication from the primary Tx to the primary Rx, such as TV and radio broadcasts. The only way of detecting this kind of Rx's is to sense the leakage signals from active Rx's. Two-way communication systems have bidirectional communications, and there are interactions between the Tx and the Rx, which can be used for spectrum sensing. Next, we will introduce the sensing methods for the two kinds of systems, respectively.

1) Local Oscillator Detection: In most wireless communication systems, Rx's need to convert the signal from carrier frequency to *intermediate frequency* (IF) for further processing. However, during such conversion, some of the local oscillator power couples back through the input port and radiates out of the antenna, which leads to inevitable reverse leakage. In [21], such leakage signals have been used in spectrum sensing for TV Rx detection. When the frequency and phase of the leakage signals are known to CR users, matched filter detection is used. When there is no information of the leakage signals, energy detection (ED) is used. Because the leakage signal is extremely weak, it leads to a short detection range and a long detection time. For example, it may take the order of seconds for spectrum sensing when a CR detector is 20 m away from a TV Rx.

2) Proactive Detection: Closed-loop control schemes, such as power control, adaptive modulation/coding, automatic request retransmission, have widely been used in wireless systems with feedback channels [22]. This way, the primary Rx can report the quality of the received signal back to the primary Tx. Then, the Tx can adjust its transmission parameters to maintain the quality of the received signals at the primary Rx. Recently, such closed-loop controls have independently been used for primary Rx detection in [23] and [24], and the proposed scheme is called *proactive spectrum sensing* in [24] and [25]. Different from traditional sensing methods [15] that detect spectrum holes by *listening* to primary signals, the proactive sensing detects primary Rx's by sending a sounding signal and observing the possible response of the primary signal that is caused by closed-loop controls. In particular, *closed-loop power control* (CLPC) has been used for proactive sensing [25]. A CR Tx first sends some sounding signals to trigger the CLPC. If there is a primary Rx nearby, the interference power will temporally grow, which decreases the *signal-to-interference-plus-noise ratio* (SINR) at the primary Rx. Accordingly, the CLPC will adjust the power of the transmit signals to compensate for the SINR loss. If there is no primary Rx nearby, the power of the primary signal will not change with the sounding signal. Therefore, by detecting whether the CLPC is triggered by the sounding signal, the nearby primary Rx can be sensed by the CR user. However, because the CR Tx sends sounding signals when performing spectrum sensing, it may temporally cause interference to the primary Rx's. Thus, the sounding signal needs to carefully be designed to meet interference constraints. Aside from power control, other closed-loop control schemes [26] have also been used for proactive spectrum sensing.

B. Indirect Spectrum Sensing

In primary Tx detection, indirect spectrum sensing detects the presence or absence of primary signals, which can be regarded as a binary hypothesis testing problem. Denote the signal that comes from a primary Tx and is received at the CR Rx as $s(n)$, $\mathcal{H}_1$ and $\mathcal{H}_0$ as the presence and absence of the primary signal, respectively. Then, the received signal at the CR Rx can be expressed as

$$y(n) = \begin{cases} w(n), & \mathcal{H}_0 \\ s(n) + w(n), & \mathcal{H}_1 \end{cases} \tag{1}$$

where $w(n)$ denotes the *additive white Gaussian noise* (AWGN). According to the level of information of primary signals known to the CR users, different kinds of detection schemes can be used for spectrum sensing. Here, we introduce matched filter detection, ED, cyclostationary detection, and two blind-sensing schemes. For a more complete review on various spectrum-sensing schemes and design challenges, see the recent survey papers [15]–[18].

1) Matched Filter Detection: When the received signal of the primary Tx is known to the CR users, matched filter detection can be used for spectrum sensing, and it is the optimal detector in an AWGN environment [19]. The main advantage of matched filter detection is the short sensing time to achieve a good performance, because coherence detection is used. In practice, most of the primary systems have pilot, preamble, or training sequence for synchronization and channel estimation; thus, the CR Rx may estimate the received signal from the primary Tx. However, when the SNR is low, the estimation error can be very large. Furthermore, CR users usually need to observe a wide spectrum band with multiple primary systems, and thus, they need the Rx's to estimate different types of primary signals, which leads to high complexity in implementation.

2) ED: When the primary signals are unknown to the CR users, ED can be used for spectrum sensing. It has been shown in [19] that ED is the optimal detector if only the noise power is known to the CR users.

Let Y be the energy output over m sensed samples, i.e., $Y = \sum_{i=n}^{m} |y(n)|^2$. The decision of the ED can be made by comparing the energy Y with a threshold λ, i.e.,

$$D = \begin{cases} \mathcal{H}_1, & \text{if } Y > \lambda \\ \mathcal{H}_0, & \text{if } Y < \lambda. \end{cases} \tag{2}$$

If both the signal and noise are real valued and follow Gaussian distributions with zero mean and they are independent from one sample to another, the probability of detection and the probability of false alarm can be expressed, respectively, as [27]

$$P_d = \text{Prob}\{Y > \lambda|\mathcal{H}_1\} = \frac{\Gamma\left(m/2, \lambda/(2+2\gamma)\right)}{\Gamma(m/2)} \tag{3}$$

$$P_f = \text{Prob}\{Y > \lambda|\mathcal{H}_0\} = \frac{\Gamma(m/2, \lambda/2)}{\Gamma(m/2)} \tag{4}$$

where γ is the SNR when the primary signal is active, and $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are the complete and incomplete gamma functions, respectively. When designing the detection threshold λ, the detection probability should be chosen high enough to protect the PUs. Otherwise, a high probability of misdetection may result in intolerable interference to the PUs. On the other hand, the probability of false alarm represents the ability of finding the spectrum holes, and a high probability of false alarm will lead to low utilization of the spectrum holes.

Although ED is with low implementation complexity, it has several shortcomings in practice. First, ED cannot distinguish different types of signals, which increases the probability of false alarm when the received signal contains unintended interfering signals. Furthermore, ED is susceptible to the uncertainty of noise power [20], which makes it challenging to determine the detection threshold.

3) Cyclostationary Detection: Modulated signals are usually cyclostationary, and such a feature can be used for spectrum sensing, which is called cyclostationary detection [28]–[30]. Mathematically, it can be realized by analyzing a spectrum correlation function as

$$R_y^{\alpha}(\tau) = E\left[y(n)y^*(n-\tau)e^{-j2\pi\alpha n}\right] \tag{5}$$

where α is called the cyclic frequency. Then, the cyclic spectral density (CSD) function of the received signal can be expressed as

$$S(f,\alpha) = \sum_{\tau=-\infty}^{\infty} R_y^{\alpha}(\tau)e^{-j2\pi f\tau}. \tag{6}$$

Because the noise is a stationary process, the main advantage of cyclostationary detection is that it can differentiate the primary signal from the noise, as well as any interference signals with different cyclic frequencies. Furthermore, the cyclostationary feature does not vary with the SNR, which enables the cyclostationary detector to work in a very low-SNR region [31]. However, compared with matched filter detection and ED, cyclostationary detection involves much higher computational complexity.

4) CBD: When the PU signal waveform, the noise power, and the cyclic frequency of the PU signal are all unknown to the CR users, none of the aforementioned schemes can be used for detecting the PU signal. *Blind-spectrum-sensing* schemes need to be developed for such a purpose. In practice, the received signal $s(n)$ from the primary Tx is, in general, temporally correlated, and the noise is AWGN; thus, the flatness of the spectrum of the received signal at the CR Rx can be used to infer the presence or absence of the primary signal. Covariance-based detection (CBD) [32], [33] has been developed as one of the blind-spectrum-sensing schemes. The detection decision is made by checking the significance of the correlations of the received signals with nonzero lags compared with the correlation with zero lag. This method does not require *a priori* knowledge of noise variance; thus, it is robust to noise power uncertainty.

5) Spectrum Sensing Using Multiple Antennas: When the CR Rx is equipped with multiple antennas, eigenvalue-based detection (EBD) can be used for spectrum sensing [34], [35]. By constructing the sample covariance matrix of the received signals, EBD simultaneously estimates the noise variance and signal power by calculating the minimum and maximum eigenvalues of the matrix. When the primary signal is not present, the two eigenvalues are supposed to be the same; however, when the primary signal is active and the signal covariance matrix is not a scalar of the identity matrix, the difference between these two eigenvalues is expected to be larger. Thus, the condition number of the sample covariance matrix can be used as the test statistics for signal detection [34], [35]. A closed-form formula for the probability density function of the test statistics can be derived by using a random matrix theory [35], through which the detection threshold can be determined for a target probability of false alarm.

Because EBD simultaneously estimates the noise variance and signal power, it tends to be robust to noise power uncertainty. In [36], it is shown that EBD has a theoretical root in generalized likelihood ratio testing, from which other versions of sensing algorithms can be developed. For example, the test statistics can be chosen as the ratio of the arithmetic mean over the geometric mean of the eigenvalues of the sample covariance matrix. On the other hand, if the noise variance is known to the CR Rx, the maximum eigenvalue can be used as the test statistics [37].

III. COOPERATIVE SPECTRUM SENSING

A. General Principle

As aforementioned, the spectrum-sensing capability is critical to enable CR features and enhance spectrum utilization. Local spectrum-sensing techniques do not always guarantee a satisfactory performance due to noise uncertainty and channel fading. For example, a CR user cannot detect the signal from a primary Tx behind a high building, and it may access the licensed channel and interfere with the primary Rx's. Through the collaboration of multiple users in spectrum sensing, the detection error possibility will be reduced by the introduced spatial diversity [38], and the required detection time at each individual CR user may also decrease [39], [40].

In cooperative spectrum sensing, CR users first send the raw data that they collect to a combining user or fusion center. Alternatively, each user may independently perform local spectrum sensing and then report either a binary decision or test statistics to a combining user. Finally, the combining user makes a decision on the presence or absence of the licensed signal based on its received information.

B. Combination Schemes

One straightforward form of cooperative spectrum sensing is to transmit and combine the samples received by all the CR users in the local spectrum-sensing phase. In [41], a combining scheme is proposed to process all the samples using tools from a random matrix theory. Consider K CR users, each taking N samples. Denote $y_k(n)$ as the sample that is received by the kth $(1 \leq k \leq K)$ user at the nth $(1 \leq n \leq N)$ time instant. Then, we can construct the following matrix:

$$\mathbf{Y} = \begin{bmatrix} y_1(1) & y_1(2) & \cdots & y_1(N) \\ y_2(1) & y_2(2) & \cdots & y_2(N) \\ \vdots & \vdots & \ddots & \vdots \\ y_K(1) & y_K(2) & \cdots & y_K(N) \end{bmatrix}. \tag{7}$$

Let λ_i's be the eigenvalues of $(1/N)\mathbf{Y}\mathbf{Y}^H$ and $\alpha = K/N$. Denote the noise variance at each CR user as σ^2. If σ^2 is known at the combining user and when $K \to \infty$ and $N \to \infty$, the final decision will be $\mathcal{H}_0$ if

$$\lambda_i \in \left[\sigma^2(1-\sqrt{\alpha})^2, \sigma^2(1+\sqrt{\alpha})^2\right] \tag{8}$$

for all i's, and $\mathcal{H}_1$ if there are eigenvalues outside the aforementioned range. If the noise variance is unknown, the final decision will be $\mathcal{H}_0$ if

$$\frac{\max_i \lambda_i}{\min_i \lambda_i} \leq \frac{(1+\sqrt{\alpha})^2}{(1-\sqrt{\alpha})^2}. \tag{9}$$

Otherwise, the final decision will be $\mathcal{H}_1$. This cooperative spectrum-sensing scheme [41] uses the same test statistics as the EBD in [35], and the decision threshold is chosen as a fixed value. Assuming that both K and N tend to infinity, the decision threshold in [41] is, indeed, not related to the system parameters, because the test statistics converge to a deterministic value [42], and the cooperative spectrum-sensing scheme can achieve a nearly optimal performance with the utilization of all the samples. For practical values of K and N, the performance of the aforementioned scheme significantly degrades, because the test statistics are no longer deterministic but are a random variable. Near-optimal solutions directly quantify the distribution of the test statistics as in the EBD method [35], [43], through which the decision threshold can be chosen based on the target probability of false alarm.

Combining schemes using all the samples require significant bandwidth to report the data from the individual users to the combining user, which is usually implemented over a wired high-speed backbone, whereas these CR users are, in fact, base stations (BSs). If this is not the case, we have to consider communication constraints during reporting. One natural idea is that each CR user reports a summary statistic. One commonly used statistic is the observed energy that is acquired during ED [44]–[46]. In [44], different cooperative ED schemes with low complexity have been investigated, where the final decision is based on the weighted summation, i.e.,

$$y_c = \sum_{k=1}^{K} \omega_k y_k \tag{10}$$

where y_k is the observed energy of the kth CR user, and ω_k is the associated weight. Based on the instantaneous SNR of each CR user, an optimal weighting scheme using the Neyman–Pearson criterion, which maximizes the detection probability for a given false-alarm probability, has been proposed. Without the knowledge of instantaneous channel information, equal-gain combination is also proposed for practical use, which also has a reasonable performance. Ideal reporting is assumed in [44], whereas reporting channel noises are considered in [45], and the optimal weights under the Neyman–Pearson criterion are derived.

The optimization of cooperative sensing has been an active research topic in recent years. In [46], combination schemes are designed from the sensing-throughput tradeoff perspective, i.e., maximizing the throughput of SUs under the PU protection constraint. Combining the results from multiple time slots is also considered in [46]. Wideband spectrum sensing with cooperation is addressed in [47] using ED. If individual CR users use the cyclic detector, the cyclic statistics can be reported to the fusion center for cooperation optimization [48].

In case that the communication constraints are more strict, hard combination schemes have been proposed in [38], [44], and [49]. In these schemes, CR users transmit quantized sensing information to the combining user. The counting scheme is the simplest approach, in which each CR user makes a binary decision based on its observation, e.g., the threshold test in ED, and forwards the 1-b information to the combining user. If there are at least n out of K CR users who infer $\mathcal{H}_1$, the primary signal will be declared present [50]. The optimal n is, in general, a design parameter and can be optimized based on various criteria [49], [51], [52]. In [44], 1-b combination is also extended to 2-b combination, in which three thresholds are used to divide the observed energy into four regions. Each CR user reports 2-b information to indicate the region of its observed energy. Then, the combining user calculates a weighted summation of the numbers of CR users who fall in different regions. The optimal partition of the regions and weight allocation have been given in [44], and the performance is shown to be comparable with the equal-gain combination of the observed energies.

C. Limitations and Practical Considerations

1) Asynchronous Sensing Information: In practice, local observations of different users may be obtained at different times and sent to the combining user with delay, which affects the performance of the aforementioned combination schemes, assuming synchronous sensing. In such a case, the combination approach should take asynchronous sensing into account. In [53], a probability-based scheme is proposed by utilizing the statistics of licensed band occupancy. Assume that there are K cooperative users in the CR network and the kth $(k = 1, 2, \ldots, K)$ CR user sends its sensing information u_k that is obtained at t_k to the combining user. The combining user makes the final decision on the absence or presence of the licensed signal at t. The optimum decision is based on the following likelihood ratio:

$$\rho = \frac{P(u_1, u_2, \ldots, u_K|\mathcal{H}_1)}{P(u_1, u_2, \ldots, u_K|\mathcal{H}_0)} \tag{11}$$

which, through licensed band occupancy statistics, can be represented as functions of u_k's, t_k's, and t. Then, the final decision at t can be made by comparing the likelihood ratio with a predetermined threshold.

2) Nonideal Reporting Channel: Aside from the sensing channels from the PU to the CR users, the reporting channels from the CR users to the combining user may also experience fading, which limits the performance improvement from cooperative spectrum sensing without proper design. In [54], *space–time block coding* (STBC) is proposed to ensure robust reporting. When there are two CR users U_1 and U_2 with local information as D_1 and D_2, respectively, they exchange their sensing information and then U_1 send $\{D_1, D_2\}$, whereas U_2 sends $\{-D_2, D_1\}$. When the interuser channel between the two users is good, diversity gain can be achieved. When that channel is poor, there is no diversity gain, but there is still a coding gain of around 3 dB. If there are more users, they can form pairs, and each pair uses a given slot to apply the same scheme. Similarly, *space-frequency* (SF) coding can be applied for *orthogonal frequency-division multiplexing* (OFDM)-based CR users.

3) Decentralized Network: As aforementioned, the CR network is assumed to be centralized with a combining user. In a decentralized network, it has been shown in [39] that the *amplify-and-forward* (AF) cooperation protocol [55], in which one user acts as a relay for the other user and then amplifies and forwards the signal received from its partner without any further processing, can be applied. Because AF cooperation improves the performance of spectrum sensing only under certain scenarios, appropriate pairing of cooperative CR users is needed to optimize the overall detection capability of the CR network. In [40], an efficient pairing algorithm has been given for a decentralized CR network with corresponding performance analysis.

IV. Cognitive Spectrum Access

So far, spectrum-sensing techniques for identifying the spectrum holes have been reviewed from the signal processing perspective. Based on the sensing results, the CR users can perform cognitive spectrum access through the OSA model. Alternatively, if the CR Tx has obtained the channel-state information involved for primary Rx protection [56], the CSA model can be used for cognitive spectrum access. In this section, transceiver design for the OSA and CSA models will be discussed. In particular, transmit signal waveform design is considered for the OSA model, and transmit resource allocation is studied for the CSA model. The capacity limits of CR channels with genie cognitive capability have been considered in [11] and [57] from the information-theoretic perspective. The transmit strategies for the CSA model are also reviewed in [58] from the convex optimization perspective, as well as in [54], with additional considerations of cooperative communications.

A. Transmit Signal Design for OSA

The OSA model allows the CR users to coexist with the PUs in an opportunistic way, and most CR transmission schemes fall into this category. As the SUs of a licensed spectrum, the CR users in OSA ideally transmit only within the spectrum holes. They attempt to avoid interference with the PUs through spectrum-sensing results and other knowledge that is acquired before and during their operation. In particular, the CR users may access a spectrum band when the PUs are not active, which means that the CR and the PUs can be deployed in the same geographic region but at different time slots. Furthermore, the CR users may access the spectrum band when the CR and PUs are in different geographic regions, where path loss and shadowing in wireless channels separate them without interfering with each other.

Each of the identified spectrum holes may have different bandwidths, and they may be either contiguous or discontiguous in the spectrum domain. In PHY-layer implementation, the spectrum holes can be bonded together and share the same set of modulation schemes as discussed in the following paragraphs, and this approach is called channel bonding. Alternatively, the spectrum holes can be classified into several subgroups, each of which may contain one or multiple (possibly discontiguous) spectrum holes and is realized by the same set of modulation scheme. This scheme is called channel aggregation. Using channel aggregation, the bandwidth of the modulation scheme for each group is much reduced compared to channel bonding, particularly when the spectrum holes are far apart from each other in the spectrum domain. In the following paragraphs, we will discuss two PHY-layer schemes for designing the signal waveforms suitable for each subgroup.

In OSA, multicarrier modulation techniques become natural candidates for CR transmission mainly due to the flexibility in spectrum usage. As the most popular multicarrier technique, OFDM, with its own advantages of combating fading and interference, has been proposed for the PHY layer of CR. By properly nulling subcarriers, the CR users can dynamically and efficiently avoid interference with active PUs over these subcarriers. OFDM-based spectrum pooling has extensively been discussed in [59], where several potential problems for realizing the pooling scheme have been identified, among which, the mutual interference between the CR users and the PUs is critical for CR users to work on a noninterference basis. Windowing and active subcarrier cancelation techniques have been proposed to reduce the power leakage in the sidelobes of OFDM subcarriers to limit the interference level [60], [61].

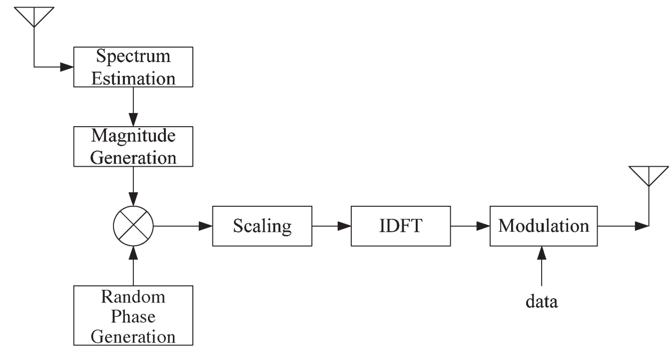

Fig. 5. TDCS transmitter structure.

The *transform-domain communication system* (TDCS) is another approach for realizing OSA, which was originally proposed in [62] for military communications, with the basic idea of using spectrum information to avoid jammers. In OSA, similarly, information from spectrum sensing can be used to dynamically shape the transmitted waveform such that the interference to and from licensed systems can be avoided. It has been shown in [63] that TDCS is also a potential candidate for CR transmission. In TDCS, a basic waveform is first generated based on the available spectral bands for secondary communications, and then, information is transmitted through modulation, which is determined by the basic waveform. As shown in Fig. 5, the TDCS Tx first takes samples from the surrounding spectrum environment to identify interference-free spectrum bands. Spectral estimation may be used for such a purpose. The magnitude of the basic waveform is set to be unity for frequency bands with interference less than a threshold and is set to zero otherwise, which makes the TDCS symbols similar to noise. After scaling and inverse Fourier transform, the resulting basic waveform is used to modulate the data with either antipodal signaling, cyclic shift keying, or other more complicated and efficient ways.

Although both OFDM and TDCS are based on Fourier transform and use frequency nulling, they are essentially different. Notably, TDCS randomizes the phase of the spectral components. Moreover, OFDM is designed to mitigate the interference, whereas TDCS is mainly designed to deal with jammers. The basic principle of OFDM is to split a wideband spectrum into a number of narrowband subcarriers, whereas TDCS uses the entire spectrum band to represent one symbol. In TDCS, symbol orthogonality is achieved by randomizing the phases. In OFDM, subcarrier orthogonality is realized by properly choosing the subcarrier spacing.

B. Transmit Power Allocation for Single-Antenna CSA

As aforementioned, in CSA, the CR users coexist with the PUs at the same time and the same geographic region, as long as they do not cause harmful interference to the primary Rx's [64]. Recalling Fig. 2 in the single-antenna CSA model, the

CR communication can only be established with a constraint on the power received at a third-party (primary) Rx. Therefore, the knowledge of channel gain g_0 is of significance to the CR Tx to protect the primary Rx. In [65], the channel capacities of the secondary CR link under the interference power constraint at the primary Rx for AWGN and fading channels have been analyzed, respectively. It is shown that the CR link capacity in the fading channel exceeds the AWGN channel. This is because the AWGN channel lacks variation, which leads to fewer opportunities for the CR transmission. In [66], both the peak and the average interference power constraints are considered, whereas in [67], both the average and the peak power constraints on the primary Rx have been studied, together with the transmit power constraint. It shows that the capacity under the average power constraint is larger than under the peak power constraint. When the channel gain between the secondary Tx to the primary Rx is imperfectly known, the effect of such imperfectness on the mean capacity of the secondary link has been addressed in [68]. It is shown that the interference power limit has to be reduced due to the channel imperfectness, by which the secondary link capacity is eventually reduced. The results for multiple-access and broadcast channels under interference power constraints can be found in [69] and [70].

C. Resource Allocation for Multiantenna CSA

The use of multiple antennas for wireless transmissions provides us both multiplexing and diversity gains [71], [72]. In the following sections, we will review transmit and receive strategies for the CSA model when the CR nodes are equipped with multiple antennas.

1) Cognitive Multiple-Input–Multiple-Output (MIMO) Channel: Let us first consider a secondary system where both the CR Tx and the CR Rx are equipped with multiple antennas. The received signal at the CR Rx is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{12}$$

where $\mathbf{x}$ is the n_T-D signal vector that is transmitted by the CR Tx, $\mathbf{H}$ is the $n_R \times n_T$ full-rank channel matrix between the Tx and its intended Rx, $\mathbf{y}$ is the n_R-D vector that is received by the CR Rx, and $\mathbf{n}$ is the n_R-D noise-plus-interference vector at the CR Rx. It is proposed to use a set of power and interference constraints to realize several practical considerations for the CR, including, but not limited to, the following conditions.

- Maximum transmit power for the Tx
  We have
  $$\mathrm{Tr}(\mathbf{Q}) \le P_t \tag{13}$$
  where $\mathbf{Q}$ is the covariance matrix of the CR Tx, and P_t is its own transmit power constraint.
- *Null power constraints*. We have
  $$\mathbf{U}^H\mathbf{Q} = \mathbf{0} \tag{14}$$
  where $\mathbf{U}$ is a matrix whose columns represent the spatial and/or the frequency "directions" the CR Tx is not allowed to transmit.
- *Average power constraints*. We have
  $$\mathrm{Tr}(\mathbf{G}^H\mathbf{Q}\mathbf{G}) \le P^{\mathrm{ave}} \tag{15}$$
  where the range space of the matrix $\mathbf{G}$ identifies the subspace where the interference level should be kept under the required power constraint P^{ave}.
- *Peak power constraints*. We have
  $$\lambda_{\max}(\mathbf{G}^H\mathbf{Q}\mathbf{G}) \le P^{\mathrm{peak}} \tag{16}$$
  where $\lambda_{\max}(\cdot)$ denotes the maximum eigenvalue of a matrix, and P^{peak} is the corresponding maximum peak power constraint.

With the aforementioned constraints, different transmit schemes can be designed to maximize the achievable rate of the secondary link as

$$R = \log_2 |\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^H|. \tag{17}$$

For example, standard optimization methods are used to design the transmit strategy in [73]. When the CR Rx and the primary Rx each have a single antenna, the transmit strategy is termed *cognitive beamforming* [73], which balances the transmissions to the CR Rx and the primary Rx. The interference alignment idea has been used in [74], where the secondary MIMO transmission operates on the eigenspaces that are unused by the primary MIMO link. When the acquired channel-state information is imperfect, a robust criterion can be used to design the transmit strategy such that the primary Rx can be protected for all its possible channel states, and the solution is called *robust cognitive beamforming* [75], [76].

2) Cognitive Multiple-Access Channel: If multiple CR users share the same spectrum with the PUs to transmit independent messages to a common BS in the secondary network, this channel is called the *cognitive multiple-access channel*. In this scenario, all the CR Tx's need to jointly design their transmission strategies to achieve the maximum secondary network performance under the transmit and interference power constraints. In [77], the CR Tx's are equipped with single antenna each, and the Rx's are equipped with multiple antennas. Power allocation at the CR Tx's and receive beamforming at the CR Rx are designed either to maximize the sum rate of the secondary network using zero-forcing-based decision-feedback equalizer or to maximize the achievable SINR targets among all the CR users who use linear minimum-mean-square-error Rx. Note that suboptimal Rx's are considered in [77], whereas optimal Rx's are considered in [78].

3) Cognitive Broadcast Channel: If the transmission from a common BS (CR Tx) of the secondary network to multiple CR Rx's in the presence of primary transmissions is of interest, this scenario is described as a *cognitive broadcast channel*. In [79], the secondary network is a multiuser MIMO broadcast channel, and the problem of interest is to maximize the weighted sum capacity of the SUs under the interference power constraints at the primary Rx and the sum power constraint at the CR Tx. The duality between the conventional MIMO broadcast channel and the MIMO multiple-access channel under the sum power constraint [80] was first extended to a generalized duality with an arbitrary linear transmit covariance matrix constraint, through which the optimal transmit strategy at the CR Tx was derived. When the number of secondary Rx's is large, opportunistic spectrum sharing is designed in [81] such that a group of mutually orthogonal secondary Rx's are selected for service, yet maintaining low interference to the primary Rx.

Under the primary Rx protection constraint, distributed beamforming and rate control are addressed in [82], and cognitive multicast beamforming has been studied in [83], where each secondary Rx intends to receive the common information from the multiantenna secondary Tx.

4) Blind Channel Estimation: Note that, to efficiently utilize spectrum resource with cognitive MIMO, the CR user has to acquire the information of different channels, among which the interference channel from the CR Tx to the PU is difficult to obtain. To alleviate such a requirement, the idea of an *effective interference channel* is introduced in [84], and a practical cognitive beamforming scheme is proposed. When two PUs take turns in transmitting to each other, the CR Tx takes samples from both users over the frequency band of interest through spectrum sensing. Define the covariance matrix due to only signals from PUs as

$$\mathbf{Q}_s = \alpha_1 \mathbf{G}_1^H \mathbf{S}_1 \mathbf{G}_1 + \alpha_2 \mathbf{G}_2^H \mathbf{S}_2 \mathbf{G}_2 \tag{18}$$

where $\mathbf{G}_i$ is the channel matrix from the ith PU to the CR Tx, $\mathbf{S}_i$ is the covariance matrix of the ith PU, and α_i is the expected value of the portion of instants that the ith PU is transmitting. Based on the sample covariance matrix acquired during spectrum sensing, the effective channel, which is defined as

$$\mathbf{G}_{\text{eff}}^H = (\hat{\mathrm{Q}}_s)^{1/2} \tag{19}$$

where $\hat{\mathbf{Q}}_s$ is the estimated version of $\mathbf{Q}_s$, can be obtained. Then, the transmit covariance matrix of the CR Tx

$$\mathbf{S}_{\text{CR}} = \mathbf{A}_{\text{CR}} \mathbf{A}_{\text{CR}}^H \tag{20}$$

should ideally be designed such that

$$\mathbf{G}_{\text{eff}} \mathbf{A}_{\text{CR}} = \mathbf{0}. \tag{21}$$

This way, the CR transmission will cause no adverse effect on the primary communication.

In practice, the effective interference channel is estimated by the CR Tx using blind-signal-processing techniques [56], [85], [86] due to the two-way communications of the PUs. Due to the limited amount of time spent for channel learning, however, the obtained effective interference channel is usually imperfect; thus, the interference that is caused by the CR transmission to the primary Rx will not be zero. Fortunately, this interference power to primary Rx's is predictable by quantifying the subspace estimation errors; thus, the CR transmission power can be regulated such that the interference power constraint is met. Finally, because blind channel estimation, channel training, and secondary transmission all consume time and power resources, there exists a tradeoff design among the three operations [56], [85], [86], which is similar to the sensing-access tradeoff in the OSA model [46].

V. Impact of Spectrum Sensing on Cognitive Radio Medium Access Control Design

Conventionally, the MAC layer is responsible for handling the medium access resolution for multiple users either in a fixed manner, e.g., through time-division multiple access (TDMA) or frequency-division multiple access (FDMA), or using random access mechanisms, e.g., carrier sensing multiple access (CSMA). In CRNs with multiple CR users, the spectrum holes are opportunistic resources; thus, the CR MAC needs to support the identification of spectrum holes and access of multiple frequency channels in a dynamic manner. Furthermore, the CR MAC design needs to consider practical constraints, e.g., the availability of a common control channel for information sharing and the number of transceivers available for sensing and communication operations. This condition implies that the CR MAC must be spectrum aware, i.e., providing medium access flexibly in the spatial, time, and frequency domains, and at the same time, it must understand the underlying limitations due to practical constraints.

As aforementioned, spectrum sensing is an important task in CR design. Aside from its signal-processing nature, the execution of spectrum sensing needs to be scheduled by the MAC layer. In addition, when the spectrum holes are identified by more than one CR user, the CR MAC has to decide how the spectrum can effectively be accessed. In this section, we review the design considerations for the CR MAC related to sensing operation, which include sensing scheduling, sensing-access coordination, and cooperative spectrum sensing.

The following criteria need to be considered when designing the CR MAC.

- *Sensing accuracy*. In general, spectrum sensing should be carried out to meet certain target probabilities of false alarm and detection. This condition, when translating into MAC-layer requirements, means that each spectrum sensing must be carried out for a minimum period of time, e.g., T_s, and involves a minimum number of nodes with certain sensing signal strength. Furthermore, to avoid self interference, which causes false alarms, the MAC layer usually needs to ensure that, when spectrum sensing is carried out, all CR (secondary) communications are postponed. This case leads to the schedule of the so-called *quiet sensing periods*.
- *Sensing timeliness*. At the MAC layer, spectrum-sensing tasks should frequently be scheduled to quickly detect PUs when they become active on the channels at which a CR user operates. Usually, this case translates into the minimum interval between two consecutive sensing activities. This interval can be denoted by T_i.
- *CR transmission QoS*. When quiet periods are scheduled for spectrum sensing, all CR communications are suspended, and this case causes negative effects on the QoS of various applications, e.g., video streaming or voice over Internet Protocol (VoIP). Therefore, sensing scheduling

must be designed to minimize negative effects on the system performance while meeting the accuracy and timeliness requirements.

Because both spectrum sensing and spectrum access require time-domain resources, one of the research challenges in MAC design is how we can balance the sensing and spectrum access times [87]. For OSA with frame-based MAC and periodic spectrum sensing, this challenge is related to the following three design issues.

- Where should the sensing slot be allocated within each frame?
- How much time should be spent for spectrum sensing in each frame?
- How frequent should the sensing operation be carried out?

In general, these questions become complex when sensing and communication share the same transceiver (antenna and RF front end), for which a tradeoff between sensing performance and spectrum access opportunity needs to be considered. In fact, if we also taking into account the cost that is related to energy consumption for each operation, it is clear that the optimization result also depends on the environment, application, and, even, user preferences.

The first and second questions are related to sensing scheduling and sensing-access tradeoff design, respectively. With regard to the third question, one study is given in [88], where, assuming that the PU's short-term traffic statistics are known, the frame duration is designed by optimizing CR's transmission throughput under the collision constraint introduced to PUs.

A. Spectrum-Sensing Scheduling

The first question is related to sensing scheduling. If we purely look at the sensing requirement, one simple way is to allocate a fixed portion of each frame as a sensing period (quiet period), and the duration of the sensing period needs to be long enough such that the sensing accuracy requirement is satisfied. For stringent sensing requirements such as in IEEE 802.22, the required sensing duration can be very long, which may affect the transmission QoS of CR users. Thus, one alternative way is to split the whole sensing duration in each frame into multiple sensing slots [46]. By doing so, the transmission QoS of CR users can be improved, and at the same time, we may achieve better sensing accuracy due to the exploitation of sensing diversity under fading environments.

A unified control framework that jointly considers spectrum sensing and CR data transmission is proposed in [89]. The method treats each sensing period as a *virtual packet transmission*. By introducing virtual sensing users and virtual sensing packets, the problem of joint scheduling of spectrum sensing and packet transmission can be abstracted as a parallel queuing network. This approach allows us to schedule the traffic in this parallel queuing system so that the packet loss due to deadline violation for data nodes is minimized, whereas all virtual sensing packets meet their sensing deadline requirement [90].

B. Sensing-Access Tradeoff

For a given frame duration, the optimal sensing time design for periodic spectrum sensing is studied in [46]. The key design methodology is described as follows. Because the spectrum-sensing time affects the two probabilities associated with spectrum sensing, by adjusting the detection threshold for a given frame duration, the optimal sensing duration is designed by maximizing the achievable throughput of the SUs under the constraint that the PUs are sufficiently protected. The achieved probability of detection at the worst-case SNR is used to quantify the protection to PUs. Using the ED sensing scheme as the basis, one interesting sensing-access tradeoff problem is formulated, and it is shown that the formulated problem, indeed, has one optimal sensing time, which yields the highest throughput for the SUs.

The sensing-access tradeoff design in [46] is based on single-band sensing and point-to-point communications in the secondary network. In [91], the design methodology has been extended to wideband multichannel sensing by designing the optimal common sensing time across all the bands. Channel aggregation and power allocation across all the bands have been considered. Cooperative spectrum optimization has been studied in [92] by considering such sensing-access tradeoff and optimizing the fusion schemes in the fusion center. In [93], the tradeoff design idea has also been extended to the case when the secondary network makes use of CSMA-based random access. By adjusting the sensing time (quiet period) and the probability of false alarm, the number of SUs who enter into the CSMA random access is controlled, through which the saturated throughput and delay performance can be optimized.

Note that the tradeoff design in [46] considers the case that the PUs are either ON or OFF in a long time scale. In other words, it does not take into account the short-term traffic pattern of the primary networks (PNs). In [94], the authors consider a spectrum access scenario when the transmission of PUs is slotted and evolves in a Markovian manner between active and idle, and the SUs follow the same slot structure and independently sense the channels prior to opportunistic data transmission. The opportunistic spectrum sensing and access policy is jointly designed under the formulation of finite-horizon partially observable Markov decision process (POMDP). Interestingly, in [95], the authors show that a separation principle exists, which decouples the design of sensing policy from the spectrum access policy. A somewhat-similar approach can be also found in [96], which considers an unslotted PN.

The work in [97] attempts to bridge the gap between [46] and [95]. The PN operates in a time-slotted manner and switches between the idle and the active states according to a stationary Markovian process. At the beginning of each time slot, the instantaneous state of the PN is not directly observable, and the SU needs to decide whether to stay idle or to carry out spectrum sensing. If the SU chooses to carry out spectrum sensing, it needs to decide the duration of the sensing period and to configure related parameters to meet a minimum detection probability. Subsequently, if spectrum sensing indicates that the PN is idle, the SU proceeds to transmit data during the rest of the time slot. By staying idle in a particular time slot, the SU conserves energy but, at the same time, suffers increase in delay and reduction in throughput. By carrying out spectrum sensing, the SU consumes time and energy to acquire knowledge of the state of the PN and stands a chance to transmit data if the PN is idle. Furthermore, there are tradeoffs that involve energy consumption, sensing accuracy, and transmission time when the duration of sensing periods is varied. For the SU, given the delay cost that is associated with staying idle in a time slot, the energy costs that are associated with spectrum sensing and data transmission, and the throughput gain that is associated with a successful transmission, the authors consider the problem of finding an optimal policy that decides the idle and sensing modes, together with spectrum-sensing time, to maximize the expected net reward.

C. Cooperative Spectrum Sensing

As pointed out in [29], the following three main questions with regard to cooperative spectrum sensing should be considered.

- How much can be gained from cooperation?
- How can CR users cooperate?
- What is the overhead that is associated with cooperation?

In Section III, signal-processing techniques of cooperative spectrum sensing have been addressed, and the gain due to cooperation depends on the frequency band of interest and channel characteristics [98], [99]. In fact, the cooperative spectrum sensing can benefit from the knowledge of the topology of primary and secondary networks, particularly information on the locations of the sensing Rx's. This concept has been considered in [100] from a theoretical perspective, in [101] and [102] in the context of radio environment maps, and in [103] for *ad hoc* networks.

MAC-layer design should address how cooperation is achieved and what overhead is involved. One of the works that follows this direction is [104], where the tradeoff between the sensing accuracy and overhead of exchanging sensing outcomes among distributed CR users is explored. Nodes make individual spectrum-sensing decisions, which incurs false alarms and misdetections. To improve sensing reliability, nodes can share their sensing outputs with other nodes and apply decision fusion. The more the shared information that a node receives, the lower the probability of false alarms and misdetections becomes. However, sharing information among distributed nodes can take significant time, which, in turn, affects communication. It is shown that there is a tradeoff between these two activities, which indicates an optimal number of outcomes that a node should collect from other nodes.

The issue of cooperation overhead has also been considered based on the concept of price of anarchy [105], price of ignorance [106], or its complementary presentation as a value of perfect information [107].

VI. Cognitive Radio Medium Access Control Protocols

CR MAC needs to be spectrum aware by taking into account the heterogeneity and dynamics of the available spectrum holes while protecting the PUs from harmful interference. The complexity of this task depends on the spectrum access model used and whether centralized or distributed control can be assumed. In this section, we provide a brief review on CR MAC protocols. See two recent and detailed surveys in CR MACs [12], [108], which summarize several MAC-layer-related issues and challenges for CR design.

A. Classification of CR MAC Protocols

Cormio and Chowdhury [108] classify CR MAC protocols by considering the following two dimensions: 1) one dimension on dividing the access as random access, time slotted access, or hybrid access and 2) another dimension on separating the protocols between *ad hoc* and centralized MACs. This classification is interesting from the operational and implementation perspective of CR MACs. Here, we consider two new dimensions that can be used to further classify the CR MACs.

The third dimension of CR MAC classification is to consider whether the CR has out-of-band signaling capability. The stipulation of specific frequency band for signaling has its pros and cons that need to carefully be considered, and this approach depends on the deployment scenario. We do not analyze this issue deeply in this paper, but clearly, this case is one of the key differentiators that must be considered by commercial entities and system engineers when making decisions.

The fourth dimension of MAC classification is related to the required information on the system state and parameters. The *blind MAC protocols* do not assume any or require very little external information about the primary and other secondary networks. On the other hand, some CR MACs require detailed information on the system state through a specific signaling method. These *information-rich MACs* may even require statistical information on the usage patterns of PUs. To do so, empirical models and measurement campaigns of spectrum usage are needed for an effective MAC design and a reliable MAC performance analysis.

B. Centralized CR MAC

Recent works that consider centralized channel assignment for multichannel CRN include [109]–[111]. In [109], the authors consider a problem of opportunistically allocating multiple licensed channels to a set of CR users so that the total number of channel usages is maximized. In [110], the authors study a similar problem and introduce a reward function that is proportional to the coverage areas of BSs. In [111], a local-bargaining approach is proposed to support distributed spectrum allocation in mobile ad hoc networks. However, power control is not considered in [109]–[111], and interference is restricted based on the physical separation of communication entities. The disadvantage of this distance-based interference model is that it does not take into account the aggregated interference effect when multiple transmissions happen on a single channel.

A CRN that consists of multiple cells is considered in [112]–[115]. Within each cell, there is a BS that supports a set of fixed-location wireless subscribers commonly called customer premise equipment (CPE) in the referred papers. The spectrum of interest is divided into a set of multiple orthogonal channels. Each CPE can be either *active* or *idle*, and a BS needs one channel to support each active CPE. The objective is to maximize the number of active CPEs that can be supported, subject to the following two conditions: 1) The total amount of interference that is caused by all cognitive transmissions to each PU must not exceed a predefined threshold, and 2) for each supported CPE, the received SINR must be above a predefined threshold. When global knowledge of active CPEs across all the cells is available for making control decisions, a channel/power allocation scheme that maximizes the number of CPEs supported can be obtained by solving a mixed-integer linear programming (MILP). For a network with a large number of nodes, solving such an MILP can be highly complex. A more scalable scheme called *dynamic interference graph allocation* (DIGA) can be used, which is based on a dynamic interference graph that captures the aggregated interference effects when multiple transmissions simultaneously happen on a channel. When no global knowledge of active CPEs is available for making channel/power allocation decisions, a *two-phase resource allocation* (TPRA) scheme is proposed. In the first phase of TPRA, channels and power are allocated to BSs, with the aim of maximizing their total coverage. In the second phase, each BS allocates channels within its cell so that the number of active CPEs supported is maximized.

We conclude by referring to a more centralized MAC-layer approach that is introduced by Zou and Chigan [116], which is a game-theoretic DSA framework. This approach is particularly interesting, because it combines several components into the same MAC framework, i.e., the OSA algorithm, clustering algorithm, negotiation, and collision avoidance. The OSA algorithm to optimize global performance by using the game-theoretic approach.

C. Distributed CR MAC

For a distributed control scenario, one closely related class of control problems is the multichannel MAC problems [117]–[120]. One important issue to be addressed includes the so-called *multichannel hidden terminal* problem. For a single-channel scenario, the traditional hidden terminal problem can be solved by exchanging request-to-send (RTS) and clear-to-send (CTS) messages. However, for the multichannel problem, in which each node is only equipped with a single half-duplex transceiver, because nodes can listen on different channels, they may not receive the RTS and CTS transmitted by other nodes. This case leads to the so-called multichannel hidden terminal problem [119]. This problem is even more complicated when the set of available channels dynamically changes in CR networks.

As pointed out in [121], existing proposals for using multiple channels in wireless networks, e.g., [117]–[120], typically make several assumptions that may fail to hold in DSA networks. For example, most proposals assume that the set of available channels is static, i.e., the channels that are available for use are fixed at the time of network initiation. Because CRs may allow the spectrum available to dynamically change, the set of channels may also dynamically change. Furthermore, existing proposals often assume that the available channels are homogeneous, i.e., different channels have similar range and support similar data rates. The homogeneity assumptions are broken when different channels may be located on widely separated slices of frequency spectrum with different bandwidths and different propagation characteristics. Thus, there is a need to design higher layer protocols that suitably manage the dynamically changing/heterogeneous channels supported by a CR.

In [122], the authors propose a protocol called cognitive medium access control (C-MAC) for supporting multichannel distributed CRN under OSA. The protocol is designed to support negotiation/cooperation among nodes within each channel and among different channels. This approach is based on setting up frame structure for each available channel and allowing nodes to exchange messages through beacon transmissions. Through this approach, sensing scheduling is also supported. However, it still remains to compare the efficiency of the proposed protocol with other protocols, because the major effort was placed in enhancing the robustness, and not the efficiency, of the protocol.

In [123], a framework called a cognitive mesh network (COMNET) is proposed to support OSA in wireless mesh networks. Both spectrum sensing and spectrum allocation are taken into account. The objective is to allow the setup of a cognitive wireless mesh network based on off-the-shelf IEEE 802.11 WLAN cards.

In [124], the authors propose MAC mechanisms that exploit idle periods between bursty transmissions of PUs for multi-access communication channels. They also discuss approaches for sensing and modeling the idle periods of PUs. In [125], the authors consider the problem of MAC-layer configuration for CRNs. They propose a distributed algorithm that addresses the following two important issues: 1) how nodes identify their neighbors and communicate with them and 2) how nodes decide on the set of channel(s) that can be used for communication across the entire network.

In [126], the authors propose a multichannel MAC protocols for OSA. The aim is to incorporate both sensing and communication requirements in the design. Unfortunately, spectrum sensing is oversimplified by assuming that sensing is perfect (no false alarms and misdetections). The effect of carrying sensing activities on communications is also not considered.

In [127], opportunistic spectrum medium access control (OS-MAC) is proposed, which provides adaptive and DSA by coordinating the use of spectrum among CRs. It is based on the control information exchange through some common control channel and also requires time windows (periodic) to synchronize the coordination. Nevertheless, it can support *ad hoc* network operations.

The hardware and PHY-layer constrain the spectrum-sensing operations and, generally, the capability with which the MAC-layer can be equipped. Hardware-constrained medium access control (HC-MAC) [128] emphasizes this fact by specifically considering hardware constraints. This contribution is valuable, because it specifically draws the attention to PHY-layer limitations and implementation challenges.

Another interesting CR MAC protocol is dynamic open-spectrum sharing (DOSS) MAC [129], which allows the dynamic combination of available spectrum opportunities. It is also one of the MAC studies that specifically consider hidden and exposed node problems. Similar to several other proposals, it relies on the existence of an out-of-band signaling channel for busy tones and control signaling. These assumptions, although making practical MAC design easier, limit their applicability, particularly if common a control channel is not standardized. This case is one of the areas where standards and regulations have a strong impact on the MAC design.

The adaptive spectrum band pooling based MAC is also proposed in [130] under the name single-radio adaptive channel (SRAC) MAC. This MAC protocol seems to be particularly suitable for *ad hoc* networks, and it is based on random access principles. However, the paper does not carefully address the issue of signaling overhead and long periods of time, during which CR cannot monitor the control packets.

Finally, reconfigurable and multipurpose MACs have been studied in software-defined radio (SDR)-based CR context [131]–[133].

VII. Cognitive Radio Networks

As aforementioned, CR users can identify the spectrum holes and establish opportunistic communication links on a secondary basis. A CRN is composed of multiple CR users, and each CR user may want to access the identified spectrum opportunity. One of the critical issues for CRN design is to coordinate the transmissions of each CR user based on the identified spectrum holes while avoiding interference to the PUs or the PN.

In general, CRNs can be classified as centralized or *ad hoc* networks [12], [13], and CRN architectures must support the mechanisms for CR operation and primary–secondary network coexistence. In a centralized CRN, a central unit, such as a BS in cellular networks, coordinates the spectrum sensing and spectrum access operations among the CR users. In this case, the whole centralized CRN can be treated as a super-CR user, but in a detailed level, different users may be required to carry out different tasks; thus, each CR user may have different cognitive capability. In *ad hoc* CRNs, there is no central unit to coordinate the CR users; thus, each CR user is required to have a certain level of CR capability to support its communications with other users.

In this section, we first define three CRN models from the operational perspective and then introduce several schemes for CRN tomography, i.e., PN traffic pattern recognition. In the next section, spectrum-aware routing and QoS control will be reviewed. With regard to some of the important issues that are related to CRNs, including spectrum analysis, spectrum decision, and spectrum handoff, see two review papers [12], [13].

A. CRN Models

There are different operational models for CRNs. One model is that all CR nodes have the same level of cognitive capability and execute the same set of networking protocols. This model is used in the IEEE 802.22 wireless regional area networks [134], [135], where each cell is treated as a centralized CRN (a super-CR user) that is requested to carry out spectrum sensing over the bands. Another model is that the CRN contains a collection of heterogeneous wireless networks in which the CR nodes support the coexistence and facilitate efficient exploitation of heterogeneous networks. This model has been used in IEEE P1900.4 and the European Telecommunications Standards Institute Reconfigurable Radio Systems (ETSI RRS) [136]–[138]. By exploiting the cognitive capability, CRNs can overcome the problems in conventional networks, including the unawareness of network status and the lack of intelligent adaptation, by observing, reacting to, learning, and adapting to various environment stimuli [139].

In a more general sense, a CRN model can be defined as a collection of CR nodes in the secondary networks and the nodes of coexisting multiradio systems, including the PNs that execute the same set of CR networking protocols [140]–[145]. The links might adopt primary or secondary network protocols. This case means that the nodes of all coexisting networks, including both primary and secondary networks, can be interconnected and cooperatively internetworked. Within such a CRN, the packets from a source node will reach a destination node through multihop/multipath cooperative relay networks that are composed of PNs and/or secondary networks.

B. CRN Tomography

In designing CRNs, aside from sensing the presence of the PUs, sometimes, the CR nodes should also sense the traffic patterns of the PNs and coexisting networks, and this process is referred to as CRN tomography [146]. The traffic patterns of the PNs and coexisting networks are important for the routing design and packet-level understanding of the utilization of the network. The state of art in this field largely relies on Internet tomography [147]–[153]. In [146], the CRN tomography acquires the parameters and traffic patterns required for CRN operations through the passive monitoring and active probing of the coexisting networks and using statistical measuring, processing, and inferring techniques. In [154], schemes are proposed to obtain information with regard to connectivity, in general ad hoc CRNs, to enable routing algorithms. Finally, the interference and spectrum usage pattern information can be derived by analyzing the correlation between the packet-level tomography results and the information on measurement, modeling, and characterization of radio spectrum [99], [155], [156].

VIII. Routing and Control of Cognitive Radio Networks

So far, we have focused on the one-hop delivery of packets from a CR node to its immediate neighboring node. The research community has also considered the general situation, where multihop or relay communication is enabled in the CR context. This case can be considered to be a cognitive and cooperative wireless network that creates a new dimension of design challenges [11], [154], [143].

Prior to studying the network layer of CRNs, we have to examine the properties of an opportunistic CR link. The CR link in CRNs can be characterized as a Markov chain model [143] based on the measurement reported in [124]. However, another critical property, i.e., the unidirectional feature [140], [143], is generally overlooked in the literature. The unidirectional feature of CR links primarily comes from the following two factors: 1) the short availability in time duration (i.e. opportunistic timing window) in any specific opportunistic CR link and 2) an upper layer network operation. A more realistic CR link model for white spaces is studied in [157], and a self-similar traffic model is observed in [158]. A Bayesian network approach is used in [159] to model link availability in multilink CRNs. Another way of characterizing CRNs is to analyze the degree distribution of connectivity by considering interference and percolation in random networks [160].

Due to the short available timing window for opportunistic links and heterogeneous networking in CRNs that consist of multiple-radio systems/networks, a node in a CRN may cooperatively relay packet(s) based on trust [145], whereas a security mechanism may consume too many radio resources and may not possible to operate in such a short time frame. Such a unidirectional nature may not warrant an automatic repeat request (ARQ) operation over every link in CRNs, which creates challenges in the control of CRNs, in addition to the routing in CRNs.

For general-sense CRNs, conditions for successful transmissions include communication bandwidth available for CR Tx and Rx within the communication range and tolerable interference at reception, which relies on successful power control. Together with scheduling and routing, the problem leads to a mixed integer nonlinear programming problem, which can be solved using linear relaxation and local search [161]. Furthermore, to identify relay selection criteria such that cooperation is beneficial to both primary and secondary networks, we may properly select relays to reduce power consumption in primary transmissions and to simultaneously reduce interference from the primary traffic to the secondary network [162]. The performance improvement of the secondary network due to the extra spectrum opportunities can be characterized by analyzing the extension of its connectivity region through a percolation theory. Such self-motivated cooperation leads the way toward self-organizing wireless networks. Finally, cognitive relaying in the CSA has been addressed in [163] and [164].

A. Spectrum-Aware Routing

There are two issues that should be considered for spectrum-aware routing. The first issue is that routing algorithms and protocols should be aware of the dynamically available spectrum holes and adapt their operations to such a changing environment. Second, routing algorithms should interact with dynamic spectrum allocation routines to choose the routing paths through which the generated interference is minimized.

The concept of using different frequencies for different links is not completely new. In general, this approach is related to the frequency allocation problem, which is also considered in the context of dynamic industrial, scientific, and medical (ISM)-band operations [165]–[167]. However, the use of dynamic spectrum allocation increases the degrees of freedom and the need for quick adaptation. Several classical packet routing algorithms, particularly algorithms that are developed in the domain of *ad hoc* networks, take into account the fact that links may be unreliable [168]. However, the introduction of dynamic spectrum allocation changes the problem. Similar to the case of mobile *ad hoc* networks, we also have to consider the possibility that unidirectional links appear in the routing graphs. The difference for CRNs is that unidirectional links may become significantly more probable than for *ad hoc* networks. In the case of joint coding or multihop routing, there is also a natural issue on trusts and cooperation. However, we leave the trust issue out, because it has been a widely studied topic and is slightly out of the scope of this paper [169]–[172].

Spectrum-aware routing, also called opportunistic spectrum routing, has been considered by several authors [173]–[176]. The concept allows a source node to efficiently and practically explore the cooperative diversity on the commodity hardware of multiradio systems/networks, with the significant throughput performance gain advantage. This approach naturally requires a support from intermediate (relay) nodes. In other words, opportunistic routing takes advantage of the numerous yet unreliable wireless links in a wireless cooperative network in a probabilistic manner. It is very similar to the well-known cooperative communications, but this time, we exploit the concept at the level of networking structure and routing plane.

The idea of opportunistic routing and the expected transmission count (ETX) metric in the context of *ad hoc* networks are well-known ideas [177]–[179]. A number of elaborate schemes build on this approach and other earlier ideas to enable opportunistic spectrum routing. Medium-access-control-independent opportunistic routing (MORE) provides opportunistic routing through the network-coding approach [174]. Without a global medium access scheduler, the forwarder can exploit spatial reuse, and the algorithm is extended to multicast. Spectrum-aware network coding has also been studied in [180] by considering interference power constraints to the PUs within the service area of the secondary network.

The stability-aware routing protocol (STRAP) has been developed for multihop DSA networks and can utilize unused frequency bands without compromising the stability of the network [181]. Another proposal is the spectrum-aware routing protocol (SPEAR), which can establish robust paths even in the diverse spectrum environment with rather stringent latency conditions [182]. Spectrum-aware on-demand routing for CRNs was also considered by Cheng *et al.*, where the on-demand-based approach has been adopted with cumulative path delay estimation [183]. The routing and spectrum allocation (ROSA) algorithm is one of the recent proposals for enabling throughput maximization in this context, taking care of the interference minimization and maximizing the weighted sum of differential backlogs so that the system stays stable [184]. See a related work in [185] and the references therein.

Spectrum-aware mesh routing (SAMER) in CRNs is based on a mesh network framework where the routing algorithm passes traffic across paths with higher spectrum availability and opportunistic performance [186]. In general, the spectrum-aware routing problem is also related to interference-minimizing routing; for example, see [187]. Moreover, the problem is often considered a part of interference minimizing networks, where frequency and also transmission control are parts of the optimization parameters [188], [189]. Finally, by incorporating the nature of opportunistic links into the routing design, it is shown in [190] that a more effective routing algorithm can be designed in terms of delay performance.

B. *Statistic* QoS *Control*

In addition to routing, a successful CRN requires QoS control, error control, congestion control, and topology control. To handle these mechanisms over CRNs that consist of opportunistic links, "statistical control" may be used to serve our purpose. With the statistics of the node-to-node availability, the statistical QoS control [191] and the control of delay [192] are practical alternatives for end-to-end services in CRN operations. We can also apply this scenario to CRN tomography [193] to obtain information useful to routing. To infer such prior knowledge or estimation of node-to-node availability that is associated with cooperative relay(s), we may observe the history and statistics of successful packet transportation over a specific cooperative relay path. Because there involves packet transmissions (either implicit traffic packets or explicit probing packets) over multiple links, an active CRN tomography at the network level can be implemented based on traffic patterns. Considering a scenario with a set of possible cooperative relay paths among coexisting systems, the source node estimates the success probability of packet transmission according to the historical record from the reception of the destination node.

The control and autonomous adaptation of PHY-layer parameters have also been considered by several research groups, typically centering at the concept of cognitive engine [194], [195] or a cognitive resource manager framework [196]. Lower level optimization and cross-layer operations in the context of QoS control have been considered by the same groups. This topic is also the area where Mitola's original cognitive cycle concept with learning capabilities becomes unavoidable.

C. *Error Control*

Link-level ARQ is difficult to implement over an opportunistic link in CRNs [197]. To construct an end-to-end hybrid automatic repeat request (HARQ) by combining information from multiple reception paths at the destination may be an attractive alternative as a generalization of macroscopic cooperative communications [197]. Incremental redundancy is generated through cooperative relay to exploit spatial diversity [198], although a bidirectional link is assumed. In CRNs, however, there exist several unidirectional links due to interference avoidance with the PUs. Link-level HARQ based on a feedback channel is generally unavailable. For this session-level HARQ, error control is performed at the session level (end-to-end) between the source and the destination. We generate a coded packet from a message packet at the source and divide the coded packet into several coded subpackets. Then, these packets are sent over different paths of CRNs. Decoding is only performed at the destination by combining the coded subpackets that it has received, which may not receive all transmitted packets. Link-level error control [acknowledgment (ACK) between each link] is, therefore, avoided. Each intermediate node amplifies and forwards packets to the next hop along its routing path. A session-level ACK/negative acknowledgment (NACK) is only generated by the destination node, provided that the original message is (not) successfully recovered. According to simulations, such HARQ can approach similar-level reliable communication similar to regular wireless communications without opportunistic links.

IX. Emerging Cognitive Radio Networks

CRNs have actively been developed in various standardization committees toward commercial applications. In December 2003, the United States Federal Communications Commission (FCC) adopted a Notice of Proposed Rulemaking and Order that sets forth proposals and seeks comment on the use and applications for CR systems. Following this notice, there is a significant upsurge in academic research and industrial application initiatives. For example, IEEE Std. 802.22 defines a standard on wireless regional area networks, which supports last-mile broadband wireless access over unused TV bands (also called TV white spaces) for large areas such as rural environments [134], [135]. In 2008, the FCC conducted phase-II tests on spectrum-sensing devices that are submitted by several organizations, including Adaptrum, the Institute for Infocomm Research, Agency for Science, Technology and Research (A*STAR), Microsoft, Motorola, and Philips. The performance on detecting the TV and wireless microphone signals was evaluated, and the results of the tests somehow helped the FCC to obtain firsthand information on how spectrum sensing can be used to protect the legacy systems. In November 2008, FCC approved the use of wireless devices in TV white spaces. With this approval, the IEEE 802 Executive Committee approved the following two study groups to work toward setting up new IEEE standards on TV white-space devices: One group is under IEEE 802.11, which standardizes wireless local area network (WLAN)-type white-space devices, and the other group is under IEEE 802.19.4, which studies the coexistence mechanisms and solutions that support all IEEE 802 family white-space devices. There are also activities on prototyping WLAN devices over TV white spaces; for example, see [199].

As the first CR standard, IEEE 802.22 is a centralized CR system with a frame structure that consists of a quiet period for supporting spectrum sensing. In fact, to protect the primary systems, such as TV transmission and microphone users, IEEE 802.22 has defined very stringent sensing requirements. Different sensing schemes discussed in Section II can be adopted, as long as they can meet the sensing requirements. The sensing-access tradeoff design methodology in Section V can be used to optimize the design of a quiet period to maximize the benefit of the IEEE Std. 802.22 system while protecting the primary systems.

For TV white-space applications, FCC's most recent ruling seems to be in favor of geolocation database solutions. This approach is, indeed, a safe scheme for protecting the TV broadcasters if such a database can provide the SUs the updated information about the available spectrum holes. For other types of PUs such as wireless microphone, it may be difficult for the database providers to acquire updated usage information about these PUs if these PUs are not required to do so. Therefore, spectrum sensing is still needed for the SUs to identify the spectrum holes to protect all types of PUs. Furthermore, spectrum sensing may become a service for companies to provide the database providers the updated spectrum-hole information.

The momentum also increases over the simple TV white-space use for considering CRNs as more general overlay networks. For example, the IEEE Standards Coordinating Committee (SCC) 41 has developed the IEEE 1900 standard on heterogeneous wireless networks [136]. The CR concept can be also applied into future cellular systems. For example, channel aggregation (also called carrier aggregation) is one of the key techniques that are adopted in Long-Term Evolution (LTE) Advanced. In [200], CR resource management is also applied to the femtocell networks of LTE Advanced. There is also an interest in the context of license-free secondary cellular operations that exploit vacant TV channels. Although the regulation and standardization in this domain are still very preliminary and there has been much speculation on what kind of applications and CRN concepts can commercially be built, the future of the field in this domain looks promising.

X. Economics of Spectrum Sharing

The concepts for enhancing spectrum utilization and spectrum management are theoretically promising. However, in practice, we have to consider that there are always costs related to exploiting spectrum opportunities. Moreover, there exists vulnerable period in spectrum sensing, and there is no reason for PUs to give away their spectrum privileges, unless some sort of incentives exist. The most straightforward incentives might be profit sharing from the spectrum-sharing mechanism. Consequently, the economics of spectrum management emerges as a critical issue for realistically deploying CRNs by balancing the interests among the PUs and the CR users. It is imperative to understand what the true value of spectrum opportunities is and which economic and business boundary conditions have to be considered.

Initial solutions for the SUs have been developed to successfully compete with each other in the limited and time-varying spectrum opportunities based on auction, given experienced dynamics in the wireless network [201]. Spectrum sharing among a PU and multiple SUs can be formulated as an oligopoly market competition and uses a noncooperative game to execute the spectrum allocation for the SUs [202]. Operating the SUs in a self-organizing (typically *ad hoc*) network has been considered to adaptively and efficiently allocate transmission powers and spectrum among the CR users according to ambient surroundings without disturbing the PUs [203].

A pricing-based collusion-resistant dynamic spectrum allocation approach has been proposed not only to optimize overall spectrum efficiency but to combat the collusion among selfish SUs as well [204]. The collusion behavior among the SUs may seriously deteriorate the efficiency for wireless networks. Three different pricing models (i.e., market-equilibrium, competitive, and cooperative) through the game theory among service providers and the SUs have been investigated [205]. The interaction between the PUs (or service providers) and the SUs who can adopt the spectrum acquisition by observing the variations in price and QoS offered by the PUs (or service providers) can be modeled as an evolutionary game [206]. A second-price auction mechanism has been adopted in spectrum pricing among the auctioneer (i.e., service provider) and the SUs and to maximize the revenue of the service provider while satisfying the QoS requirements of the SUs [207]. A novel efficient mechanism for multiwinner spectrum auction can efficiently improve spectrum utilization with collusion-resistant pricing strategies between the service provider and the SUs [208]. Because the collusion behavior among the SUs may decrease the revenue of service providers, [205] addresses the spectrum pricing in a CRN where multiple service providers compete with each other to offer spectrum access opportunities to the SUs under a QoS constraint for the PUs. The initial trial for considering all four parties that are involved in CRN operations (i.e. PUs, CR users, operators, and regulators to ensure the overall spectrum utilization efficiency) is given in [209] to ensure robust operation of CRNs that support every party's practical or economic interests. This mechanism is facilitated through the real-time Vickrey auction at the BSs of the PS to warrant gaining interests for each party involved in CRN operations. A general framework for truthful double spectrum auctions has been proposed to enhance the economical viability of OSA [210], and in this context, multiple parties can trade spectrum based on their *individual* needs. The proposed framework is aimed at guaranteeing improved spectrum utilization while also making auctions economically robust. Other recent papers and references therein include [208] and [211]–[216].

XI. Challenges and Open Questions

Overall, effective CR communications should exploit the available degrees of freedom in frequency, time, and space as much as possible and react to changes in these dimensions as quickly as possible. Incorporated with advanced PHY-layer transmission techniques, including multiple antennas and cooperative communications, spectrum efficiency can greatly be improved with enhanced system capacity. From the CRN perspective, if each node has such a cognitive capability, the end-to-end transmission efficiency can greatly be improved.

Due to space limitation, we have also left out some important topics such as security, trust, policy issues, spectrum auctions and CR aspects of cellular applications. The readers may refer to other publications in recent reviews [217], [218] and recent special issues, e.g., [219]–[222], that may cover some of these topics. Finally, the application of artificial intelligence to CR design can be found in [223] and [224].

There are still challenges and open problems for realizing effective and efficient spectrum sharing for CR communications as follows.

- *Common control channel*. There is a pertinent question on whether we need a common control channel for CR operations. A common control channel will pave the path to an easier way of enabling information exchange during spectrum sensing and access in CR networks. However, unlike conventional networks, a common control channel may not be available in the initial phase when spectrum holes are not sufficiently identified. Furthermore, an identified channel may be reoccupied by the PUs at any time, which may interrupt the coordinating messages if it is used as a common control channel. How we can set up and maintain the common control channel is particularly crucial for proper operations in CRNs.

- *Joint spectrum sensing and access*. Spectrum sensing and access are usually separately designed, because spectrum sensing achieves certain detection performance, whereas spectrum access mainly focuses on improving the system capacity based on the identified spectrum hole. However, the two aspects are inevitably coupled. For example, different transmission power levels of the CR users may require different decision thresholds in spectrum sensing, and *vice versa*. Furthermore, the joint design of multichannel sensing and distributed random access will be a challenging issue in CRN.
- *True opportunities and economy models*. We need to quantify the economic and engineering benefits of using CRN-based systems over the traditional wireless communications systems. In addition, the underlying network economy models need to be developed so that the commercial community can feel comfortable with CRNs. More spectrum measurements are required to understand how many of the spectrum holes are *commercially viable*. The low utilization does not necessarily mean that the SUs can use the opportunity in any economically sensible way.
- *CRN and CR implementation architectures*. The actual implementation architecture for supporting fully functioning prototypes needs a cross-layer design concept, and it becomes challenging to build. In particular, handling the coordination and control of various levels of protocol stack and enforcing cooperation among the CRs still require considerable research and development work.

XII. Conclusion

In this paper, we have provided a systematic overview on CR communications and networking. Due to the explosion of research and publications in this field, this paper had difficulty in covering all the related topics. Instead, our focus has been on the key elements of the PHY, MAC, and network layers of a CR user who operates in a CRN, as well as the interrelation among these elements across different layers. We hope that this paper can help researchers and practitioners have a cross-layer view on designing CRNs.

Acknowledgment

The authors would like to thank X.-W. Zhou of the Georgia Institute of Technology, G.-D. Zhao of Beihang University, and Dr. A. T. Hoang of the Institute for Infocomm Research, Agency for Science, Technology and Research, for their contributions to this paper and the anonymous reviewers for their comments, which have helped to greatly improve the presentation of this paper.

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