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Spectrum Sensing Methods and Dynamic Spectrum Sharing in Cognitive Radio Networks: A Survey

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Abstract – Dynamic spectrum access and cognitive radio (CR) are emerging technologies to utilize the scarce frequency spectrum in an efficient and opportunistic manner. They have been receiving tremendous amount of well-deserved attention in the literature. One of the challenging problems in dynamic spectrum access for cognitive radios is to sense the spectrum in wide band regime of heterogeneous networks to identify the spectrum opportunities. Our main goal in this paper is to present the state-of-the-art research results in signal processing techniques for spectrum sensing in CR network to make automatic and wise decision by unlicensed secondary users to adapt their transmission parameters according to their operating RF environment and respect the primary users. Specifically, we present dynamic spectrum sharing models for spectrum access and signal processing techniques for spectrum sensing by categorizing them into five basic groups. We also present the comparison of different signal processing techniques from different perspectives including networking metrics for the evaluation of the methods e.g. how accurate and how fast can sense spectrum utilization given the various methods and how this will affect networking functionality, and pros and cons of all the methods in the context of networking systems. We also present the status, research challenges and perspectives of signal processing/detection techniques for spectrum sensing in cognitive radio networks.

Keywords –Spectrum sensing methods, signal processing in cognitive radio, cognitive radio networks.

1. Introduction

The next generation (XG) wireless networks and devices are emerging towards ad-hoc networking with uncertain topologies, and the idea in XG wireless networks is to design networks that are self-configuring, self-organizing, self-optimizing, and self-protecting. Therefore, such networks should be able to learn and adapt instantaneously their operating environment depending on their operating RF (radio frequency) environment thus providing much needed flexibility and functional scalability. Moreover, in order to adapt their operating parameters automatically and wisely, signal processing for spectrum sensing is regarded as a fundamental step in these types of networks. Currently existing wireless communication systems and networks are operating based on fixed spectrum assignment to the service providers and their users for exclusive use on a long-term basis and vast geographic area. The exclusive RF spectrum assignment, which is licensed by government regulatory bodies, such as the Federal Communication Commission (FCC) in the United States, was an efficient way for interference mitigation among adjacent bands. However, the fixed spectrum assignment leads to inefficient use of spectrum creating "spectrum drought" [1] since most of the channels actively transmit the information only for short duration while the certain portion of the spectrum is idle when and where the licensed users are not transmitting [2, 3, 4, 5]. This implies that the inefficient radio spectrum usage has been a serious bottleneck for deployment of larger density of wireless devices. We note that the scarcity of RF spectrum is not a result of lack of spectrum but a result of wasteful static spectrum allocations.

In order to alleviate the spectrum scarcity, cognitive radio (CR) [6, 7, 4, 8, 9, 10] has been introduced to facilitate the spectrum sharing [11, 12, 13] to increase the spectrum efficiency so that the larger density of wireless users can be accommodated without creating a new RF spectrum band. The secondary CR network, which is software defined radio along with some intelligence to work automatically according to their operating environment, the radio components are implemented in software rather than in hardware, therefore it is possible to adapt system configurations to any frequency to transmit and receive the data. It is important to note that the primary users (PUs) are authorized users of the licensed frequency band, and secondary users (SUs), who are not the PUs but want to use the licensed frequency band, are the cognitive users in CR networks. It is also worth to mention that allowing a secondary user to access the licensed spectrum (imposing some constraints on SUs) improves the spectrum utilization. In CR network, devices detect each

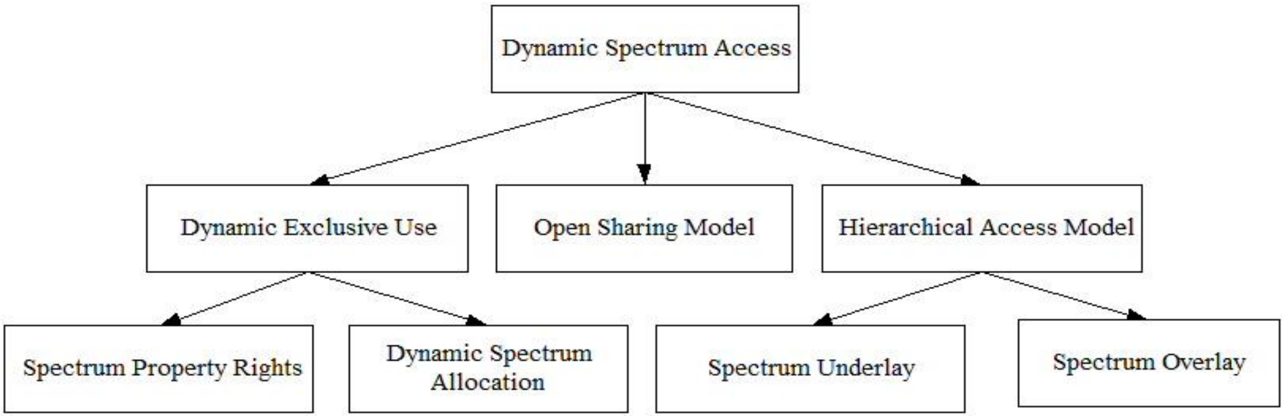

Figure 1. Classification of dynamic spectrum access [14]

other's presence as interference and try to avoid the interference autonomously by changing their behavior accordingly. In dynamic spectrum sharing, SUs are not allowed to cause harmful interference to the incumbent primary users. It is worth to note that the SUs are essentially invisible to the PUs in CR network, hence possibly no changes are needed for licensed users/devices. In such scenario, SUs can either be allowed to transmit at low power as in UWB system or be allowed to use spectrum opportunities dynamically to transmit without causing the harmful interference to PUs. In latter case, the CR network autonomously detects and exploits idle spectrum where and when the PUs are not active. This helps to increase the system capacity and efficiency, and the dynamic spectral access implies the SU be able to work in multi-band, different wireless channels, and support multimedia services and/or applications.

As conventional and existing wireless communication networks are operating based on fixed spectrum assignment to the service providers and their users for exclusive use on a long-term basis result in spectrum scarcity, the CR technology uses the spectrum opportunities dynamically without creating harmful interference to licensed users. In order to fully realize the CR system, the detection of primary user signal is the most important and fundamental step. Therefore CR system requires a signal processing for spectrum sensing implementation to detect both interference and the absence or presence of primary users.

The paper is organized as follows: Section 2 presents the background. Section 3 deals with signal detection methods followed by their comparison in Section 4. Section 5 summarizes the paper.

2. Background

In CR network, the spectrum sensing play a major role to realize its full potential of spectrum utilization in real environment since the sensed information is used to decide the operations of CR users. CR users perform the sensing of spectrum, and the sensed information is analyzed to make wise decision in timely and accurate manner. A significant number of projects have addressed cognitive radio all over the world during the recent years. In the following Section, we first review the spectrum sharing models for dynamic spectrum access [14] for CR networks and capabilities of cognitive radio users.

2.1. Spectrum Sharing Models of Dynamic Spectrum Access

The dynamic spectrum access is the new concept opposite of static frequency spectrum assignment and its management. The dynamic spectrum access strategies can be broadly categorized in three groups as sown in Figure 1.

2.1.1. Dynamic Exclusive Use Model

This spectrum access model is like a traditional model in which the spectrum bands are licensed to service providers for exclusive use. However, in order to introduce the flexibility to improve the spectrum efficiency, this model has two approaches. The first is *spectrum property rights* in which licensee have exclusive rights to freely choose technologies, and sell and trade their spectrum. The other one is *dynamic spectrum* allocation in which the spectrum is allocated exclusively for service providers for given region and time.

2.1.2. Open Spectrum Sharing Model

This model consists of wireless services operating in unlicensed industry, scientific and medical (ISM) radio band such as in wireless LAN or WiFi, where all users has equal opportunities to access the spectrum. However, the CR user can prefer the channels, which has sparse or moderate traffic (or users) than the channel with heavy traffics (or users).

2.1.3. Hierarchical Spectrum Access model

This model consists of hierarchy between primary licensed user and secondary unlicensed CR users. In this sharing model, unlicensed secondary users can access the spectrum dynamically, which is not licensed to them; but by making sure that the interference created to licensed primary user is within the tolerable range or using the idle spectrum opportunistically without interfering the primary user transmissions. This model has two basic approaches: spectrum overlay and spectrum underlay. In spectrum overlay model, the CR will have to identify the idle spectrum band, which are not used by licensed system at a given time and location, and use those idle bands dynamically. This model is presented in Figure 2 (a). Whereas in spectrum underlay approach, the secondary CR users are allowed to transmit with low transmit power as in UWB (ultra-wide band) technology. This model is presented in Figure 2 (b). Both methods have their advantages and disadvantages. For instance, in spectrum overlay approach; secondary CR users

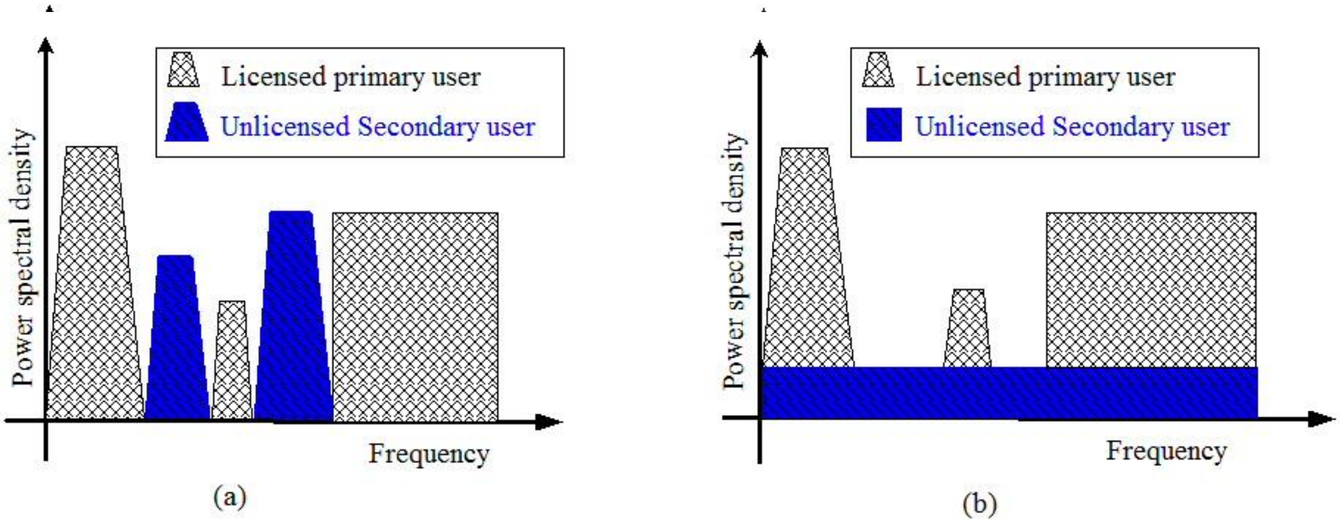

Figure 2. Spectrum overlay and underlay approaches

can transmit with high transmission power to increase their rates for given spectrum opportunities however they have to identify the idle frequency bands which are not used by primary users. Similarly, in spectrum underlay approach, the secondary users do not need to identify the spectrum opportunities and can transmit simultaneously coexisting with primary users however they are not allowed to transmit with high transmission power even if entire RF band is idle (i.e., entire RF is not used by primary users).

Moreover, the dynamic spectrum sharing by CR users in given spectrum band can be categorized as in Figure 3, that is

- **Horizontal sharing**, where CR users and primary users have equal opportunities to access the spectrum such as in wireless LAN operating in ISM band at 2.4GHz, and in order to improve the overall system performance, CR users can choose the channels which have less traffics or less number of users. In this approach CR users and primary users coexist in the system and use the bands simultaneously.
- **Vertical sharing**, where CR users have less preference over the primary users, and thus CR user must vacate the spectrum as fast as possible once the licensed primary user are detected in the band. However, CR users can use the spectrum with potential whenever they detect the idle spectrum band. Moreover, in vertical sharing, CR system needs operator’s assistant.

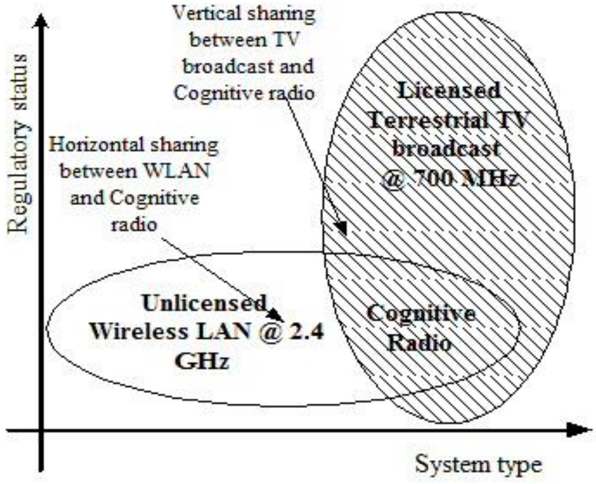

Figure 3. Spectrum sharing by CR users with different types of systems depending on regulatory status of incumbent radio systems: vertical and horizontal sharing of spectrum

2.2. *Capabilities of Cognitive Radios*

Cognitive radio technology is regarded as emerging technology for efficient spectrum use in dynamic fashion. The main capabilities of cognitive radios can be categorized according to their functionality based on the definition of the cognitive radio in [4] as follows:

- **Sense the environment**, which is cognitive capability, where a CR sense the spectrum either to identify the frequency band not used by licensed primary users or to make sure that the cognitive radio is not creating harmful interfere to primary users. In order to sense the environment, it will first discover the network around it. Furthermore, cognitive radio will identify its location in order to choose the transmission parameters according to its position.
- **Analyze and learn sensed information**, which is self-organized capability, in which CR should be able to self-organize their communication based on sensed information.
- **Adapt to the operating environment**, which is re-configurable capability, for which the CR will choose best transmission parameters such as operating frequency, modulation, transmission power and so on.

Main capabilities of CR users depend on sensed information from which they analyze and learned and then adapt their own operating parameters accordingly. Therefore spectrum sensing is a fundamental step in CR system, which is the major subject matter of the following section.

2.3. *Spectrum Sensing Methods for Cognitive Radios*

As we noted in previous section, most of the functionalities of CR users depend on the information

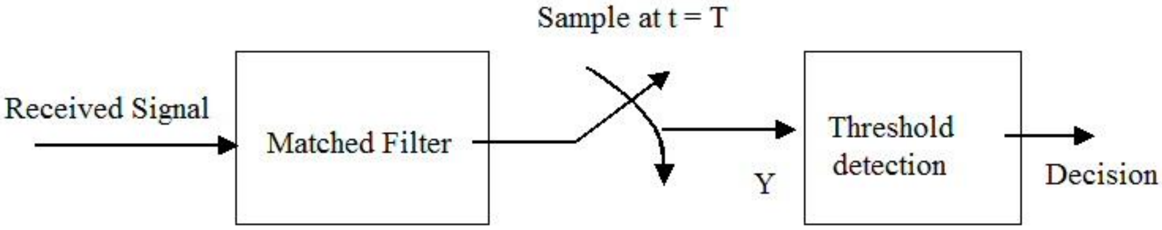

Figure 4. Matched filter for signal detection

obtained from spectrum sensing. Furthermore, in order to access the available unused spectrum opportunistically and/or dynamically, CR network requires a spectrum sensing or estimation implementation to detect both interference and/or the presence of PUs. Several techniques have been proposed in the literature [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] to detect the primary user signal in spectrum sensing.

We note that the signal processing for spectrum sensing or estimation can be categorized into *direct* and *indirect* methods. The *direct* method is recognized as frequency domain approach where the estimation is carried out directly from signal. Whereas the *indirect* method is known as time domain approach where the estimation is performed using autocorrelation of the signal.

Furthermore, the other way of categorizing the spectrum estimation and sensing techniques is by grouping them into model based *parametric* method and periodogram based *non-parametric* method [30].

However, in this paper, we present signal detection techniques for spectrum sensing by categorizing into five groups as follows:

- **Primary transmitter detection**: Detection of primary users/signal is performed based on the received signal at CR user-receiver. This approach includes matched filter (MF) detection [19, 31], energy based detection [21, 22, 17], covariance based detection [15], waveform-based detection [18], cyclostationarity based detection [20], radio identification based detection [32], and random Hough Transform based detection [23].
- **Primary receiver detection:** In this method, spectrum opportunities are detected based on primary user-receiver's local oscillator leakage power [25].
- **Cooperative detection:** In this approach the primary user-signal for spectrum opportunities are detected reliably by interacting or cooperating with other users [16, 27, 28], and the method can be implemented as either centralized access to spectrum coordinated by a spectrum server [33] in distributed approach implied by the spectrum load smoothing algorithm [34] or an external detection [29].
- **Interference temperature management:** In this approach, CR system works as an UWB technology where the secondary users coexist with primary users and are allowed to transmit with low power and restricted by the interference temperature level so as not to cause harmful interference to primary users [35, 36].
- **Other Approaches**: We put some methods, which do not fit into above categories such as wavelet-based detection [24], multi-taper spectrum sensing or estimation [37, 4], and filter bank based spectrum sensing [26] in this group.

Our main goal in this paper is to present the comprehensive state-of-the-art research result of signal detection techniques for spectrum sensing CR networks in which the sensed information is used to make automatic and wise decision by CR users so that they operate according to their RF environments. In the following section we present the system description and signal processing methods for cognitive radio networking.

3. Signal Detection Methods for Spectrum Sensing

In this section, we present details of different methods for signal processing which are applicable in spectrum sensing for CR users grouping them in different categories.

3.1. Primary Transmitter Detection

This approach contains several methods in which we process the received signal (actually transmitted from primary transmitter to primary receiver) at CR receiver which want to use the spectrum opportunities locally for a given time and location. In this section, we present most common techniques for signal detection for spectrum sensing in CR systems.

In order to detect the primary user signal in the system to find the spectrum opportunity, we consider the received signal at CR receiver in continuous time as

$$y(t) = gs(t) + w(t) \tag{1}$$

where y(t) is the received signal, g is channel gain between primary transmitter to CR receiver, s(t) is the primary user's signal (to be detected), and w(t) is the additive Gaussian white noise (AWGN).

In order to use the signal processing algorithms for spectrum sensing, we consider the signal in the frequency band with central frequency fc and bandwidth W, and sample the received signal at a sampling rate fs, where fs >W, and Ts = 1/fs is the sampling period. Then we can define y(n) = y(nTs) as the received signal samples, s(n) = s(nTs) as the primary signal samples and w(n) = w(nTs) as the noise samples, and can write the sampled received signal as

$$y(n) = gs(n) + w(n) \tag{2}$$

If we consider the channel gain g=1 (i.e., ideal case) between the terminals then (2) becomes

$$y(n) = s(n) + w(n) \tag{3}$$

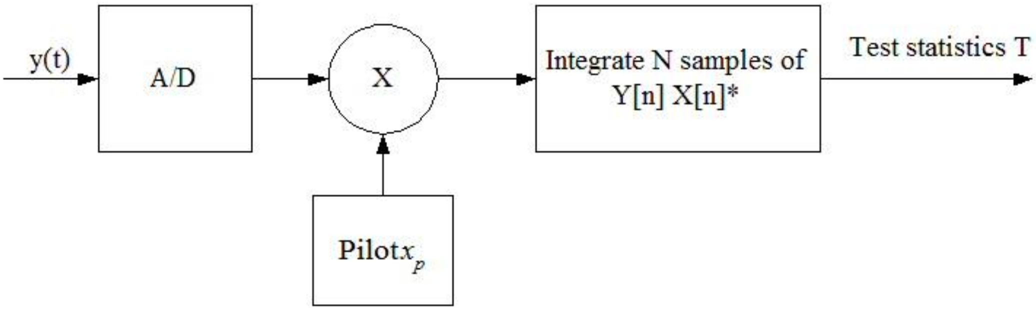

Figure 5. Pilot signal and matched filter based detection [19]

For the received signal, two possible hypotheses considered for primary user detection can be written as: H0 to denote that the signal s(n) is not present, and H1 to denote that the signal s(n) is present. That is, the received signal samples under the two hypotheses are

$$y(n) = \begin{cases} w(n) & \mathrm{H}_0 \\ s(n) + w(n) \quad \text{or} \quad gs(n) + w(n) & \mathrm{H}_1 \end{cases} \tag{4}$$

In this section, we will deal with the system model given in equation (2) or (3) with given two hypotheses in (4) for primary transmitter detection methods, and then proceed with detection techniques to identify the presence of the primary user signal. If the signal component s(n)=0 in equation (3), the particular frequency spectrum band may be idle (if the detection is error free). When the signal is present (i.e. s(n) ≠ 0), the particular frequency spectrum/band is in use and there is no spectrum whole for a given time and location.

3.1.1. *Matched Filtering Based Signal Detection*

When the transmitted signal is known at receiver, matched filtering (MF) is known as the optimal method for detection of primary users [31] since it maximizes received signal-to-noise ratio (SNR), and the SNR corresponding to the equation (3) is

$$\gamma = \frac{|s(n)|^2}{E[w^2(n)]} \tag{5}$$

Simple matched filter based detection can be implemented as shown in Figure 4, where threshold is used to estimate the signal.

Cabric et al [19] use matched filter for pilot signal and matched filter-based detection where the method assumes that the primary user sends pilot signal along with data. The process is depicted in Figure 5. The matched filter performs best when the signaling features to be received are known at the receiver.

In spite of best performance, the MF has more disadvantages than its advantages: *First*, MF requires perfect knowledge of the primary user signaling features (such as modulation type, operating frequency, etc), which is supposed to be detected at cognitive radio. As we know cognitive radio will use wide band of spectrum wherever it finds the spectrum opportunities. Therefore it is almost impossible to have MF implemented in cognitive radio for all types of signal in wide band regime. *Second*, MF implementation complexity of detection unit in CR devices is very high [19] because CR system needs receivers for all signal types of wide band regime. *Lastly*, large power will be consumed to execute such several detection processes as CR device sense the wideband regime. Therefore the disadvantages outweigh the advantages of MF based detection. It is important to note that MF based technique might not be a good choice for real CR system because of its above-mentioned disadvantages.

3.1.2. *Covariance Based Signal Detection*

This is another method to detect the primary signal by CR users. Zeng and Liang [15] have proposed covariance based signal detection whose main idea is that to exploit the covariance of signal and noise since the statistical covariance of signal and noise are usually different. These covariance properties of signal and noise are used to differentiate signal from noise where the sample covariance matrix of the received signal is computed based on the receiving filter. We consider the system model for received signal as in equation (2), and the received signal in a vector channel form can be written as [15]

$$\mathbf{y} = \mathbf{Gs} + \mathbf{w} \tag{6}$$

where G is channel matrix through which the signal travels. The covariances corresponding to the signal and noise can be written as

$$\left.\begin{aligned} \mathbf{R_y} &= E[\mathbf{yy}^T] \\ \mathbf{R_s} &= E[\mathbf{ss}^T] \\ \mathbf{R_n} &= E[\mathbf{ww}^T] \end{aligned}\right\} \tag{7}$$

where *E*[.] is the expected value of [.]. If there is no signal (**s** = 0), then $\mathbf{R_s}$ = 0 and therefore the off-diagonal elements of $\mathbf{R_y}$ are all zeros. If there is signal (**s** ≠ 0) and the signal samples are correlated, and thus $\mathbf{R_s}$ is no more a diagonal matrix. Therefore, some of the off-diagonal elements of $\mathbf{R_y}$ should not be zeros. Hence, this method detects the presence of signals with the help of covariance matrix of the received signal. That is, if all the off diagonal values of the matrix $\mathbf{R_y}$ are zeros, then the primary user is not using the band at that time and location, and otherwise the band is not idle.

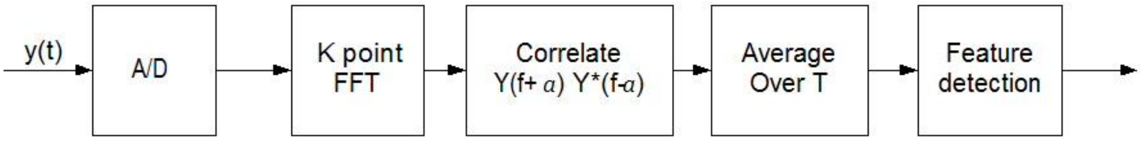

Figure 7. Digital implementation of cyclostationarity based feature detection [19].

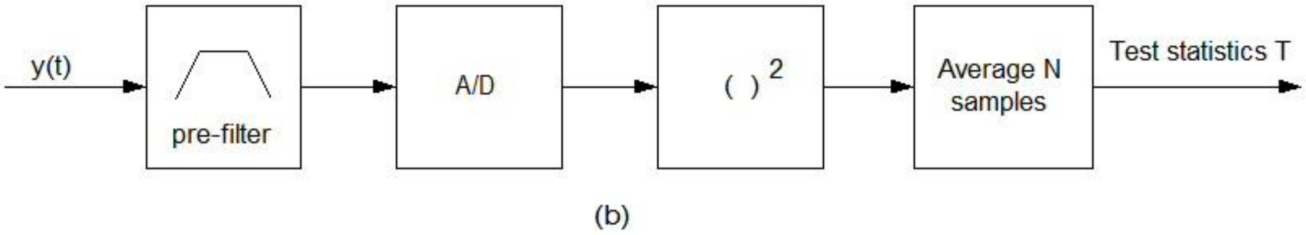

Figure 6. Digital implementation of energy detection (a) with periodogram: FFT magnitude squared and averages, (b) with analog pre-filter and square-law device [16].

3.1.3. Waveform-Based Detection

This is another approach for primary signal detection. In this approach, the patterns corresponding to the signal, such as preambles, midambles, regularly transmitted pilot patterns, spreading sequences, etc, are usually utilized in wireless systems to assist synchronization or detect the presence of signal. When a known pattern of the signal is present, the detection method can be applied by correlating the received signal with a known copy of itself [18] can be performed and the method is known as waveform-based detection. Tang in [18] has shown that waveform-based detection is better than energy based detection (presented in the following section) in terms of reliability and convergence time, and also has shown that the performance of the algorithm increases as the length of the known signal pattern increases.

In order to perform waveform-based signal detection, we consider the received signal in (3) and compute the detection metric as [18]

$$\begin{aligned} D &= \mathrm{Re}\left[\sum_{n=1}^{N} y(n)s^*(n)\right] \\ &= \sum_{n=1}^{N} |s(n)|^2 + \mathrm{Re}\left[\sum_{n=1}^{N} w(n)s^*(n)\right] \end{aligned} \qquad (8)$$

where N is length of known pattern. The detection metric D for waveform-based detection in equation (8) consists of two terms: the first term $\sum_{n=1}^{N} |s(n)|^2$ in second equality is related to signal and the second term $\mathrm{Re}\left(\sum_{n=1}^{N} w(n)s^*(n)\right)$ of second equality consist of noise component. Therefore we can conclude that when the primary user is idle (i.e. *s(n)=0)*, the detection metric D will have only second term of second equality in (8) that is only noise, and when $s(n)\neq 0$, then D will have both terms of second equality in (8). In order to detect the signal, the metric D value can be compared with some threshold value λ and the detection of the signal can be formulated as

$$\left.\begin{aligned} P_T &= \Pr(D > \lambda \mid \mathrm{H}_1) \\ P_D &= \Pr(D > \lambda \mid \mathrm{H}_0) \end{aligned}\right\} \qquad (9)$$

where P_T is the probability of true detection, that is, when signal is present in the frequency band and the detection is successful, and P_F is the probability of false alarm, that is, the detection algorithm shows that the frequency is occupied however actually it is not.

The basic idea is to reduce probability of false alarm P_F. We note that the choice of threshold λ plays major role in this detection approach and can be estimated or predicted based on noise variance. We also note that measurement results presented by Cabric, et al. in [16] show that waveform-based detection requires short measurements time, however, it is susceptible to synchronization errors.

3.1.4. Energy Detection

Another approach for primary user detection for spectrum sensing is energy detection. This method is regarded as the most common way of signal detection because of its low computational and implementation complexities [19]. Unlike in matched filters and other approaches, in energy detection method, the receivers do not need any kind of knowledge of the primary users' signals.

In this method, the signal detection is performed by comparing the output of energy detector with a given threshold value [21] and the threshold value as in waveform-based approach depends on the noise floor and can be estimated based on it. The Figure 6 (a) and 6 (b) show the digital implementation of energy detection. In periodogram approach as in Figure 6(a), first of all the signal is converted from analog to digital and applied Fast Fourier Transform (FFT). The output of FFT process is squared and then averaged it to get test statistics. Based on the test statistics, the absence or presence of the signal in the particular band is identified. In analog pre-filter approach as depicted in Figure 6 (b), the signal is pre-filtered before converting from analog to digital. Then the signal is converted to digital followed by

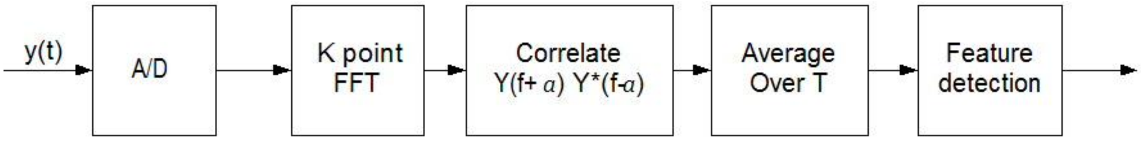

Figure 7. Digital implementation of cyclostationarity based feature detection [19].

squaring and averaging to get the test statistics. In both implementations, the statistics are compared with given thresholds and then made decision about signal's presence or absence.

For energy detection method, we can consider system model given in (3) and compute the decision metric as

$$D = \sum_{n=1}^{N} | y(n) |^2 \qquad (10)$$

Assuming the variance of AWGN σ_n and the variance of the signal σ_s, the decision metric D follows chi-square distribution with $2N$ degrees of freedom $(\chi_{2N})^2$ [21], and can be modeled two hypotheses as follows

$$D = \begin{cases} \dfrac{\sigma_w^2}{2} \chi_{2N}^2 & H_0 \\ \dfrac{\sigma_s^2 + \sigma_w^2}{2} \chi_{2N}^2 & H_1 \end{cases} \qquad (11)$$

In this approach, the false alarm probability P_F and true detection probability P_T can be calculated using two hypotheses making comparison with the chosen threshold value as in (9). Again we note that the method has some disadvantages such as without proper choice of threshold value results in undesirable probability of true detection and false alarm, poor performance under low Signal-to-Noise-Ratio (SNR) value [18], and inability to differentiate between interference from licensed users and noise that might limit the performance of this approach. In addition, this approach does not work optimally for detecting spread spectrum such CDMA signals [19].

3.1.5. Cyclostationarity-Based Detection

The cyclostationarity based signal detection method is also regarded as a good candidate for spectrum sensing in CR systems. This method takes advantage of cyclostationarity properties of the received signals [20, 38] to detect primary user transmissions. The digital implementation of this approach is depicted in Figure 7.

The basic idea in this method is to use the cyclostationarity features of the signals. In general, the transmitted signals are stationary random process and furthermore the cyclostationarity features, that are the periodicity in signal statistics such as mean and autocorrelation, are induced because of modulation of signals with sinusoid carriers, cyclic prefix in OFDM, and code sequence in CDMA. On the other hand, the noise is considered as Wide-Sense Stationary (WSS) with no correlation. Therefore, this method can differentiate primary users' signals from noise [20]. In this method, cyclic spectral correlation function (SCF) is used for detecting signals present in a given frequency band and the cyclic SCF of received signal in equation (3) can be calculated as [20, 38]

$$S_{yy}^{\alpha} = \sum_{\tau=-\infty}^{\infty} R_{yy}^{\alpha}(\tau) e^{-j2\Pi f} \qquad (12)$$

where $R_{yy}^{\alpha}(\tau)$ is the cyclic autocorrelation function which is obtained from the conjugate time varying autocorrelation function of *s(n)*, which is periodic in *n*, and the α is the cyclic frequency. We note that when the parameter $\alpha = 0$ the SCF becomes power spectral density. When the signal is present in the given frequency spectrum, this method gives the peak in cyclic SCF implying that the primary user is present. If there is no such peak, the method implies that the given spectrum band is idle or there is no more primary user active at given time and location. Based on this observation, CR users identify the status of absence or presence of primary users in the particular band in a given time and location.

3.1.6. Random Hough Transform Based Detection

This approach is borrowed from image processing filed. We note that the Hough transform is widely used for pattern (such as lines, circles) detection in image processing. Recently, Random Hough transform has been proposed for CR in [23], where the Random Hough transform of received signal *y(n)* is used for identifying the presence of radar pulses in the operating channels of IEEE 802.11 wireless systems. If some patterns related to primary users are identified, CR

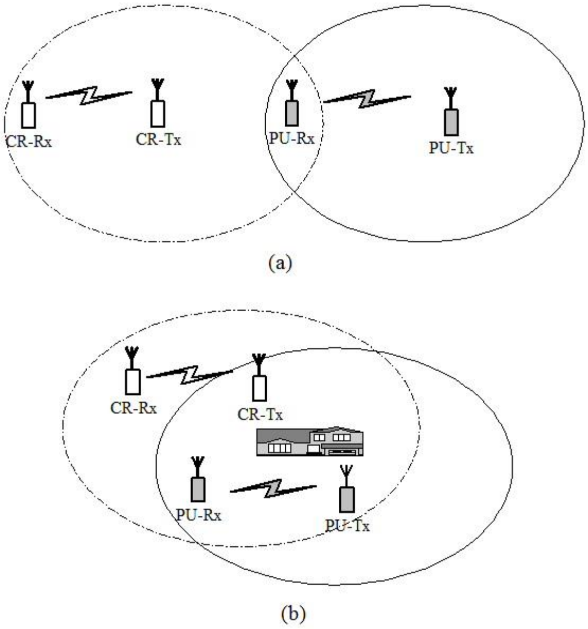

Figure 8. Hidden primary user problem because of (a) path loss and (b) shadowing/blocking

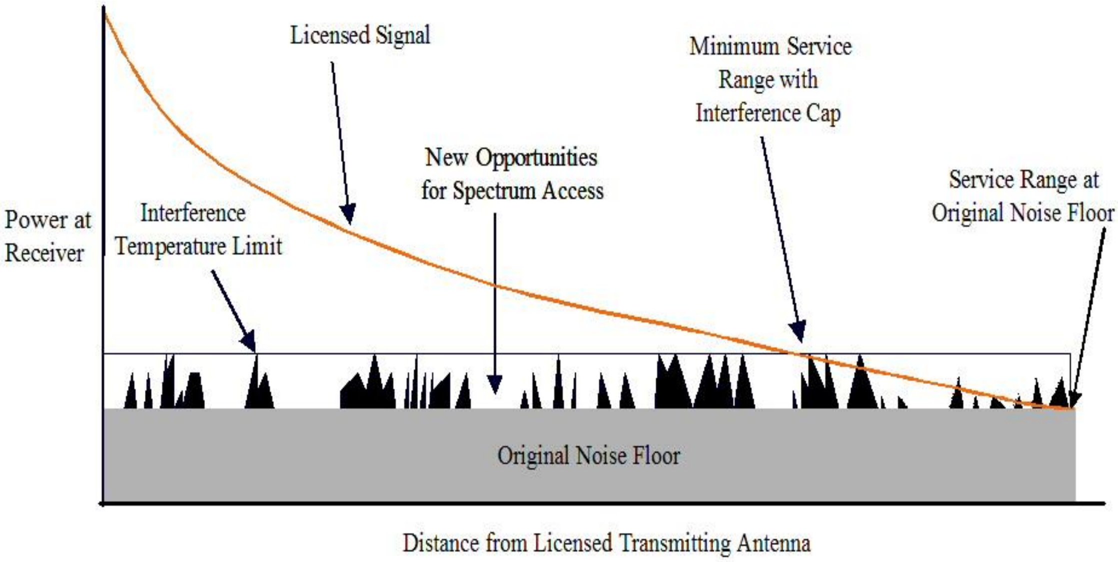

Figure 9. Interference temperature model

users assume that primary user uses the spectrum. Otherwise, CR users will assume that the band is idle for given time and location.

3.1.7. Radio Identification Based Detection

This approach is used in European Transparent Ubiquitous Terminal (TRUST) project for feature extraction and classification techniques, and this extracted information can be used in cognitive radio networks. In radio identification approach, several features such as transmission frequency, transmission range, modulation technique, etc, are extracted from the received signal $y(n)$ in (3), which are used for selecting the most suitable secondary user technology [32] for the CR transmission. In this approach, CR users decide the transmission parameters and technology suitable according to the sensed information.

3.2. Primary Receiver Detection

This is alternative of primary transmitter detection method. Basically, in primary *receiver detection* method, the usage of primary spectrum is identified based on primary user-receiver's local oscillator leakage power of RF front end. In order to detect idle bands of licensed system, the basic idea in this approach is to detect primary user-receivers, which are within the communication range of CR system users. In general, primary receiver emits the local oscillator (LO) leakage power from its RF front-end while receiving the data from primary transmitter. Using that leakage power, one can detect the primary signal as in [25]. Wild and Ramchandran [25] have proposed a new CR architecture consisting of sensors to detect the LO leakage, and those sensors communicate the spectrum usage to the CR system. We note that this approach does not introduce any modification to primary user devices however the CR system need to be equipped with sensor and communication capability to detect the primary receiver LO leakage power, and report to the CR transmitter. Using received information from sensors; the CR transmitters will identify the spectrum opportunities for given time and location to transmit their data.

This method is more realistic in a sense that when the CR transmitter communicates with its receiver, it creates interference to the primary receivers if the primary receiver is nearer than the CR receiver. Moreover, the primary transmitter might be far way and the primary signal might be faded out when it is received at secondary CR users and identification of spectrum opportunities might not be reliable. In these cases this approach can be considered as robust one.

3.3. Cooperative Detection

In cooperation based spectrum sensing, CR users can use any suitable method for primary spectrum sensing and collaborate for the sensed information among participating users in order to increase the reliability of sensing.In cooperative detection, the spectrum estimation can be done by interacting or collaborating with other wireless users [16] in order to get reliable and accurate information regarding spectrum opportunities. In wireless system, there is well known hidden terminal (primary user) problem as shown in Figure 8 (a) because of path loss (or network coverage) and Figure 8 (b) because of shadowing or blocking of transmission. This hidden terminal problem in detecting primary user results in increase in false alarm, which is undesirable for spectrum sensing in cognitive radio systems. Therefore, in order to address this kind of problem as well as to increase the reliability of sensed information, the CR user can cooperate or collaborate with other CR users and/or primary users to share the information. Therefore, this method can solve the hidden terminal (primary user) problem [16]. In addition, this method helps to solve many problems in spectrum estimation; for instance, it reduces both probability of miss-detection and false alarms.

Cooperative detection for spectrum sensing can be performed in one of the ways: centralized server based, external detection, and distributed detection. We will discuss one by one in the following section.

3.3.1. Centralized Server Based Detection

In centralized detection, a central unit, that is a server, collects all the sensed information related to spectrum occupancy from CR devices, aggregates the available information centrally, and then disseminates or broadcasts the aggregated information related to spectrum status to all CR users [33, 39]. When the CR user receives the aggregated information related to spectrum occupancy, CR users adapt their transmission parameters according to the received information. Since the spectrum server gathers the information from all other users, this spectrum server is assumed to be just an information collector without having spectrum sensing capability built on it. It is noted that the central server acts like an information fusing device for CR systems and does not play any role on spectrum sensing. Furthermore, individual CR users sense the information and transmit it to their server. Individual CR users are participating in information collaboration. Individual CR users decide to utilize the spectrum opportunistically and dynamically based on aggregated information received from centralized server instead of individually sensed information.

3.3.2. External Detection

External detection technique can be considered as an alternative approach of centralized server based cooperative detection. In this method, similar to centralized server based approach, all CR users obtain the spectrum information from external detection agent [29]. However unlike the centralized server based detection, an external agent performs the spectrum detection or sensing since the external agent is equipped with sensing capability with spectrum sensors. Once external agent senses the spectrum, it disseminates the sensed information of spectrum occupancy for CR users. It is important to point our here is that the individual CR devices will not have spectrum sensing capability unlike in centralized server based detection. CR users do not have their own sensing unit however they decide which spectrum band is to be used and with what transmission parameters and technologies. Because of the external agent based sensing, this approach also helps to overcome hidden primary user problem as well as the uncertainty due to shadowing and fading [29]. Furthermore, this method is also efficient in terms of time, spectrum and power consumptions from the prospective of CR systems since CR users do not spend time and power for signal detection [29] as the spectrum sensing is performed by external agent. This approach can be seen as good candidate for CR system to overcome technical problems however it is important to perform cost benefit analysis before recommending it for the implementation in CR system.

3.3.3. Distributed Detection

In contrast to the centralized and external detection, in distributed cooperative detection, CR users make their own decision based on their individually sensed information and the information received from other interacting or cooperating users. Unlike in centralized and external detection, in this approach individual CR users need to have installed individual sensing unit on them. Therefore, we do not need a high capacity centralized backbone infrastructure (centralized spectrum server or external agent) in this approach. This can be seen as economically advantageous over other methods. Instead of deciding the utilization of spectrum opportunities based on individually sensed information, this approach considers the sensed information from other collaborating CR users who are also seeking the spectrum access dynamically and opportunistically, to make decision regarding the dynamic spectrum utilization. This method increased the probability of true detection and decreases the probability of false alarm related to actual spectrum occupancy. Basically, the distributed approach can be implemented in CR devices by using spectrum load smoothing algorithms [34].

3.4. Interference Temperature Management

This approach considers the spectrum underlay approach for dynamic spectrum access or spectrum utilization. When primary and secondary user co-exist and transmit their data simultaneously, the *interference temperature management* is the best approach to protect primary users from the interference caused by secondary users by imposing some constraints (e.g., low transmit power) to secondary CR users so as not to exceed specified interference limit. The interference temperature based approach is illustrated in Figure 9.

The basic idea behind the interference temperature management is to set up an upper limit in interference power for given frequency band in specific geographic location such that CR users are not allowed to create harmful interference while using the specific band in specific area [35, 36]. This approach works as an UWB technology where the secondary users' are allowed to transmit simultaneously with primary users using low transmit power, and are restricted by the interference temperature level so as not to cause harmful interference to primary users [35, 36]. In this approach, CR users do not have to sense and wait for spectrum opportunities for their communications but they are restricted by some operating constraints, as they have to respect the incumbent primary users.

However, secondary CR users cannot transmit their data with higher power because of imposed low transmit power and interference temperature limit even if the licensed system is completely idle for given time and location. This can be seen as a disadvantage of the approach.

3.5. Other Approaches

Some methods, which do not fit in above groups and are

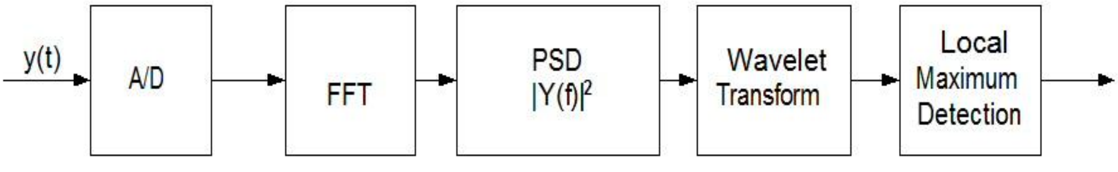

Figure 10. Digital implementation of a wavelet detector

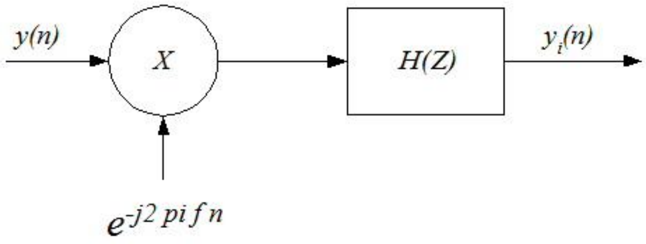

Figure 11. Demodulation of received signal with ith sub-carrier before it is processed through root-Nyquist-filter [26].

applicable for spectrum sensing in CR system are kept in this category. Some of these methods are seen as more suitable candidate for future development of CR systems. We present such some approaches in the following section.

3.5.1. Wavelet-Based Detection

The wavelet based detection method is popular in image processing for edge or boundary detection. Tian and Giannakis in [24] use wavelets for detecting edges in the power spectral density (PSD) of a wideband channel. The process for wavelet-based detection is illustrated in Figure 10.

In this approach, signal spectrum is decomposed into smaller non-overlapping sub-bands to apply the wavelet-based approach to detect the edges in PSD. We note that the edges on the PSD are the divider of occupied bands and non-occupied bands (or spectrum holes) for a given time and location. Based on this information, CR users can identify spectrum holes or opportunities and exploit them optimally.

Hur et al in [40] has proposed another wavelet approach for spectrum sensing by combing coarse and fine sensing resulting in Multi Resolution Spectrum Sensing. The basic idea is by correlating the received signal with the modulated wavelet to obtain the spectral contents of the received signal around the carrier frequency in the given band processed by the wavelet. By analyzing dilated versions of the wavelet and scaling functions, wavelet has the capability to dynamically tune time and frequency resolution [41]. In addition, time resolution can be compromised and traded-off with high frequency resolution for segments of slow varying signal [41].

3.5.2. Multi Taper Spectrum Sensing/Estimation

Thomson proposed Multi Taper Spectrum Estimation (MTSE) in [37], in which the last N samples of received signal are collected in a vector form and represented them as a set of Slepian base vectors. The Slepian base vectors are used to identify the spectrum opportunities in the targeted spectrum band. The main idea of this approach is that to utilize its fundamental property, that is, the Fourier transforms of Slepian vectors have the maximal energy concentration in the bandwidth f_c-W to f_c+W under a finite sample-size constraint [37, 4]. After MTSE, by analyzing this feature, CR users can identify whether there is spectrum opportunity or not. This method is also regarded as efficient method for small sample spaces [26].

3.5.3. Filter Bank Based Spectrum Sensing

Filter Bank Based Spectrum Sensing (FBSE) is simplified version of MTSE by introducing only one prototype filter for each band, and is proposed for cognitive radio network in [26]. The main idea of FBSE is to assume that the filters at the receiver and transmitter sides are a pair of matched root-Nyquist filters $H(z)$ as in Figure 11. Specifically, the FBSE has been proposed for multi-carrier modulation based CR systems by using a pair of matched-root-Nyquist-filter [26]. The approach for demodulation of received signal with i^{th} sub-carrier before it is processed through root-Nyquist-filter is presented in Figure 11.

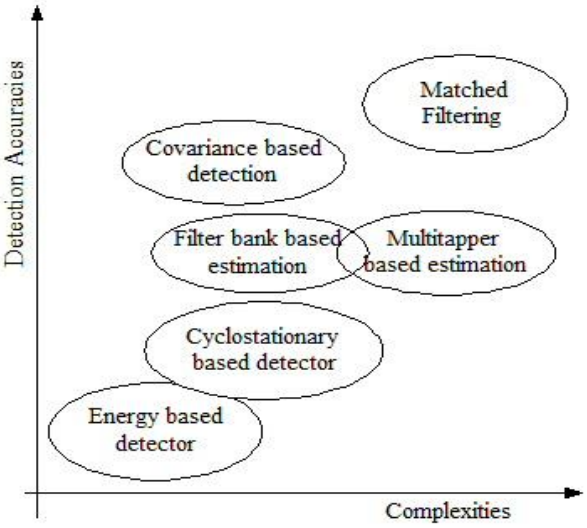

Figure 12. Comparison of different techniques for spectrum sensing methods for spectrum overlay in terms of sensing accuracies and implementation complexities.

As noted, FBSE is simplified version of MTSE, it uses the same concept of maximal energy concentration in the bandwidth f_c-W to f_c+W. Based on this information, spectrum occupancy can be obtained to identify the spectrum opportunities. For the comparison, MTSE is better for small sample spaces whereas FBSE is better for large number of samples [26]. Furthermore, MTSE approach increases the computational complexity and hence might not be suitable for CR system in which CR users have to sense the wideband regime.

4. Comparison of spectrum sensing methods

We presented several signal processing methods for spectrum sensing applicable to cognitive radio systems. Among them some methods are suitable for one system consideration and technologies and others are suitable for different system consideration and technologies. We note that there is no optimal and universal such technique available yet where the method is suitable to all kind of technologies for CR systems in wideband regime. In this section we compare main signal processing techniques for spectrum sensing in terms of sensing accuracies and complexities. We present the different methods for primary transmitter detection in Figure 12. Among them, MF is giving highest accuracies with high complexity. High complexity is because of implementation of many MFs in CR devices for spectrum sensing in wide band regime. Whereas energy based detector is least accurate and least complex since we do not need any special kind of filers and the detector uses the energy of the signal during the detection process. In terms of implementation complexity this approach is suitable for CR system, however it is more prone to noise level and interference from close proximity. Others are in the kind of middle in terms of accuracy and complexities.

Sometime the primary transmitter might be far way from CR users. In this case if we apply primary transmitter detection approach for spectrum sensing, low probability of true detection results in because of fading and other blockings. In this case primary receiver detection is suitable for spectrum sensing. However, in this system CR users should be close enough to listen LO power leakage in order to sense the spectrum. This might be seen a disadvantage of this approach.

We note that in spectrum overlay approach; CR users need to identify the spectrum opportunities or holes to utilize them opportunistically. If primary users use the spectrum all the time, CR users will not get a chance to access the channel for their transmission. In such case spectrum underlay approach is applicable in which interference temperature management is important where CR users do not need to sense for the spectrum but have to transmit with severe low transmit power so as not to create harmful interference to the primary systems. However they are not allowed to transmit with high power when the primary system is idle leaving whole spectrum unutilized. This is the drawback of this method. However, there are many challenges to differentiate the legitimate CR users and malicious CR users whose intention to disturb the primary users' transmissions.

In single CR user based spectrum sensing methods, a CR user can come up with wrong decision of spectrum occupancy and create the interference to the primary users. For this type of problem, cooperative or collaborative spectrum sensing is more practical. In such collaborative approaches, CR users rely on aggregated sensing information rather than only on its sensed information, the reliability and accuracy is increased significantly, and problems such as hidden primary user problem will be overcome. However, collaboration will create some network overhead both economically (to install external agent, or spectrum server, etc) and technically (network traffic overload).

Similarly, Farhang-Boroujeny and Kempter in [26] have noted that FBSE outperforms MTSE with low PSD since MTSE uses multiple prototype filters [37, 4] for a given frequency band and the best response corresponds to the largest eigenvalue of the auto-correlation matrix of the observation vector. Moreover, MTSE is better for small sample spaces whereas FBSE is better for large number of samples. In addition, MTSE approach increases the computational complexity and hence might not be suitable for CR system. Recently, FBSE has attracted the researcher from both academia and institutes [43]. However, FBSE assumes that multi-carrier modulation technology as the underlying communication technique, which can be considered as its drawback if we try to implement FBSE in other system with different communication technologies.

In order to realize the CR system in wireless communications for efficient utilization of underutilized scarce spectrum, the interference and spectrum sensing methods should be reliable and prompt so that the primary users will not be hampered or disturbed from CR system to utilize their own spectrum. We note that the licensed primary users can claim their own frequency band at any time while CR system is operating on the band opportunistically in spectrum overlay model and coexist in spectrum underlay model. Whatever model and methods have been implemented, the CR system should be able to identify the presence of primary user as fast as possible in order to respect the primary user. However, the signal detection methods have limitations on the performance of detection in terms of time and frequency resolution. Since the CR system is still in its early stages of development, there are number of challenges for its implementation such as time for primary user signal detection, hardware implementations in CR devices and computational complexities in CR devices [42]. Furthermore, the "spread spectrum primary user" (or CDMA system user) detection is also difficult since the energy is spreaded all over wider frequency range for the user.

Last but not least, the best signal processing technique for spectrum sensing in CR system would be the one that offer low sensing time, minimum hardware and computational complexities, and fine tuned time and frequency resolution. In some sense, FBSE and wavelet based spectrum estimation seem suitable for the time being. However, future research should be focused to address the existing problems in order to realize the full potential of CR system for dynamic spectrum access.

5. Summary

In this paper, we presented state-of-the-art research results in signal processing methods for spectrum sensing in CR system for dynamic spectrum access. Considering the challenges raised by cognitive radios, the use of spectrum sensing method appears as a crucial need to achieve satisfactory results in terms of efficient use of available spectrum and limited interference with the licensed primary users. As described in this paper, the development of the cognitive radio network requires the involvement and interaction of many advanced techniques, including distributed spectrum sensing, interference management, cognitive radio reconfiguration management, and cooperative communications. Furthermore, in order to fully realize the CR system in wireless communications for efficient utilization of scarce RF spectrum, the method used in identifying the interference and/or spectrum sensing should be reliable and prompt so that the primary user will not suffer from CR system to utilize their licensed spectrum. We presented the different signal processing methods by grouping them into five basic groups and their details in turn. We have also presented the pros and cons of different spectrum sensing methods, and performed the comparison in terms of operation, accuracies, complexities and implementations. Since the CR system is still in its early stages of development, there are number of challenges for its implementation such as time for primary user signal detection, detection of "spread spectrum primary user" (or CDMA) signals, hardware implementation in CR devices and computational complexities.

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