AN OVERVIEW OF COGNITIVE RADIO NETWORKS

1. INTRODUCTION

Radio spectrum needed for applications, such as mobile telephony, digital video broadcasting (DVB), wireless local area networks (WiFi), wireless sensor networks (ZigBee), and Internet of things, is enormous and continues to grow (1,2,3). This exponential growth is set to continue (4). For example, by 2019, the monthly mobile data traffic will exceed 24.3 exabytes, mobile devices per capita will be 1.5 and the average speed of a wireless connection will increase to 4 Mbps, over 59% of mobile connections will be from smartphones, and mobile-to-mobile connections will be the majority (4). Therefore, the demand for wireless connectivity, coverage, capacity, and services will continually expand. However, a critical bottleneck is the radio spectrum, a finite resource that cannot be readily expanded. For example, although theoretically ranging from 3 Hz to 3000 GHz, the entire spectrum is not usable; thus, the prime spectrum for current wireless standards may be roughly 1–5 GHz. This is because the spectrum below 1 GHz has already been reserved for applications such as radar, military communications, and terrestrial radio/television, while the spectrum above 5 GHz suffers from increased attenuation and atmospheric absorption. Therefore, the limited spectrum presents a roadblock for the rapid growth of wireless networks and users.

Now given this real, physical spectrum constraint, an obvious question is how efficient is the current use of spectrum? Quantitatively, spectral efficiency is measured in bits per second per Hertz (bps/Hz), which is the data rate that can be sent over a unit bandwidth. While this efficiency has steadily increased due to technical improvements, such as the use of higher order modulation and adaptive techniques (5,6), the rate of growth has decreased recently (7). Due to this saturation, improving spectral efficiency by other means is essential for the growth of wireless networks.

How do we improve the spectral efficiency of wireless networks as a whole? Before answering this question, we must look at the inefficiencies of current spectrum usage. First of all, spectrum is assigned in a fixed manner by national regulatory bodies, and their main principle is to avoid radio interference, which is achieved by dividing spectrum into bands (e.g., frequency division) that are allocated to one or more services. These radio services include mobile, satellite, amateur radio, navigation, and others (e.g., Table 1). A license gives an exclusive right to operate (transmit and receive wireless signals) in a specific frequency band, in a specific location or geographic area. But much of the licensed spectrum remains unused in practice at different times and/or locations. Those temporary spectrum slots (aka spectrum holes or white spaces) (8,9) can be as high as 15–85 % of the licensed spectrum (10). Clearly, to improve the overall spectral efficiency, unlicensed users can be allowed to access such spectrum holes. Thus, this fact suggests the need for opportunistic spectrum access without causing undue interference to licensed users (11,12). Such capability is the defining characteristic of cognitive radio (CR) nodes, which require algorithms and protocols for rapid spectrum sensing, coordination, and cooperation. In other words, CR nodes can recognize unused parts of spectrum and adapt their communications to utilize them while minimizing the interference on licensed users. Consequently, CR improves the overall spectrum usage, by moving away from static assignments into more dynamic forms of spectrum access.

Thus, to enable access to idle or underutilized spectrum, CR networks have already been standardized in IEEE 802.22 WRAN (Wireless Regional Area Network) and its amendments, IEEE 802.11af for wireless LANs, IEEE 1900.x series, and has also been a motivating factor for licensed shared access (LSA) for LTE mobile operators (13). Furthermore, test beds have been built to verify the feasibility of CR within LTE systems (14).

In the context of CR, licensed spectrum users are called primary users (PUs) and unlicensed users are called secondary users (SUs) or CR nodes (both terms will be used interchangeably henceforth.) Thus, SUs must opportunistically access spectrum holes, while keeping the interference on the PU receivers at either zero or below a prescribed level. The coexistence of a group of secondary CR networks and a primary network is shown in Figure 1.

CR networks can be divided into the following three paradigms (Figure 2) (15,16,17,18,19,20):

- *Interweave networks.* These operate on an interference free basis and hold true to the original premise of utilizing spectrum holes (e.g., spectrum slots or chunks which are vacant or underutilized within a given geographical area) (15). As soon as a spectrum hole appears, interweave devices can begin data transmission, but must end their transmissions when the sensing algorithms indicate that PU devices are resuming (17). Such algorithms include matched filter, cylostationary, signal energy or eigenvalues-based detection, waveform sensing, and beacon detection (21,22). Other schemes use out-of-band beacon transmissions (23) or geolocation databases (22,24). These will be described in detail subsequently.
- *Underlay networks.* In these, both PU and SU devices simultaneously transmit over the same spectrum slots (15,17,19,25,26). Thus, there is no need to detect spectrum holes. However, the interference temperature (Section 3.4) experienced by a PU receiver must be below a threshold. To reduce the interference temperature (19), the SU devices may reduce their transmit power, cancel interference, and implement nontransmitting regions (guard regions) around primary receivers (11,27). These regions can be enforced either through prior location information from a centralized controller using a geolocation database, GPS (Global Positioning System) data, or sensing pilot signals originating from the PU nodes (28,29,30).
- *Overlay networks.* These also allow concurrent PU and SU transmissions. However, the difference from the underlay mode is that SU devices must have knowledge about the PU transmitted data sequence

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 2017 John Wiley & Sons, Inc.
DOI: 10.1002/047134608X.W8355

Table 1. Existing Frequency Assignment for Different Services

Service	Frequency
E-GSM-900 (Mobile)	880–915, 925–960 MHz
DCS (Mobile)	1710–1785, 1805–1880 MHz
FM radio (Broadcasting)	88–108 MHz
Standard C Band (Satellite communication)	5.850–6.425, 3.625–4.200 GHz
Nondirectional radio beacon (Navigation)	190–1535 kHz

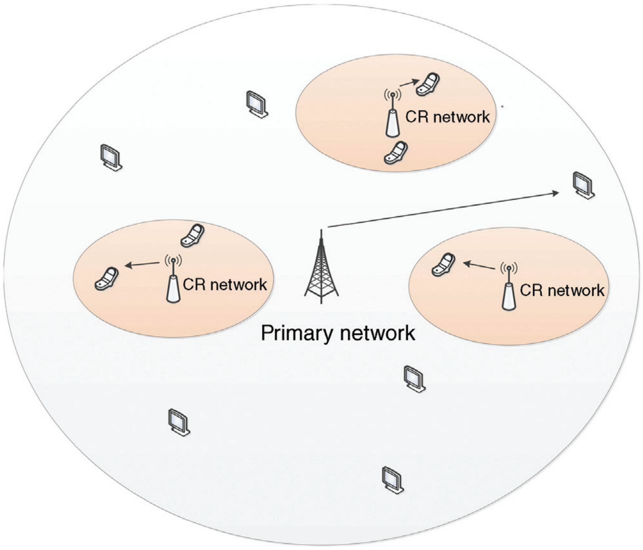

Figure 1. Cognitive radio (CR) networks existing within a primary network.

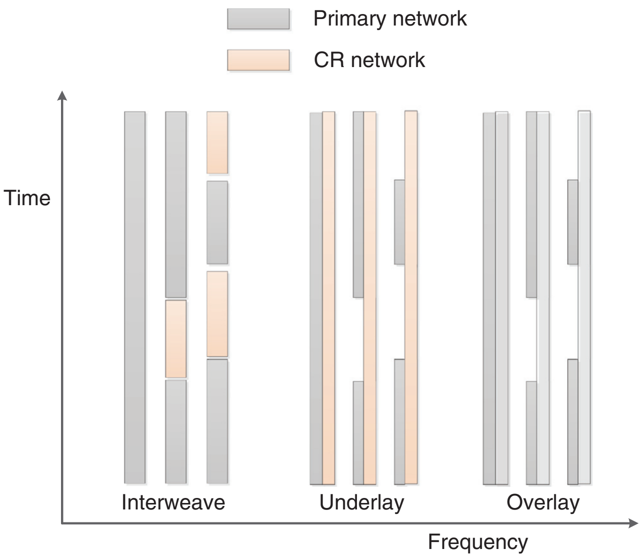

Figure 2. Interweave, underlay, and overlay modes of cognitive radio.

(e.g., message) encoding methods (code book) (17,19). This information can be utilized in two different ways. First, it can be used to cancel the PU interference on SU receivers, using canceling techniques such as dirty paper coding (DPC) that precodes transmitted data to negate the effects of interference (31). Second, it can be used by SU nodes to cooperate with the primary network by relaying PU messages.

2. COGNITIVE RADIO FUNCTIONALITIES

To enable opportunistic spectrum access, the key functions of CR networks are (1) spectrum sensing, (2) spectrum management and decision, (3) spectrum sharing, and (4) spectrum mobility (15). These are briefly described next.

2.1. Spectrum Sensing

This refers to detecting spectrum holes accurately. Furthermore, it must be ongoing and continuous such that whenever the PU reaccesses the spectrum, it indicates to CR nodes to cease transmission immediately. It can be implemented via in-band sensing, out-of-band-sensing, and geolocation databases (Section 3). It also helps to adjust additional parameters such as power levels, codes, and frequencies in order to limit unwanted interference (15).

2.2. Spectrum Management and Decision

When multiple spectrum holes are distributed over a wide frequency range (15), spectrum management involves selecting the best possible one. The choice is made by considering transmit power, bandwidth, modulation schemes, coding schemes, and scheduling (15). The choice also depends on Quality of Service (QoS) criteria for the needs of CR communication, such as packet error rate, latency, and throughput, and these can be based either on the optimality for a single pair of communicating nodes or for a whole set of CR devices. In the latter case, a central entity makes the decisions and disseminates those to the participating nodes.

Before a spectrum decision can be made, the available spectrum holes must be characterized based on the following factors (10,15):

(a) Interference on the primary network: The potential interference on primary network when using a spectrum hole depends on several factors. For a given spectrum hole within a specific geographical area, there may be adjacent PUs, which also could be subject to interference. Furthermore, underlay nodes can transmit even with PU activity. In addition, even if a nearby PU transmitter is silent, it may reaccess the spectrum hole at any moment. If multiple spectrum holes exist that are otherwise equal apart from potential interference to the PUs, the one with the lowest potential interference must be chosen.

(b) Mutual CR interference: This occurs when multiple CR nodes access the same spectrum hole. Thus, the level of their mutual interference is a factor in choosing the spectrum hole. Low potential interference levels permit the use of higher transmit powers, and thus higher order constellations such as 256 QAM (quadrature amplitude modulation) may be used instead of lower order QPSK (quadrature phase shift keying).

(c) Holding time: This is the time period a CR node occupies a spectrum hole before having to release it due to the reentering PUs. Large holding times enable uninterrupted CR communication.

(d) Frequency band: The frequency range of available spectrum holes is important in many aspects. First, high frequencies increase free space path loss, requiring an increase of transmit power levels. However, this reduces the battery life and energy efficiency. Especially for handheld cell phone devices, increasing power may not be viable, and thus the CR communication range decreases rapidly. Second, higher frequency bands, such as the millimeter wave frequency band (30–300 GHz), suffer additional channel impairments such as blockages due to objects, because at such frequencies signals exhibit weak scattering properties. Third, certain frequencies are highly attenuated due to oxygen absorption at 60 GHz or water vapor absorption at 24 GHz. Overall, spectrum holes in such frequency bands are not highly desirable.

(e) Channel capacity: This is the theoretical maximum data rate supported by a given channel. The channel capacity C in bits per second is given by the following well-known Shannon formula:

$$C = B\log_2\left(1+\frac{S}{N+I}\right) \tag{1}$$

where B is the bandwidth in Hertz, S is the received signal power, N is the noise power at the receiver, and I is the interference power at the receiver. The units of S, N, and I are Watts. The channel capacity is a main criterion for making spectrum decisions (15).

Taking all these factors into consideration, there are three ways to perform spectrum access decisions: (1) centralized, (2) distributed, and (3) cluster based (10,32).

- Centralized decision-making. This involves a fusion center (FC), which can be an access point, a base station, sink node, or a central controller. The FC collects individual spectrum sensing results from different SUs and those by itself. It may also use a geolocation database that lists the spectrum activity of PUs within different geographical areas (Section 3.1). Finally, by appropriately combining all these results, it decides if PU signals are present or not, thereby identifying spectrum holes.
  The main advantage is that a centralized process can take into consideration multiple factors such as optimizing the overall network throughput, reducing intranetwork and internetwork interference, ensuring fairness among SU devices, and prioritizing critical devices with added resources (32). However, the centralization requires high overhead due to SU nodes sending their sensing results and location information and receiving spectrum access, power levels, scheduling, and other information from the FC. This overhead grows as the network gets denser and more congested. Furthermore, this process needs a dedicated control channel with reserved spectrum slots and energy, thus reducing the overall spectral and energy efficiency. Finally, this extra energy expense may not be feasible for small handheld, battery-powered SU devices.
- Distributed decision-making. This refers to each SU making its own spectrum access decisions. This may be a preferred way for nodes in ad hoc networks without any base station or a centralized controlling entity. In this approach, each SU node has complete control on the decisions, which can be taken to maximize a suitable performance measure. Moreover, decisions suffer little latency. To sudden changes in spectrum activities, the node can make real-time responses without having to wait for the FC. However, those locally optimal decisions may not be optimal for the network as a whole. Furthermore, incorrect decisions will risk the interference on both primary and SU networks. The chances of this occurring are lower with centralized decisions.
- Cluster-based decision-making. A group of nearby CR nodes may form clusters, and a cluster head among this group makes spectrum decisions (32). This approach has the advantages of both distributed and centralized schemes while limiting disadvantages. The cluster size can be kept small enough to reduce control information transfers, but large enough to make decisions optimal for an area. Consequently, clustering reduces the power requirements for the transmission of control signals.

2.3. Spectrum Sharing

Spectrum sharing refers to the fair division of spectrum holes among different CR devices. It is based on scheduling and may be performed in time, frequency, code, and even space dimensions. It is also designed to avoid unwanted intranetwork interference (10). It can be centralized or distributed. In the former, a central entity controls access and allocation by using the sensing results it receives from distributed nodes. This entity computes the spectrum decisions. In the latter, without a central entity, each node makes spectrum decisions based on local information and rules.

In a broader sense, spectrum sharing can involve not only CR devices but also PU nodes. This situation is mostly applicable to the underlay CR mode where concurrent transmissions occur. In such cases, priority should always be given to the PU.

2.4. Spectrum Mobility

This refers to the ability of CR nodes to hop among different spectrum holes seamlessly depending on the conditions. These include PUs reaccessing the spectrum hole, adverse channel conditions within the current frequency band, or increasing bandwidth to cater to a higher demand for data rate among others. The transition between different spectrum holes is referred to as a spectrum handoff (15). These are analogous to traditional cellular handoffs where a mobile transfers to a different serving base station (with different codes/time, slots/frequencies, etc.) when the conditions of the current cell deteriorate. However, handoffs should be seamless to avoid CR outages or latency.

3. IDENTIFICATION OF SPECTRUM OPPORTUNITIES

As mentioned before, unlicensed SU devices can opportunistically access spectrum holes. Holes may exist in vacant, underutilized, or occupied spectrum. Vacant spectrum is where PU activity is absent within a particular geographical area (19). For example, this may occur when the licensee does not use the spectrum in a specific location or geographic area. Underutilized spectrum occurs when PU activity is only present within certain times, but absent during others. For example, cellular frequency slots may be idle at times depending on traffic levels. Even PU-occupied spectrum can be accessed by CR devices under certain conditions. For example, transmit beamforming allows the signals to focus toward the intended receiver without interfering on other devices. The PU spectrum can thus be used at the same geographical location by CR devices without mutual interference (19).

Spectrum identification techniques include geolocation databases, in-band sensing, out-of-band sensing, interference temperature-based detection, and co-operative sensing (15,19,33,34). We will elaborate on these schemes next.

3.1. Geolocation Databases

Having first measured its geographical location, an SU queries a geolocation database for a list of available frequencies at this location. The database may also supply additional information such as the associated maximum permitted transmit power levels for each of available frequencies and the validity time of the provided parameters (20,34).

These centralized databases store up-to-date information about spectrum usage within different geographical areas to identify spectrum holes readily (20,34). These databases may be administered by the regulators, who will have final say on whether a particular CR device is allowed to access regulated spectrum. With such centralized schemes, each CR device connects to the decision-making entity (base station or an access point) while this entity in turn communicates with the database through a backhaul channel.

A given geographical area is divided into a grid. Spectrum usage pattern is stored in the geolocation database. The size of the grid impacts both the performance and data transfer rates. With large scaled grid, the spectrum information might be inaccurate. Too fine grid will likely increase computational complexity and data transfer. With the database, the location of the SU can be tested for PU activity in all frequency bands. Thus the spectrum holes (if exist) can be indicated to the SU. For a more conservative allocation, even the blocks adjacent to the location of the SU can be tested before a positive response is given (34).

However, this approach has several complexity issues. First, precise determination of the location of the SU is crucially important. Because at any location errors increase the risk of the interference on licensed users, the SU should maintain this accuracy while in operation. For this purpose, Global Positioning System (GPS) or transmitting pilot signals to location-aware nearby users or base stations in order to perform triangulation calculations may be required. Second, geolocation-based systems are not robust to rapid network changes, but are ideal for relatively static primary systems such as digital terrestrial television networks. In such systems, the locations of primary base stations, and their activities are readily available beforehand. In contrast, heterogeneous cellular networks present a more complicated situation (10,35). Although legacy macro base station information can be easily stored, this is not possible for new nano and femto cells. These smaller access points have low power and are located within user premises. These micro base stations can be either active, inactive, or partially active without prior knowledge. Furthermore, their locations can also change without any prior warning. Third, geolocation databases may not be able to capture temporal opportunities (34) where some time–frequency slots are available dynamically. Fourth, the latency (34) in a dynamic wireless environment may lead to loss of spectrum opportunities. Fifth, implementation complexity can also be an issue. The database must cater to hundreds or even thousands of CR devices that require feedback. Furthermore, it has to communicate with multiple primary devices regularly to ensure robustness. Finally, a central database presents a single point of failure.

3.2. In-band Sensing

In-band sensing refers to the direct measurement of the primary band by an SU device that is trying to access or is currently using this band. While in-band sensing is best suited to use with distributed decision-making, it can also be adapted for centralized decisions. A major disadvantage is that it relies upon the detection of primary transmitters, but cannot identify the presence of primary receivers (which are silent, nontransmitting nodes) which are the entities actually affected by interference (Figure 3). This applies to broadcast-based schemes such as digital terrestrial television and frequency division duplexing based schemes. Therefore, in-band sensing can only establish the presence of a transmitter within a given range, but not location of primary receivers. Therefore, having not detected a primary transmitter, when SU transmits on the band, there can be interference on nearby primary receivers. This is called the hidden terminal problem (34).

In-band spectrum sensing techniques include energy detection, cylostationary feature detection, eigenvalue-based detection, matched filter detection, p-norm detection, and Anderson–Darling sensing (36). Other schemes such as filter-based sensing (37), fast sensing (38), learning-based sensing, measurement-based sensing, and diffusion-based detection schemes (36) have also been proposed. We will elaborate on some of these schemes below.

Energy Detection. An energy detector computes the energy level of a signal over a target frequency band and compares to a threshold (36,39,40). If the computed energy

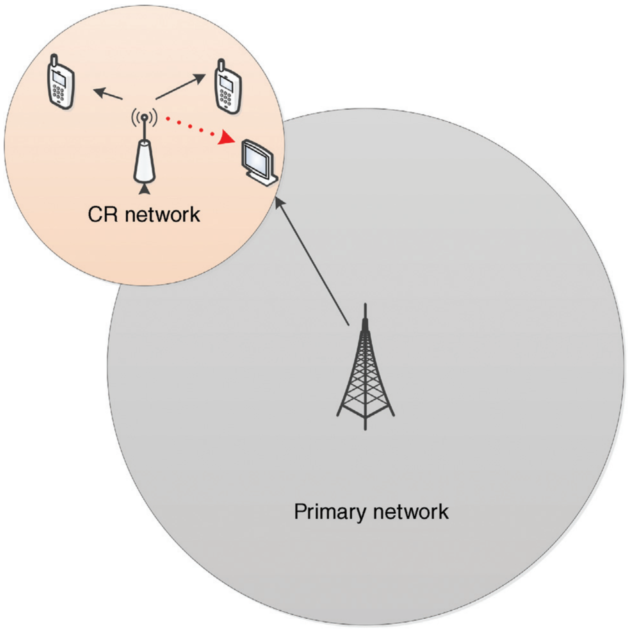

Figure 3. Interference from a CR transmitter to a primary user (PU) receiver. The PU transmitter is beyond the sensing range of the CR transmitter, however, the primary receiver is still within the range.

is below the threshold, the spectrum band is identified as a spectrum hole; otherwise, the band is identified as occupied (41,42). This detector is optimal under the presence of additive white Gaussian noise (AWGN) and when no prior information is available about the PU signals.

The energy detection problem can be formulated as a choice between two hypotheses. The first is that there is a spectrum hole (i.e., no primary signal is present) ($\mathcal{H}_0$), and the second is that a primary signal is present ($\mathcal{H}_1$). $\mathcal{H}_0$ and $\mathcal{H}_1$ may be written as (19),

$$y(t) = \begin{cases} n(t) & \mathcal{H}_0 \\ hx(t) + n(t) & \mathcal{H}_1 \end{cases} \tag{2}$$

where $y(t)$ is the received signal, $x(t)$ is the transmitted PU signal, h is the fading coefficient, and $n(t)$ is the AWGN term. By processing the samples of $y(t)$, the energy detector chooses either $\mathcal{H}_0$ or $\mathcal{H}_1$.

This choice depends on the energy (Y) of the received signal. The energy measure may be given as the squared sum of the output samples of a band-pass filter corresponding to the frequency band surveyed. We may thus write Y as

$$Y = \frac{1}{N}\sum_{i=1}^{N} |y_i|^2 \tag{3}$$

where N is the number of samples and y_i is the ith sample. Using the threshold λ, $\mathcal{H}_1$ is taken to be true if $Y > \lambda$, and $\mathcal{H}_0$ is taken to be true otherwise.

The performance of the energy detector (and other spectrum sensing schemes) is measured by the probabilities of false alarm (P_f) and missed detection (P_m). P_f is the probability that $\mathcal{H}_1$ is taken to be true when $\mathcal{H}_0$ is true (e.g., the detector output declares a PU signal when it is actually not present), while P_m is the probability of not detecting a PU signal when it is present. These two probabilities are expressed as (43)

$$P_\mathrm{f} = \Pr[Y > \lambda | \mathcal{H}_0] \tag{4}$$

$$P_\mathrm{m} = \Pr[Y < \lambda | \mathcal{H}_1] \tag{5}$$

Ideally, a detector should aim for low P_f and P_m. For example, IEEE 802.22 prescribes P_f and P_m to be less than 0.1 (44). A higher false alarm probability results in a loss of potential spectrum access opportunities, a failure to improve spectral efficiency. Furthermore, fewer frequency bands are then available for CR transmissions, and QoS issues may occur. A high missed detection probability results in SU devices transmitting concurrently with PUs, which will generate interference on the primary network. Conversely, the PU signal will interfer on the SU devices.

The performance of an energy detector (or that of other detectors) is typically characterized using the receiver operating characteristic (ROC) curve (45). This is the plot of the detection probability $(1 - P_\mathrm{m})$ versus the false alarm probability (P_f) for different detection thresholds. Moreover, the area under the curve (AUC) of the ROC plot can also be of interest (45). The performance of the energy detector has been investigated in References 46 and 47, among other papers.

The main advantages of the energy detector are the ease of implementation, low computational complexity, and the lack of need for PU signal information (15). However, it has several shortcomings. First, there is a lack of resilience against noise uncertainty, which refers to changes in the system noise floor with time (48). Such random fluctuations increase both missed detection and false alarm probabilities, and moreover the threshold λ is chosen assuming a fixed noise floor. Second, it is vulnerable to interference from cochannel transmitters, which could be other primary or secondary devices in adjacent areas. Third, it cannot identify different primary signals apart (43). Thus, signals from unknown sources may increase the probability of false alarm (19). Finally, it performs poorly in low SNR (signal-to-noise ratio) (49,50).

Cyclostationary Feature Detection. This detector will exploit the periodicity of the statistics such as mean and autocorrelation of PU signals (15,19). The periodicity arises due to the features of PU modulation, up conversion to passband signals, cyclic prefixes, codes, hopping sequences, and other factors. Consequently, this phenomenon is termed as cyclostationarity. Moreover, it is not present in additive noise signals. As such, this detector will work even when the primary signal is embedded in significant noise. On the other hand, if periodic features are deliberately introduced (e.g., cyclic prefix), this detector performs even better. Another advantage of this detector is the ability to differentiate between different primary systems with differing transmit features.

This detector will thus use the cyclic autocorrelation function and transform it to the cyclic spectrum density in order to conduct a hypothesis test in the frequency domain (19). The cyclic autocorrelation function $R_{yy}(\alpha, \tau)$ is given by

$$R_{yy}(\alpha,\tau)=\lim_{M\to\infty}\frac{1}{M}\sum_{t=1}^{M}E[y(t)y^{*}(t+\tau)]\mathrm{e}^{-j2\pi\alpha t}\mathrm{d}t, \tag{6}$$

where $y(t)$ is the received signal, $E[\cdot]$ is the expectation, $y^{*}(t)$ is the complex conjugate of y, and α is the cyclic frequency. The cyclic spectrum density function in the frequency domain is written as (19)

$$S(f,\alpha)=\sum_{\tau=-\infty}^{\infty}R_{yy}(\alpha,\tau)\mathrm{e}^{-j2\pi f\tau} \tag{7}$$

However, the major disadvantages of this detector include the complexity, high sampling rate, and the requirement for a large amount of samples, which necessitates a high observation time (15). Moreover, timing and frequency offsets can reduce the degree of correlation, which in turn affects the periodicity of the received signal. In addition, when the primary network employs orthogonal frequency-division multiplexing (OFDM), identifying different primary systems is not readily possible (19). As a remedy, introducing different cyclic properties to different primary systems occupying the spectrum has been proposed (19). The complexity of this method renders it unsuitable when the SU devices are simple low-powered devices.

Matched Filter Detection. A matched filter is obtained by correlating a transmit signal with the received signal to detect the presence of the transmit signal. Equivalently, the received signal is convolved with a conjugated time-reversed version of the transmit signal. The matched filter is optimal in the sense of maximizing the SNR in the presence of additive Gaussian noise. The decision variable Y can thus be written as (51)

$$Y=\sum_{i=1}^{N}y_i x_i^{*} \tag{8}$$

where N is the number of samples, y_i is the ith ($i=1\ldots N$) sample of the received signal, and x_i is the ith sample of the transmitted primary signal. This method requires the prior information about the transmitted primary signal such as modulation format, pulse shapes, phase, and others (43). To enable such coherent processing, primary devices will have to transmit pilots periodically (43). This detector has the main advantage of a lower sensing time to achieve a certain level of required performance (19).

However, when the noise increases, it performs poorly, and the number of samples required for a particular level of performance increases (19). Furthermore, if the prior information is incorrect, it performs poorly. Furthermore, when spectrum holes are dispersed over a wide span of spectrum, different PU signals over different frequency bands must be correlated. Prior information about such disparate PUs may be unrealistic. In addition, the performance also drops when different PUs are present in the same band. While having a dedicated matched filter structure for each PU is possible, this increases the receiver complexity (36,52). Nevertheless, the matched filter detector remains the best way for CR spectrum sensing when information about the primary signal is known beforehand (19).

Eigenvalue-Based Detection. This method uses eigenvalues of the covariance matrix of the received signal to obtain the ratio between the maximum and minimum eigen values, which in turn is used to detect the presence of primary signals in the presence of noise and without prior knowledge of the signal, channel, or noise power (53). The covariance matrix of the received signal can be written as (53)

$$R_X=E[\hat{x}(i)\hat{x}^{H}(i)] \tag{9}$$

where $E(\cdot)$ is the expectation operator, $\hat{x}(i)$ is the received signal vector at sampling instance i, and $\hat{x}^{H}(i)$ is its Hermitian (conjugate-transpose). The decision variable would thus be

$$Y=\frac{\lambda_{\max}}{\lambda_{\min}}, \tag{10}$$

where $\lambda_{\max}$ and $\lambda_{\min}$ are respectively the maximum and minimum eigenvalues of R_X.

When noise is the only component present in the received signal, this ratio tends 1 while it increases when PU signals are present (43). Eigenvalue-based detection works well under low-received signal to interference and noise ratios, different fading models, and noise uncertainty. However the computational complexity is high with regards to covariance matrix formulation and eigenvalue decomposition (54). This detector may also fail when the samples of primary signals are uncorrelated (36).

***p*-norm Detection.** This is a generalization of the classical energy detector described earlier. Similar to equation 3, the decision variable of this detector can be written as (55)

$$Y=\frac{1}{N}\sum_{i=1}^{N}|y_i|^{p} \tag{11}$$

where N is the number of samples, y_i is the ith sample, and $p\in\mathbb{R}$. Clearly, the case $p=2$ yields the energy detector. However, rather than fixing p at 2, it can be optimized depending on the received SNR for the probability of false alarm, probability of correct detection, and signal sample size. Such adaptive optimization of p is shown to give significant performance gains over the energy detector (55).

Wideband Spectrum Sensing. These techniques allow for sensing spectrum blocks greater than the coherence bandwidth of the channel whereas narrowband sensing generally outputs a binary decision on spectrum occupancy for a narrow band (56). These techniques are especially critical in the UHF (ultra high frequency) band between 300 MHz and 3 GHz and the upcoming millimeter wave frequency band above 3 GHz. They can be classified according to the sampling rate. If it is greater than the Nyquist rate, we have Nyquist wideband spectrum sensing, otherwise sub-Nyquist wideband sensing (57,58).

Anderson–Darling Sensing. This is a goodness of fit test for spectrum sensing, and the test statistic is given as (59)

$$A_c^2 = -\frac{\sum_{i=1}^{n}(2i-1)(\ln(Z_i) - \ln(1 - Z_{n+1-i}))}{n} - n \qquad (12)$$

where $Z_i = F_0(Y_i)$, and $F_Y(y)$ is the empirical cumulative distribution function given as

$$F_Y(y) = |\{i : Y_i \leq y, 1 \leq i \leq n\}|/n \qquad (13)$$

where $|A|$ is the cardinality of set A. This method can check whether the samples of the received signal are from a noise distribution ($\mathcal{H}_0$) or whether they are from primary signals in the presence of noise ($\mathcal{H}_1$). If the test statistic is greater than a certain threshold t_0, $\mathcal{H}_0$ is selected, otherwise $\mathcal{H}_1$. Moreover, for a primary signal static over the observation interval, the Anderson–Darling test outperforms the energy detector (59).

3.3. Out-of-Band Sensing

Unlike in-band sensing, this does not involve directly sensing the frequency band for which spectrum access is required. Instead, a dedicated out-of-band control channel tells whether the frequency band is occupied or not by PU devices. To this end, on the control channel, PU receivers or transmitters send beacon signals. For example, such beacons have been proposed for IEEE 802.22.1 (60) and are the most suitable for CR implementation in a cellular system (34). The SU devices detect beacon signals by comparing the received signal power in the control channel with a threshold level.

Beacon signaling is efficient and simple (61,62,63). The beacon signals are simply narrowband electromagnetic waves modulated by on–off switching (64), do not necessarily have to be continuous, and can be transmitted periodically, which will reduce additional power requirement for the PUs. Furthermore, beacon detection circuits can be relatively simple. In addition, the beacon signals can be used to separate different primary devices using different time slots or orthogonal codes. Individually identifying different primary devices is not readily possible in many in-band spectrum identification strategies, including energy detection. Furthermore, beacons provide added control mechanism to the primary devices, which can actively allow or prevent CR spectrum access dynamically. This is however not possible with in-band schemes.

Beacons can be transmitted by either primary transmitters or primary receivers. With the former, transmit power is not limited. For example, primary base stations are powered by the national grid, but handheld PU receiver devices are battery limited. Since main goal is to limit interference on primary receivers, beacon transmissions from them can help to identify their locations and avoid the hidden node problems. For example, these occur when the CR device is out of range of the primary transmitter, but not from the primary receiver.

Beacon signals can be permission or denial type (65,66). Permission (grant) beacons indicate the absence of primary activity and thus allow SUs to transmit, while denial beacons indicate otherwise. Denial beacons appear more feasible simply because the active primary device can transmit them simultaneously with its own data transmissions. Denial beacons become problematic if the primary device goes into a sleep mode, loses power, or turns off. However, the reliability of beacon signaling can be further increased by dual beacons that combine grant and deny beacons, and can be implemented using the IEEE 802.11 standard (64).

If the beacons are not individualized to make the sender identifiable, aggregating beacons coming from all the primary devices can be used to access the spectrum. However, if individual beacons are identifiable, other beacon processing techniques emerge. For example, beacons from individual primary devices (usually the PUs within a specific geographical area such as a cell) can be checked, and a decision can be made if no individual beacon is sensed. Moreover, as a less conservative approach, only the beacons from the nearest or $M > 1$ nearest primary devices can be sensed to make a spectrum decision.

The main drawback of out-of-band sensing is the use of additional spectral resources in the form of the beacon channel and power transmit beacons. Moreover, due to multipath fading, shadowing and path loss, and receiver uncertainty, SU devices may not correctly detect beacons, which runs the risk interference on PUs. While increasing the beacon transmit power is an obvious answer, the energy efficiency of the system will then decrease. In addition, the prevention of beacon reception outside its intended coverage area (33) is important in order to increase the spectrum available to SUs. Furthermore, if the licensed spectrum has several different sub-bands, beacon signaling will lose its simplicity.

3.4. Interference Temperature

The concept aims to capture the interference interactions between primary and secondary users. Using it, both interference impact on licensed users and also achievable capacity for the underlay network can be quantified. That it is a receiver-centric concept is especially important because the interference actually affects the primary receivers rather than primary transmitters. Furthermore, what matters is the sum interference from multiple CR devices, other cochannel primary transmitters, and unknown third party transmitters. Interference temperature-based spectrum identification is especially attractive for the underlay CR devices that do not actively sense the spectrum.

The FCC (Federal Communications Commission) Spectrum Policy Task Force has thus introduced the interference temperature (15), which is defined as the temperature equivalent of radio frequency power available at a receiver antenna per unit bandwidth (19,67). The interference temperature in Kelvin may be expressed as

$$T = \frac{P_{\rm I}(f_c, B)}{kB} \qquad (14)$$

where $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, B is the bandwidth of the channel, and $P_{\rm I}(f_c, B)$ is the interference power centered around f_c over a bandwidth of B (19). The main idea behind the interference temperature model is to jointly characterize both interference and noise (68). It is shown in Reference 69 that typical values for interference temperature range roughly from 0 to 2 K depending on the number of antennas. For a given geographic area, one can establish an interference temperature limit, T_l, which is the maximum amount of tolerable interference for a given frequency band. Any CR device utilizing this band must guarantee that their transmissions added to the existing interference must not exceed T_l at a licensed receiver (68).

In an interference temperature-based scheme, CR devices are allowed to access the spectrum as long as the interference temperature of the primary receiver is below T_l. The interference experienced at a primary receiver becomes noise impulses superimposed on the noise floor. These spikes are tolerable until an acceptable interference temperature level beyond which they degrade performance. The interference temperature level of a particular primary receiver can be independent from corresponding values of other receivers (70) depending on specific receiver characteristics. In such a scenario, the CR network needs prior information about interference temperature levels of each receiver or the level of the device having the lowest threshold. Conversely, the interference temperature limits can be set by a regulating authority for certain frequency bands.

While spectrum opportunities can be identified by monitoring the interference temperature, a major drawback is that real-time estimations of it are difficult. As a remedy, PU receivers may provide feedback to potential SU devices. While this requires a centralized CR network, it may be infeasible within a decentralized or ad hoc CR network. In a centralized CR network, a global maximum transmit power can be set, which can then be adjusted according to the feedback on interference temperature received from the primary network. The other method for each CR transmitter is to make a probabilistic estimate about the interference temperature at a primary receiver. However, locations of the primary receivers must be known in advance for such an estimate (19).

3.5. Cooperative Sensing

This refers to several SUs sharing their local spectrum sensing results for an overall decision. Thus, it achieves better sensing performance by exploiting spatial and multiuser diversity in wireless networks (19,33,66,71,72). Furthermore, minimizing the detection error and reducing individual sensing times are possible (73).

Due to wireless channel impairments, such as multipath fading, shadowing, and path loss, a CR node may not be able to detect a spectrum hole through either in-band or out-of-band sensing, which may result in the hidden terminal problem (15,34,43). That is, CR devices could not differentiate between the primary signal and noise for in-band sensing and the beacon signal and noise for out-of-band sensing, and misidentify spectrum holes and thus interfere. As an example, consider CR devices with in-band detection scheme such as energy detection. If the path between the primary transmitter and the CR node is blocked by an obstruction, the CR node will sense a spectrum hole. But suppose the link from the CR node to the primary receiver is clear. Then CR transmissions will cause interference to the primary receiver. However, there may be other CR devices within line of sight from the primary transmitter which are able to correctly identify spectrum (Figure 4). Cooperation between these devices prevent the blocked CR node from incorrectly identifying the spectrum as vacant. Thus, this is the motivation for cooperative sensing.

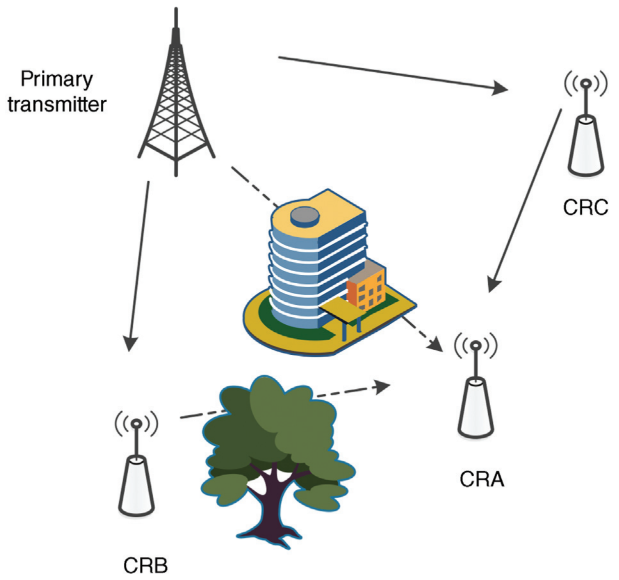

Figure 4. The primary transmitter is blocked to CR-A, but not for both CR-B and CR-C. However, CR-B is blocked by a tree. Thus, CR-A must cooperate with CR-C

Cooperation techniques among secondary nodes can be broadly classified as data fusion and decision fusion (21). In data fusion, a node amplifies and transmits the sensed information, while in decision fusion it makes a spectrum occupancy decision, which is then broadcast. With data fusion, a node may either share all the sampled information or a summary (43), and soft decisions combining such as the likelihood ratio test can be used. However, with decision fusion, each node makes a binary decision about PU spectrum occupancy, which is shared. These hard decisions are combined using the AND, OR, or majority rules (21,34). With the AND rule, if all cooperating devices indicate a PU channel occupancy, then the spectrum is designated as occupied. On the contrary, with the OR rule, the same decision is reached even with a single occupancy indication by a cooperating device. Thus, the OR rule is more conservative in allowing spectrum access. With the majority rule, a majority of cooperating nodes must indicate spectrum occupation.

However, cooperation among secondary nodes faces challenges. These include the added complexity and implementation issues. CR devices will need additional resources to (1) select optimum neighbor nodes for cooperation, (2) send their own sensed information/decisions to the cooperating nodes, and (3) fuse information from the cooperating nodes and its own to make a decision on spectrum occupancy. As such, there is additional overhead to the entire CR system (34). Ideally, for such information sharing among SUs, a separate dedicated control channel is required. However, without priority access to spectrum, CR networks may not be able to implement the control channel. Another issue with cooperative sensing is the presence of asynchronous sensing information (43). Different CR devices may have performed their individual sensing at different times. As such, some of the information shared may not be up to date. For example, a certain CR device may be reporting an idle channel, when it is in fact in use by a primary node. In addition, the sensed information is transmitted on a reporting channel with errors (43). Due to the signal corruption in this channel, a cooperating CR may indicate a spectrum hole, but the information may be erroneously received by another CR device as occupied.

Cooperating Node Selection. Suppose an SU needs to select several other SUs for cooperation. The optimal number and the criteria to select the cooperating nodes must be determined to maximize the effectiveness of SU cooperation (74,75). As a general rule, more cooperating nodes will increase the performance, albeit with increased overhead and complexity. The following are the common selection methods.

- Random node selection
  A simple method is to choose them randomly within a range. For example, the nodes within a given radius of the SU can be selected. Nodes can also be selected within a given radius from the PU transmitter. However, this method requires the distances to other nearby SUs. Moreover, if the selected number of nodes are high, there is a high overhead and resource usage in terms of power, time, processing power, spectrum when cooperating SUs share their information.
- Closest node selection
  This scheme is most advantageous for distributed decisions because the two devices can easily communicate with each other. However, the major risk of choosing the nearest CR device is the fact that shadowing and fading from the primary device and the two CR devices may be correlated. If so, the shared spectrum information does not originate from independent measurements, and the cooperation gain could be lower.
- Best instantaneous channel selection
  This scheme requires a node with best channel at each time to be selected for cooperation. While the closest CR node provides the best channel conditions on average, this may change at specific times due to the effects of fading. As such the CR device with the best instantaneous channel properties may or may not be the closest. However, the complexity of this scheme lies in the fact that real-time channel state information (CSI) is required for links to neighboring SUs.

A major factor to consider when selecting cooperating nodes is the additional resources required. The locations of the neighboring SUs are required in advance, and sometimes CSI is required for multiple links in order to select co-operating SUs. Moreover, sharing spectrum information requires additional power, spectral resources such as control channels, and higher processing capabilities from each SU.

In distributed cooperative sensing, the CR nodes must communicate with selected close by neighbors to reduce the power required for sharing spectrum information. However, this comes at the risk of the sensed data being correlated. Conversely, choosing CR nodes close to the primary device increases the probability that the shared spectrum information is correct. However, there may be additional power requirements. Furthermore, the shared information itself may get corrupt due to channel effects.

4. INTERFERENCE MODELING IN COGNITIVE RADIO NETWORKS

As was mentioned before, primary devices are highly susceptible to unwanted SU interference. While interference should ideally be zero for interweave networks, it should be less than an acceptable limit for underlay networks. Factors affecting interference include wireless propagation characteristics, spatial distribution of SU and PU devices, power control and receiver association procedures, activity factors of CR devices, and spectrum sensing techniques among others. Some of these topics are briefly described next.

4.1. Wireless Channel

The wireless channel is subject to several impairments, including small-scale fading, shadowing, path loss, and doppler shifts (3,76). Modeling these impairments is critical in order to characterize and analyze wireless systems.

Due to the superposition of many replicas of the transmit signal with different time delays and phases due to multipath propagation from random scatterers, the received signal can rapidly fluctuate, which is referred to as small-scale fading (76). The powers of different multipath components are represented by the power delay profile, and measures such as average delay and root mean square (r.m.s) delay (σ_τ) are important parameters. The coherence bandwidth is defined as $B_{\text{coh}} = 1/\sigma_\tau$, and signals whose frequencies are less than B_{coh} are said to undergo frequency flat fading while others undergo frequency selective fading. Small scale fading is described by various models such as Rayleigh fading, Nakagami-m fading, and Rician fading (3).

Shadowing refers to random variations of the received signal power due to obstruction by large obstacles such as buildings, hills, or trees. The distances in which shadowing occurs depend on the dimensions of the obstructing object (76). Shadowing is most commonly modeled using the log-normal distribution (76,77). However, due to its mathematical complexity, the Gamma model and the mixture of Gamma model have been proposed (42,78). For simultaneous shadowing and fading, it is convenient to represent the combined effect in a single PDF, rather than work with separate distributions. Thus, several composite models incorporating shadowing and fading, namely, Rayleigh-lognormal and Nakagami-lognormal models and others (79) have been proposed (80,81).

Path loss is the variation of signal amplitude between the transmitter and receiver over large distances (76). The free space path loss is the simplest path loss model, and is expressed as

$$\text{Path Loss} = \left(\frac{4\pi r f}{c}\right)^2 \tag{15}$$

where r is the transmitter receiver distance, f is the frequency, and c is the speed of light. However, this model is inaccurate in practice due to irregularities in the terrain (76). To overcome this, several empirical models such as Okumura model, Hata model, and COST 231 Hata model have been developed (3).

However, the most commonly used model is the simplified path loss model where the received power at a distance of r from the transmitter (P_r) is given by (76)

$$P_\mathrm{r} = Ar^{-\alpha} \tag{16}$$

where A is a constant depending on antenna dimensions and frequency, and α is the path loss exponent. The path loss exponent commonly varies between 1.6 and 6.5 (76), and free space propagation is a special case when α and 2.

Combining the effects of small scale fading, shadowing, and path loss, the received power P_r can be expressed as

$$P_\mathrm{r} = PX|h|^2 r^{-\alpha} \tag{17}$$

where P is the transmit power, X is the shadowing gain, and $|h|^2$ is the power gain due to small-scale fading.

4.2. Spatial Modeling

The locations of base stations and different user terminals do not usually conform to a predetermined setup. While the placement of base stations is not purely random, it is increasingly becoming irregular with the introduction of small cells and pico cells. The user terminals on the other hand are almost always random, and change location regularly. As such, conventional fixed models, such as the hexagonal grid model, do not present an accurate picture of the network. Stochastic geometry-based modeling has thus gained ground within the research community (82,83,84,85,86,87). In addition to providing a realistic network scenario, stochastic models are tractable (84). While the binomial point process is more accurate for node distributions (especially base stations) when the number of nodes within the total geographical area is known (88), the PPP is more popular due to its superior analytical tractability.

Poisson Point Process (PPP) Model. A PPP Φ is a point processes in $\mathbb{R}^2$ such that (89)

- for every bounded closed set A (in practical terms, A is the area occupied by nodes), the number $N(A)$ is Poisson distributed with mean $\lambda(A)$ and

$$\Pr[N(A) = n] = \frac{(\lambda(A))^n}{n!} e^{-\lambda(A)}, n = 0, 1, 2, \ldots \tag{18}$$

- if $A_1, A_2 \ldots, A_m$ are disjoint sets, $N(A_1), N(A_2), \ldots, N(A_m)$ are independent random variables.

The PPP has extensively been used to characterize the spatial distribution of cognitive radio nodes in literature (27,28,29,90). When the average density of nodes does not change with the location, it is a homogeneous PPP, with the mean number of nodes per unit area being λ, where λ is called the node density.

When modeling nodes as a PPP, several useful stochastic geometry tools such as mapping, thinning, and clustering can be employed (89,91). Mapping refers to transforming a point process to another point process by applying a fixed transformation (89). In formal terms, it is stated as follows (92). If Φ is an inhomogeneous PPP on $\mathbb{R}^d$ with intensity Λ, and let $f : \mathbb{R}^d \rightarrow \mathbb{R}^s$ be measurable and $\Lambda(f^{-1}\{y\}) = 0$ for all for $y \in \mathbb{R}^s$. Assume further that $\mu(B) = \Lambda(f^{-1}\{B\})$ satisfies $\mu(B) < \infty$ for all bounded B. Then, $f(\Phi)$ is a nonhomogeneous PPP on $\mathbb{R}^s$ with intensity μ.

On the other hand, thinning of a PPP refers to deleting some points. The remaining points are said to form a thinned PPP (89). Each point of the process is marked with an indicator taking the values 1 or 0 representing whether the point is to be retained or not. When the indicators are independent of each other, it is referred to as independent thinning; otherwise, dependent thinning occurs when the indicators depend on each other (89). While the resultant processes after independent thinning are also PPPs, dependent thinning generally produces a hardcore process. Matern type I and II are commonly used hardcore processes where the thinning procedure is dependent on the distance to neighbouring nodes (89). Hardcore processes are especially useful in modeling medium access protocols such as CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) employed in IEEE 802.11 (28).

A cluster involves the formation of daughter processes around a parent process. If the points within a parent process X is replaced with a set of points Z_x, the superposition of all the cluster points represents the daughter process $Y = \bigcup_x Z_x$ (89). The most commonly used cluster processes is the Matern cluster process where the parent process is a PPP in $\mathbb{R}^2$, and each cluster within the daughter process consists of M_x points independently and uniformly distributed within a disc having a radius r centered at x where $M_x = Poisson(\mu)$, and x is the location of any parent node (89). The Matern cluster process has been extensively used in the modeling of user terminals centered around base stations in cellular networks (93,94,95).

4.3. Power Control and Receiver Association

The transmitter controls its power depending on distance from the receiver, other transmissions, and channel conditions. The benefits include saving transmitter power and reducing interference. Power control methods include fixed power, distance-based schemes with channel inversion, and measurement-based schemes (96). For example, open-loop and closed-loop schemes are used in Wideband Code Division Multiple Access (WCDMA) and Long-Term Evolution (LTE) networks (3). Power control schemes have been extensively studied for noncognitive settings (97,98,99,100,101) as well as for CR networks

(28,102,103,104,105). Furthermore, it is common to have a maximum allowable transmit power for CR networks in order to prevent interference to the primary network and other CR receivers (103). This maximum allowable transmit power can be a constant for all devices or a location-dependent one. A location-dependent power level is desirable because the interference from a cognitive node on the primary receiver depends greatly on its distance from the primary receiver. Therefore, a constant maximum allowable power level disadvantages cognitive nodes which are far away from a primary device.

Receiver association schemes are the policies governing how a receiver is assigned to a particular transmitter or vice versa. Association can be made with the closest receiver/transmitter, the receiver/transmitter providing the best instantaneous SNR, or a random receiver/transmitter within a given radius (103). These schemes, power limitations, and the location of the selected receiver would greatly influence the transmitted power.

4.4. Interference Analysis

The total interference experienced by a primary receiver is the combination of interference from all active CR devices (106,107). Thus, the aggregate interference I may be written as

$$I = \sum_{i=1}^{N} I_i \tag{19}$$

where I_i is the interference caused by the ith interferer and N is the number of interferers. N can be a finite value or ∞.

The individual interference I_i is written as

$$I_i = \beta_i P_i X_i |h_i|^2 r_i^{-\alpha} \tag{20}$$

where β_i is a Bernoulli random variable depending on the activity level and spectrum identification errors of the ith CR device and P_i is the transmit power of the ith CR device. X_i, $|h_i|^2$, and r_i are the shadowing gain, small-scale fading gain, and the distance between the ith CR device and the primary receiver, respectively. α is the path loss exponent of the environment.

Since the PDF of the aggregate interference is generally intractable, an MGF (moment generating function)-based approach is generally used for analysis (108,109,110,111,112,113,114). The MGF can be obtained relatively easily because, for a sum of independent interferers, the total MGF is the product of individual MGFs (108,113).

The MGF $M_{\mathrm{I}}^{i}(s)$ of the interference from a single node can be written as

$$M_{\mathrm{I}}^{i}(s) = E[\mathrm{e}^{-sI_i}] \tag{21}$$

where $E[\cdot]$ denotes the expectation and s is the Laplace variable. If the individual interferers are independent and identically distributed, the MGF of the aggregate interference becomes

$$M_I(s) = (M_{\mathrm{I}}^{i}(s))^N \tag{22}$$

Other valuable parameters of the aggregate interference include the mean and higher moments and cumulants. The nth moment ($\mu_n = E[I^n]$) can be obtained from the MGF $M_{\mathrm{I}}(s)$ as

$$\mu_n = (-1)^n \left[\frac{\mathrm{d}^n}{\mathrm{d}s^n} M_{\mathrm{I}}(s) \right]_{s=0} \tag{23}$$

Modeling aggregate interference to fit well-known distributions has been extremely popular due to the intractability of exact analysis. Typically such distributions are Gaussian, log-normal, tailed α-stable, gamma, and as sums of normal and log-normal (108,115,116,117,118,119). This is generally achieved by matching moments of the aggregate interference with the corresponding moments of the well-known distribution.

5. UPPER LAYER ISSUES

5.1. Medium Access Control Strategies

Traditional wireless networks use fixed access schemes such as time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and others. In CR networks, available channels are dynamic in one or all degrees such as time, frequency, code, and space. Therefore, dynamic medium access control (MAC) strategies are needed to ensure a proper functioning of the CR network. They can be broadly divided into two types. These are direct access based (DAB) and dynamic spectrum allocation (DSA) algorithms (120). With DAB, each transmitter–receiver pair tries to optimize its own throughput while under DSA, a global objective is reached (120).

The MAC layer of a CR device controls two key functionalities, which are spectrum-aware sensing, and spectrum-aware access control (43). In the context of the MAC layer, the proportion of time spent on these two functions should be balanced. Factors to consider include the accuracy of sensing, the timeliness of the sensed information, and the required QoS of the SU (43). A workaround for a longer sensing duration is to divide the sensing period into chunks and spread them among spectrum access periods (43).

5.2. Common Control Channel

A common control channel (CCC) is a dedicated channel shared by CR devices that has been assumed for many MAC schemes for CR networks (121). The CCC enables CR devices to report and negotiate on channel access, and thus, the CCC needs to be available at all times. A disadvantage of the CCC is that it would hinder interoperability between different device types using different protocol stacks manufactured by different vendors (122). The control channel may be implemented either in-band or out-of-band. An issue with having an out-of-band dedicated control channel is the resource inefficiency at idle times; however, it would guarantee a reporting/signalling medium. Several options have been proposed on the spectral location of the out-of-band control channel. These include the guard regions of the primary user's spectrum block or the ISM (industrial, scientific, and medical) band (13).

The need for a dedicated control channel may be alleviated by using in-band control channels. One technique to implement in-band control channels is frequency hopping.

However, in a CR network, the available channels change in a dynamic manner, and thus the hopping sequences must adapt accordingly. Rendezvous-based control channels and ultrawideband control channels (13).

5.3. Spectrum Sharing

Spectrum sharing can be accomplished for CR networks using several criteria (13). These are the protection of PUs and fairness among SUs. Several of these methods are described below.

CSMA (Carrier Sense Multiple Access). CSMA is a multiple access protocol where a device senses a shared channel before transmitting. It is well suited to the dynamics of CR networks due to its adaptability and robustness. Furthermore, it can be implemented without any global controller or a control channel. Moreover, CSMA-based schemes may also provide PU protection due to power control features (13). However, before any CSMA scheme is applied to a CR network, it needs to be adapted keeping in mind the PU activities and QoS requirements of the SUs (19).

By applying PTS/RTS/CTS mechanisms, Chen et al. (121) tweaked the traditional CSMA/CA protocol to adapt it to the CR context. Asynchronous spectrum sensing is accomplished by sending a prepare to sense (PTS) frame to neighbouring SUs, requesting these devices to cease transmission in a following time duration. Only then would the original CR device sense the spectrum. Furthermore, a blocking mechanism may be implemented when PUs are active, which temporarily halts the back-off timer.

Dynamic Frequency Hopping. In this spectrum sharing technique, the available spectral blocks are shared among CR devices by assigning each a specific hopping sequence. In order to be robust to dynamic channel availabilities, a constant monitoring process is needed, and the hopping sequences need to be changed dynamically. To achieve this, ideally a central controller and a control channel are needed.

TDMA (Time Division Multiple Access)/FDMA (Frequency Division Multiple Access). The available time–frequency blocks are shared between participating SU nodes. For this scheme to work, the underlying primary network must also use this as a multiple access scheme (13). One disadvantage with this scheme is that some time frequency blocks may need to be released due to PU activity sooner than others, and SUs accessing those blocks may be at a temporary disadvantage.

CDMA (Code Division Multiple Access). This approach is most attractive for underlay CR (13) because SUs can use orthogonal codes to access spectrum irrespective of whether PUs are active. The interference from CR signals will be added to the noise floor of the PUs and other CR devices. Therefore, stringent transmission power limits have to be enforced such that the interference power experienced by PUs is less than an acceptable limit. Disadvantages of CDMA include the requirement of a wide bandwidth and the need for significant control information.

Stochastic Approaches. These use probabilistic objectives to reduce PU interference (122), and are most attractive when there is no common control channel. The channel selection procedure is treated as an optimization problem providing the highest probability to access a potential channel, and can be solved according to a Markov chain Monte Carlo method (122). The primary prioritized Markov approach can also be used for dynamic spectrum access in a stochastic manner where the interactions between PUs and CR devices are modeled as continuous time Markov chains (123).

Several other more specialized protocols such as dynamic open spectrum sharing (DOSS), single radio adaptive channel (SRAC), opportunistic spectrum medium access control (OS MAC), cognitive medium access control (C MAC), cognitive mesh network (COMNET), hardware constrained medium access control (H MAC), and others have also been proposed (43,120). As a final note, any MAC spectrum access strategy must consider the fluidity of available channels, the disparity of channels that may be separated by vast swathes of frequency, and the presence or absence of a control channel.

5.4. Routing

When CR devices relay data/packets from an originating CR to a destination, efficient routing protocols are needed (15,43). Routing in CR networks is a critical issue because available spectrum holes are spread far and wide (19). Furthermore, the spectrum availability for a particular node changes with time, and neighbouring nodes may not identify the same frequency band for opportunistic access. Therefore, the routing algorithms should be able to handle the dynamics of the CR environment, and deploying legacy routing algorithms designed for general ad hoc networks may not be suitable (124).

The issues with routing in a CR networks include the unavailability of a control channel to share link information needed for dynamic routing protocols among neighbours, reachability of CR devices being hampered due to channel dynamics, the necessity of having rerouting algorithms to alter the route when one or more CR devices become unavailable due to interruptions from the primary system, the inadequacy of traditional routing metrics, and managing queues of different packets in a dynamic spectral environment (15,124). For example, packets may arrive at a particular CR device when it had identified spectrum holes for communication. However, these may become unavailable. A question arises on what to do with the received packets. Furthermore, similar to ad hoc networks, most of the opportunistic links in a CR network may be unidirectional, and thus need to be identified as such. Moreover, instead of the traditional single-path routing schemes, multipath routing where multiple redundant paths exist to the destination are more attractive for the dynamic spectral environment CR nodes operating in Reference 124. However, additional metrics such as route stability, route closeness, and dead zone penetration need to be considered in selecting multipath routing schemes (124).

The routing problem in CR networks can be solved via spectrum-aware routing protocols (19,125), and probabilistic path selection schemes are needed. New routing metrics need to be introduced such as the number of channel switches along a path, frequency of channel switches along a link, and switching delay (19). In spectrum aware routing, the routing algorithms should operate collaboratively with spectrum management schemes to identify the best route (43). Different routing schemes such as opportunistic spectrum routing, stability-aware routing protocol (STRAP), medium access control-independent opportunistic routing (MORE), spectrum-aware routing protocol (SPEAR), spectrum-aware mesh routing (SAMER), spectrum tree based on demand routing protocol (STOD RP), SEARCH, and routing and spectrum allocation algorithm (ROSA) have been proposed for the context of dynamic spectral environments (43,124).

5.5. Error Control

To limit interference on the primary network, secondary devices face significant limitations on the maximum power they are allowed to transmit (126). This limit will naturally reduce the reliability and throughput of the secondary network. A potential solution is the use of error correction coding, which includes forward error correcting codes and automatic repeat request (ARQ) schemes. ARQ schemes use feedback from the receiver indicating the correct reception of data and timeouts. If the sender does not receive an acknowledgment before the timeout, retransmissions occur. However, ARQ becomes complicated in a CR network due to the available spectrum dynamically changing as licensed users enter and leave the spectrum (43). These factors suggest that the forward error correction may be preferable.

5.6. Security

Due to their unique characteristics, CR networks face several unique security challenges (19). While traditional network threats are applicable to CR networks, the cognitive capability and reconfigurability introduce additional threats to CR devices (127). Security threats specific to CR networks include adversaries mimicking PU behaviors, transmitting false spectrum information, receiver jamming during sensing phase, intruders posing as CR devices, and greedy CR devices acting selfishly (128). These threats can occur during both the sensing period, and the communicating period. Transmitter verification schemes, integrating cryptographic signatures, abnormality detection approaches, and trusted node-assisted schemes among others can be used as countermeasures for security threats (128).

6. STANDARDS

CR technology standards have been developed by the FCC in United States, the European Telecommunications Standards Institute, IEEE, and the International Telecommunications Union (10,129). These standards differ in the level of cognition and the target environment. Currently, the IEEE 802.22 Wireless Regional Area Network (WRAN) and the IEEE P1900.X standards developed by the IEEE Dynamic spectrum access networks (DySPAN) committee remain the main CR standards. Furthermore, WiFi (IEEE 802.11), Zigbee (IEEE 802.15.4), and WiMAX (IEEE 802.16) have increasingly incorporated some elements of cognition (130).

6.1. IEEE 802.22 (Wireless Regional Area Network)

While spectrum is reserved for terrestrial TV transmissions, some of those channels may not be used in a specific location or geographic area. Furthermore, the switch from analogue to digital also leaves a considerable amount of UHF and VHF (very high frequency) spectrum vacant (10). Thus, unlicensed use of television frequency bands (54–862 MHz) on a noninterfering basis with primary users is the aim of IEEE 802.22 WRAN standard (129), focusing on wireless broadband access for rural areas. This standard adopts a cellular architecture and cell radius would typically be 17–30 km while the maximum allowable range is 100 km (131). This standard is the first to define the physical and MAC layers of the air interface for CR-enabled devices (10).

This standard requires the SUs to be aware about the availability of spectrum at a given instance. Spectrum awareness is achieved via a geolocation database and spectrum sensing (130,131). To enable the geolocation process, all devices must be GPS enabled in order to accurately identify their locations. Spectrum sensing is performed for analog and digital TV bands in addition to low-powered auxiliary devices (131). Moreover, all 802.22 devices must be able to sense beacons transmitted by devices at a power of 250 mW in UHF and 50 mW in VHF, having a bandwidth of 77 kHz within the TV band. Furthermore, the standard compliant devices must dynamically adapt transmissions and move to a new channel if the current channel gets occupied by licensed users (131). The network topology is a point-to-multipoint network where base stations can serve up to 255 users and provide a minimum peak data rate of 1.5 Mbps in the downlink and 384 kbps in the uplink for cell-edge users. The physical layer uses orthogonal frequency division multiple access with 2048 carriers (10,131). The uplink and downlink are time division duplexed because paired television channels are not readily available.

6.2. IEEE DySPAN (Dynamic Spectrum Access Networks) Standards

These set of standards support new technologies and techniques on advanced spectrum management and dynamic spectrum access (DSA), which include new techniques for managing interference, sensing, network management, and coordination of wireless networks (130). The IEEE DySPAN Standards Committee was previously known as Standards Coordinating Committee 41 (SCC41) and the IEEE P1900 Standards Committee (10).

Currently there are seven separate standards being developed by different groups. IEEE 1900.1 provides precise definitions and explanations, IEEE 1900.2 provides recommended practice, IEEE 1900.3 provides dependability and evaluation compliance for radio systems with dynamic spectrum access, 1900.4 provides architectural building blocks for distributed decision-making by devices for optimum radio resource usage in heterogeneous networks, IEEE 1900.5 provides vendor independent policy and system requirements for dynamic spectrum access, IEEE 1900.6 provides the logical interfaces and data structures for information transfer between spectrum sensing devices and their clients, and IEEE 1900.7 develops a standard defining the radio interface for communication within a spectrum hole (129,130,132).

6.3. IEEE 802.19.1

This standard has been developed for devices to exploit TV spectrum holes and ensure coexistence (129,130,133). Coexistence refers to self-coexistence between CR devices using the same CR standard and coexistence among the systems using different CR standards. While self-coexistence is almost always incorporated into the CR standard, coexistence between devices using different CR standards is more challenging (133). This standard aims to achieve this through three main tasks: (1) Discovering different CR systems which need to coexist, (2) changing operating parameters of the different CR systems such that their performance is improved, and (3) providing a unified interface between the CR devices using different technologies (133). The main elements of the protocol include subscription, registration, providing coexistence set information, reconfiguration, obtaining channel classification information, sharing coexistence set information, and coexistence set element reconfiguration (133).

6.4. IEEE 802.15.4m (Zigbee)

This standard (134) rebands frequencies used by conventional IEEE 802.15.4 devices (low rate personal area networks) into the TV spectrum holes (135). The IEEE 802.15.4 has become popular for wireless sensor networks, active radio frequency identification, body area networking, and smart utility networking (135). However, as more applications emerge, it is vital to explore into additional spectrum opportunities as the current spectrum is limited. To this end, the IEEE 802.15.4m has incorporated peer-to-peer connectivity and device-to-device connectivity to keep in line with its target sensor network applications.

6.5. IEEE 802.11af (WiFi)

Modifications to the 802.11 physical and MAC layers are proposed in the IEEE 802.11af standard for local area networks (LANs) accessing TV spectrum holes (129,136). The main elements include a geolocation database, registered user secure server, and geolocation database-dependent entities (GDD) such as the GDD enabling and dependent stations (137). The registered location query protocol (RLQP) serves as a communication protocol between GDD enabling and dependent stations, and enables the dependent stations to select transmission parameters such as the power, bandwidth, and spectral band (137).

7. SUMMARY

Cognitive radio aims to access unused or underutilized spectrum more effectively as a promising solution for spectrum shortages faced by new wireless applications. Three common CR paradigms are overlay, underlay, and interleave. Moreover, identification of spectrum opportunities is a key challenge, and can be accomplished through different static or dynamic means. A key inhibiting factor of CR networks is their mutual interference, which can be characterized using statistical spatial and channel models. A successful CR implementation needs to take into account the physical layer, MAC, routing, and security issues among others. Several standards dealing with CR have already been developed, and others have been incorporated with elements of cognition.

LIST OF ABBREVIATION

ARQ	automatic repeat request
AUC	area under the curve
AWGN	additive white gaussian noise
C MAC	cognitive medium access control
CCC	common control channel
CDMA	code division multiple access
COMNET	cognitive mesh network
CR	cognitive radio
CSMA	carrier sense multiple access
DAB	direct access based
DOSS	dynamic open spectrum sharing
DPC	dirty paper coding
DSA	dynamic spectrum access
DVB	digital video broadcasting
DySPAN	dynamic spectrum access networks
FC	fusion center
FDMA	frequency division multiple access
GDD	geolocation database dependent entities
GPS	global positioning system
H MAC	hardware constrained medium access control
IEEE	institute of electrical and electronic engineers
ISM	industrial, scientific, and medical
LSA	licensed shared access
LTE	long term evolution
MAC	medium access control
MGF	moment generating function
MORE	medium access control independent opportunistic routing
OFDM	orthogonal frequency division multiplexing
OSMAC	opportunistic spectrum medium access control
PPP	poisson point process
PTS	prepare to sense
PU	primary user
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RLQP	registered location query protocol
ROC	receiver operating characteristic
ROSA	routing and spectrum allocation algorithm
SAMER	spectrum aware mesh routing
SNR	signal to noise ratio
SPEAR	spectrum aware routing protocol
SRAC	single radio adaptive channel

STOP RP	spectrum tree based on demand routing protocol
STRAP	stability aware routing protocol
SU	secondary user
TDMA	time division multiple access
UHF	ultra high frequency
VHF	very high frequency
WCDMA	wideband code division multiple access
WRAN	wireless regional area network

BIBLIOGRAPHY

1. A. Aijaz and A. H. Aghvami, *IEEE Internet Things J.* **2015**, *2*, pp. 103–112.
2. A. Ali, W. Hamouda, and M. Uysal, *IEEE Commun. Mag.* **2015**, *53*(9), pp. 18–24.
3. A. Molisch, *Wireless Communications*. Wiley-IEEE Press, 2011.
4. Cisco Systems visual networking index: Global mobile data traffic forecast update, 2014–2019. Technical report, 2015.
5. T. Nechiporenko, P. Kalansuriya, and C. Tellambura, *IEEE Trans. Veh. Technol.* **2009**, *58*(5), pp. 2258–2268.
6. G. Amarasuriya, M. Ardakani, and C. Tellambura, *IEEE Trans. Veh. Technol.* **2010**, *59*(6), pp. 3091–3097.
7. Qualcomm. The visible light communications motivation. Available at http://visiblelightcomm.com/the-visible-light-communications-motivation/, 2011.
8. S. Haykin, *IEEE J. Sel. Areas Commun.* **2005**, *23*(2), pp. 201–220.
9. H. S. Shahraki, *IET Commun.* **2015**, *9*(9), pp. 1240–1247.
10. M. T. Masonta, M. Mzyece, and N. Ntlatlapa, *IEEE Commun. Surv. Tutor.* **2013**, *15*(3), pp. 1088–1107.
11. C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, *IEEE Commun. Mag.* **2014**, *52*(2), pp. 122–130.
12. J. Mitola, Cognitive radio - an integrated agent architecture for software defined radio, Ph.D. dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.
13. L. Gavrilovska, D. Denkovski, V. Rakovic, and M. Angjelichinoski, *IEEE Commun. Surv. Tutor.* **2014**, *16*(4), pp. 2092–2124.
14. M. Matinmikko, M. Palola, H. Saarnisaari, M. Heikkilä, J. Prokkola, T. Kippola, T. Hänninen, M. Jokinen, and S. Yrjölä, *IEEE Veh. Tech. Mag.* **2013**, *8*(3), pp. 30–37.
15. I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, *Comput. Netw.* **2006**, *50*(13), pp. 2127–2159.
16. R. Menon, R. Buehrer, and J. Reed. Outage probability based comparison of underlay and overlay spectrum sharing techniques, in *Proc. of the IEEE DYSPAN 2005*; Nov. 2005, pp. 101–109.
17. S. Srinivasa and S. Jafar, *IEEE Commun. Mag.* **2007**, *45*(5), pp. 73–79.
18. E. Hossain, D. Niyato, and Z. Han, *Dynamic Spectrum Access and Management in Cognitive Radio Networks*. Cambridge University Press, 2009.
19. B. Wang and K. Liu, *IEEE J. Sel. Top. Signal Process.* **2011**, *5*(1), pp. 5–23.
20. S. K. Sharma, T. E. Bogale, S. Chatzinotas, B. Ottersten, L. B. Le, and X. Wang, *IEEE Commun. Surv. Tutor.*, **2015**, *17*(4), pp. 1858–1884.
21. S. Atapattu, C. Tellambura, and H. Jiang, *IEEE Trans. Wirel. Commun.*, **2011**, *10*(4), pp. 1232–1241.
22. A. Al-Dulaimi, J. Cosmas, and A. Mohammed, *Self-Organization and Green Applications in Cognitive Radio Networks*. IGI Global, 2013.
23. M. Vu, S. Ghassemzadeh, and V. Tarokh. Interference in a cognitive network with beacon, in *Proc. of the IEEE WCNC 2008*; April 2008, pp. 876–881.
24. A. Gupta and R. Jha, *IEEE Access* **2015**, *3*, pp. 1206–1232.
25. A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, *Proc. IEEE* **2009**, *97*(5), pp. 894–914.
26. V. N. Q. Bao, T. Q. Duong, and C. Tellambura, *IEEE Trans. Commun.*, **2013**, *61*(12), pp. 4864–4873.
27. L. Vijayandran, P. Dharmawansa, T. Ekman, and C. Tellambura, *IEEE Trans. Commun.* **2012**, vol. PP, no. 99, pp. 1–12.
28. Z. Chen, C.-X. Wang, X. Hong, J. Thompson, S. Vorobyov, X. Ge, H. Xiao, and F. Zhao, *IEEE Trans. Commun.* **2012**, *60*(2), pp. 456–468.
29. A. Rabbachin, T. Q. S. Quek, H. Shin, and M. Z. Win, *IEEE J. Sel. Areas Commun.* **2011**, *29*(2), pp. 480–493.
30. C. han Lee and M. Haenggi. Delay analysis of spatio-temporal channel access for cognitive networks, in *Proc. of the IEEE ICC*; June 2011, pp. 1–5.
31. B. Wang and P. Mu, *IEEE Trans. Veh. Technol.* **2016**, vol. PP, no. 99, pp. 1–1.
32. A. Ahmad, S. Ahmad, M. H. Rehmani, and N. U. Hassan, *IEEE Commun. Surveys Tuts.*, **2015**, *17*(2), pp. 888–917.
33. A. M. Wyglinski, M. Nekovee, and T. Hou, *Cognitive Radio Communications and Networks: Principles and Practice*. Elsevier, 2010.
34. F. Paisana, N. Marchetti, and L. DaSilva, *IEEE Commun. Surv. Tutor.* **2014**, *163*, pp 1193–1220.
35. G. Wang, Q. Liu, R. He, F. Gao, and C. Tellambura, *IEEE Wirel. Commun.* **2015**, *22*(3), pp. 100–107.
36. S. Atapattu, C. Tellambura, and H. Jiang, *Energy Detection for Spectrum Sensing in Cognitive Radio*. Springer, 2014.
37. B. Farhang-Boroujeny, *IEEE Trans. Signal Process.* **2008**, *56*(5), pp. 1801–1811.
38. H. Li, C. Li, and H. Dai. Quickest spectrum sensing in cognitive radio, in Proc. of the CISS; March 2008, pp. 203–208.
39. V. R. S. Banjade, N. Rajatheva, and C. Tellambura, *IEEE Commun. Lett.* **2012**, *16*(4), pp. 502–505.
40. S. P. Herath, N. Rajatheva, and C. Tellambura. Unified approach for energy detection of unknown deterministic signal in cognitive radio over fading channels, in *Proc. of the IEEE ICC*; June 2009, pp. 1–5.
41. S. Atapattu, C. Tellambura, H. Jiang, and N. Rajatheva, *IEEE Trans. Veh. Technol.* **2015**, *64*(11), pp. 5006–5019.
42. S. Atapattu, C. Tellambura, and H. Jiang, *IEEE Trans. Wirel. Commun.* **2011**, *10*(12), pp. 4193–4203.
43. Y. C. Liang, K. C. Chen, G. Y. Li, and P. Mahonen, *IEEE Trans. Veh. Tech.* **2011**, *60*(7), pp. 3386–3407.
44. S. Atapattu, C. Tellambura, H. Jiang, and N. Rajatheva, *IEEE Trans. Veh. Technol.* **2015**, *64*(11), pp. 5006–5019.
45. S. Atapattu, C. Tellambura, and H. Jiang, *IEEE Commun. Lett.* **2011**, *15*(12), pp. 1301–1303.
46. S. Atapattu, C. Tellambura, and H. Jiang. Spectrum sensing via energy detector in low snr, in *2011 IEEE International Conference on Communications (ICC)*. IEEE, 2011, pp. 1–5.
47. S. P. Herath, N. Rajatheva, and C. Tellambura. Unified approach for energy detection of unknown deterministic signal in cognitive radio over fading channels, in *2009 IEEE*

International Conference on Communications Workshops. IEEE, 2009, pp. 1–5.

48. A. Mariani, A. Giorgetti, and M. Chiani. SNR wall for energy detection with noise power estimation, in *Proc. of the IEEE ICC*; June 2011, pp. 1–6.
49. R. Tandra and A. Sahai, *IEEE J. Sel. Areas Commun.* **2008**, *2*(1), pp. 4–17.
50. M. S. O. Alink, A. B. J. Kokkeler, E. A. M. Klumperink, G. J. M. Smit, and B. Nauta, *IEEE Trans. Veh. Tech.* **2011**, *60*(8), pp. 3748–3757.
51. F. Salahdine, H. E. Ghazi, N. Kaabouch, and W. F. Fihri. Matched filter detection with dynamic threshold for cognitive radio networks, in *Proc. of the IEEE WINCOM*; Oct. 2015, pp. 1–6.
52. H. S. Chen, W. Gao, and D. G. Daut. Signature based spectrum sensing algorithms for IEEE 802.22 WRAN, in *Proc. of the IEEE ICCC*; June 2007, pp. 6487–6492.
53. Y. Zeng and Y. C. Liang, *IEEE Trans. Commun. 57*(6), pp. 1784–1793.
54. J. Ma, G. Y. Li, and B. H. Juang, *Proc. IEEE* **2009**, *97*(5), pp. 805–823.
55. V. R. S. Banjade, C. Tellambura, and H. Jiang, *IEEE Trans. Veh. Tech.* **2014**, *63*(7), pp. 3209–3222.
56. H. Sun, A. Nallanathan, C. X. Wang, and Y. Chen, *IEEE Wirel. Commun.* **2013**, *20*(2), pp. 74–81.
57. Z. Tian, Y. Tafesse, and B. M. Sadler, *IEEE J. Sel. Top. Signal Process* **2012**, *6*(1), pp. 58–69.
58. J. A. Tropp, J. N. Laska, M. F. Duarte, J. K. Romberg, and R. G. Baraniuk, *IEEE Trans. Info. Theory* **2010**, *56*(1), pp. 520–544.
59. N. Nguyen-Thanh, T. Kieu-Xuan, and I. Koo, *IEEE Trans. Wirel. Commun.* **2012**, *11*(10), pp. 3409–3411.
60. Z. Lei and F. Chin, *IEEE Trans. Broadcast.* **2008**, *54*(2), pp. 182–187.
61. M. Derakhshani and T. Le-Ngoc, *IEEE Trans. Veh. Technol.* **2012**, *61*(1), pp. 196–207.
62. K. Bian, J.-M. Park, L. Chen, and X. Li, *IEEE Trans. Veh. Technol.* **2014** *63*(9), pp. 4450–4463.
63. X. Song, C. Yin, D. Liu, and R. Zhang, *IEEE J. Sel. Areas Commun.* **2014**, *32*(11), pp. 2190–2204.
64. L. Barlemann and S. Mangold. *Cognitive Radio and Dynamic Spectrum Access*. John Wiley & Sons, Ltd: Chichester, 2009.
65. A. Ghasemi and E. Sousa, *IEEE J. Sel. Areas Commun.* **2008** *2*(1), pp. 41–56.
66. H. Venkataraman and G. Muntean, *Cognitive Radio and its Application for Next Generation Cellular and Wireless Networks*. Springer, 2012.
67. T. C. Clancy, *J. Wireless. Commun. Mobile Comput.* **2007**, *7*(9), pp. 1077–1086.
68. B. Jalaeian, R. Zhu, H. Samani, and M. Motani, *IEEE Sys. J.* **2016**, *10*(1), pp. 293–301.
69. C. Lameiro, W. Utschick, and I. Santamara. Interference-temperature limit for cognitive radio networks with MIMO primary users, in *Proc. of the IEEE ACSSC*; Nov. 2014, pp. 1093–1097.
70. M. Monemi, M. Rasti, and E. Hossain. *IEEE Trans. Commun.* **2016**, *64*(2), pp. 511–524.
71. S. Mishra, A. Sahai, and R. Brodersen. Cooperative sensing among cognitive radios, in *Proc. of the IEEE ICC*; *4*, 2006, pp. 1658–1663.
72. C. Jiang, N. Beaulieu, L. Zhang, Y. Ren, M. Peng, and H.-H. Chen, *IEEE Netw.* **2015**, *29*(3), pp. 88–95.
73. G. Ganesan and Y. Li, *IEEE Trans. Wirel. Commun.* **2007**, *6*(6), pp. 2214–2222.
74. A. Ghasemi and E. Sousa. Collaborative spectrum sensing for opportunistic access in fading environments, in *Proc. of the IEEE DySPAN*; Nov. 2005, pp. 131–136.
75. S. Kusaladharma and C. Tellambura. Interweave cognitive networks with co-operative sensing, in *Proc. of the IEEE GLOBECOM*; Dec. 2015, pp. 6–10.
76. A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.
77. C. Tellambura and D. Senaratne. *IEEE Trans. Commun.* **2010**, *58*(5), doi: 10.1109/TCOMM.2010.05.080640.
78. I. Trigui, A. Laourine, S. Affes, and A. Stephenne. Outage analysis of wireless systems over composite fading/shadowing channels with co-channel interference, in *Proc. of the IEEE WCNC*; April 2009, pp. 1–6.
79. S. Atapattu, C. Tellambura, and H. Jiang. Energy detection of primary signals over-fading channels, in 2009 International Conference on Industrial and Information Systems (ICIIS). IEEE, 2009, pp. 118–122.
80. G. L. Stuber, *Principles of Mobile Communication*. Kluwer Academic Publishers, Norwell, MA, 2001.
81. M. Simon and M. S. Alouini, *Digital Communications over fading channels, 2nd ed.*; John Wiley & Sons, Inc.: New Jersey, 2004.
82. M. Di Renzo, *IEEE Trans. Wirel. Commun.* **2015**, *14*(9), pp. 5038–5057.
83. M. Haenggi, J. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, *IEEE J. Sel. Areas Commun.* **2009**, *27*(7), pp. 1029–1046.
84. H. Dhillon, R. Ganti, F. Baccelli, and J. Andrews, *IEEE J. Sel. Areas Commun.* **2012**, *30*(3), pp. 550–560.
85. P. C. Pinto and M. Z. Win, *IEEE Trans. Wirel. Commun.*, **2010**, *9*(7), pp. 2176–2186.
86. E. Salbaroli and A. Zanella, *IEEE Trans. Veh. Technol.* **2009**, *58*(4), pp. 1776–1783.
87. Y. Dhungana and C. Tellambura. Outage probability of underlay cognitive relay networks with spatially random nodes, in *2014 IEEE Global Communications Conference*, Dec. 2014, pp. 3597–3602.
88. J. Chen, M. Ding, and Q. Zhang, *IEEE Trans. Veh. Technol.*, **2012**, *61*(5), pp. 2033–2043.
89. A. Baddeley, I. Barany, R. Schneider, and W. Weil, *Spatial Point Processes and their Applications*. Springer, 2007.
90. S.-R. Cho and W. Choi, *IEEE Trans. Mobile Comput.* **2014**, *13*(9), pp. 1955–1966.
91. J. F. Kingman, *Poisson Processes*. Oxford University Press, 1993.
92. M. Haenggi and R. K. Ganti, *Interference in Large Wireless Networks*. Now Publishers, 2009.
93. N. Deng, W. Zhou, and M. Haenggi, *IEEE J. Sel. Areas Commun.* **2015**, *33*(10), pp. 2167–2181.
94. Y. Liu, C. Yin, J. Gao, and X. Sun. Transmission capacity for overlaid wireless networks: A homogeneous primary network versus an inhomogeneous secondary network, in *Proc. of the IEEE ICCCAS*; Nov. 1, 2013, pp. 154–158.
95. Y. Zhou, Z. Zhao, Q. Ying, R. Li, X. Zhou, and H. Zhang. Two-tier spatial modeling of base stations in cellular networks, in *Proc. of the IEEE PIMRC*; Sept. 2014, pp. 1570–1574.
96. P. Mach and Z. Becvar. EURASIP *J. Wirel. Commun. Netw.* **2011**, 2011, 259253.

97. J. Jang and K.-B. Lee, *IEEE J. Sel. Areas Commun.* **2003**, *21*(2), pp. 171–178.
98. D. Qiao, S. Choi, and K. Shin, *IEEE/ACM Trans. Netw.* **2007**, *15*(5), pp. 1007–1020.
99. S. Gong, P. Wang, Y. Liu, and W. Zhuang, *IEEE J. Sel. Areas Commun.* **2013**, *31*(11), pp. 2397–2408.
100. C. Sun, Y. Alemseged, H.-N. Tran, and H. Harada, *IEEE Trans. Veh. Technol.* **2010**, *59*(4), pp. 1847–1857.
101. D. Senaratne, C. Tellambura, and H. A. Suraweera, *IEEE Trans. Veh. Technol.* **2012**, *61*(3), pp. 1188–1196.
102. N. Hoven and A. Sahai, in *Proc. IEEE WNCMC* **2005**, *1*, pp. 250–255.
103. S. Kusaladharma, P. Herath, and C. Tellambura. Impact of transmit power control on aggregate interference in underlay cognitive radio networks, in *Proc. IEEE ICC*; June 2014, pp. 1–6.
104. S. Kusaladharma, P. Herath, and C. Tellambura. Impact of transmit power control and receiver association on interweave network interference, in *Proc. IEEE VTC*; Sept. 2014, pp. 1–5.
105. S. Kusaladharma, P. Herath, and C. Tellambura. *IEEE Trans. Veh. Technol.* **2016**, *65*(11), pp. 8978–8991.
106. S. Kusaladharma, P. Herath, and C. Tellambura. Aggregate interference analysis for interweave cognitive networks, in *Proc. IEEE VTC*; Sept. 2014, pp. 1–5.
107. S. Kusaladharma and C. Tellambura, *IEEE Commun. Lett.* **2013**, *17*(11), pp. 2052–2055.
108. S. Kusaladharma and C. Tellambura, *IEEE Wirel. Commun. Lett.* **2012**, *1*(6), pp. 641–644.
109. C. Tellambura, A. J. Mueller, and V. K. Bhargawa, *IEEE Trans. Veh. Technol.* **1997**, *46*(4), pp. 910–922.
110. C. Tellambura, A. Annamalai, and V. K. Bhargava, *IEEE Trans. Commun.* **2003**, **51**(4), pp. 539–542.
111. C. Tellambura, *IEEE Trans. Commun.* **1996**, *44*(12), pp. 1693–1699.
112. S. Kusaladharma, P. Herath, and C. Tellambura. Secondary user interference characterization for underlay networks, in *Proc. of the IEEE VTC*; Sept. 2015, pp. 1–5.
113. S. Kusaladharma and C. Tellambura, *IEEE Wireless Commun. Lett.* **2013**, *2*(1), pp. 58–61.
114. S. Kusaladharma and C. Tellambura. Massive MIMO based underlay networks with power control, in *Proc. of the IEEE ICC*; May 2016, pp. 1–6.
115. M. Hanif, M. Shafi, P. Smith, and P. Dmochowski. Interference and deployment issues for cognitive radio systems in shadowing environments, in *Proc. of the IEEE ICC*; June 2009, pp. 1–6.
116. A. Babaei and B. Jabbari. Interference modeling and avoidance in spectrum underlay cognitive wireless networks, in *Proc. of the IEEE ICC*; May 2010, pp. 1–5.
117. K. Woyach, P. Grover, and A. Sahai. Near vs. far field: Interference aggregation in TV whitespaces, in *Proc. of the IEEE GLOBECOM*; Dec. 2011, pp. 1–5.
118. X. Hong, C.-X. Wang, and J. Thompson. Interference modeling of cognitive radio networks, in *Proc. of the IEEE VTC*; May 2008, pp. 1851–1855.
119. S. Kusaladharma and C. Tellambura, *IEEE Commun. Lett.* **2014**, *18*(4), pp. 596–599.
120. A. D. Domenico, E. C. Strinati, and M. G. D. Benedetto, *IEEE Commun. Surv. Tutor.* **2012**, *14*(1), pp. 21–44.
121. Q. Chen, W. C. Wong, M. Motani, and Y. C. Liang, *IEEE J. Sel. Areas Commun.* **2013**, *31*(11), pp. 2289–2300.
122. X. Y. Wang, A. Wong, and P. H. Ho, *IEEE J. Sel. Areas Commun.* **2011**, *29*(4), pp. 770–783.
123. B. Wang, Z. Ji, K. J. R. Liu, and T. C. Clancy, *IEEE Trans. Wirel. Commun.*, **2009**, *8*(4), pp. 1854–1865.
124. M. Youssef, M. Ibrahim, M. Abdelatif, L. Chen, and A. V. Vasilakos, *IEEE Commun. Surv. Tutor.*, **2014**, *16*(1), pp. 92–109.
125. Q. Wang and H. Zheng. Route and spectrum selection in dynamic spectrum networks, in *Proc. of the IEEE CCNC*; Jan. 1, 2006, pp. 625–629.
126. J. S. Harsini and M. Zorzi, *IEEE Trans. Commun.* **2014**, *62*(6), pp. 1790–1802.
127. A. G. Fragkiadakis, E. Z. Tragos, and I. G. Askoxylakis, *IEEE Commun. Surv. Tutor.* **2013**, *15*(1), pp. 428–445.
128. R. K. Sharma and D. B. Rawat, *IEEE Commun. Surv. Tutor.* **2015**, *17*(2), pp. 1023–1043.
129. S. Filin, H. Harada, H. Murakami, and K. Ishizu, *IEEE Commun. Mag.* **2011**, *49*(3), pp. 82–89.
130. M. Sherman, A. Mody, R. Martinez, C. Rodriguez, and R. Reddy, *IEEE Commun. Mag.* **2008**, *46*(7), pp. 72–79.
131. C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, *IEEE Commun. Mag.* **2009**, *47*(1), pp. 130–138
132. S. Filin, F. Kojima, D. Noguet, J. B. Dore, B. Mawlawi, O. Holland, M. Z. Shakir, and H. Harada. IEEE 1900.7 standard for white space dynamic spectrum access radio systems, in *Proc. of the IEEE CSCN*; Oct. 2015, pp. 218–223.
133. S. Filin, T. Baykas, H. Harada, F. Kojima, and H. Yano, *IEEE Commun. Mag.* **2016**, *54*(3), pp. 22–26.
134. "IEEE standard for local and metropolitan area networks - part 15.4: Low-rate wireless personal area networks (LR-WPANs) - amendment 6: TV white space between 54 MHz and 862 MHz physical layer," *IEEE Std 802.15.4m-2014 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, IEEE Std 802.15.4g-2012, IEEE Std 802.15.4j-2013, and IEEE Std 802.15.4k-2013)*, pp. 1–118, April 2014.
135. C. S. Sum, L. Lu, M. T. Zhou, F. Kojima, and H. Harada, *IEEE Commun. Mag.* **2013**, *51*(4), pp. 74–82.
136. H. Sawada, K. Mizutani, K. Ishizu, T. Matsumura, H. N. Tran, H. Murakami, F. Kojima, and H. Harada. Path loss and throughput estimation models for an IEEE 802.11af prototype, in *Proc. of the IEEE VTC*; May 2015, pp. 1–5.
137. A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, *IEEE Commun. Mag.* **2013**, *51*(10), pp. 92–100.

SACHITHA KUSALADHARMA &
CHINTHA TELLAMBURA
University of Alberta,
Edmonton, Alberta, Canada