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Spectrum Sensing and Energy Efficiency Strategies in Cognitive Radio Networks-Perspective and Prospects

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Abstract

With the rapid ongoing multiplication of wireless users it has become inevitable to make utmost use of available spectrum to sustain the growth. The solutions for problems emerging with conceptual development of Cognitive Radio Networks (CRN) have mainly addressed the spectrum utilization issues so far. But now the spectrum scarcity and electrifying growth of high data rate communications have also motivated the promising concept of energy efficient CRN which depends on the spectrum sensing, dimensionality of users, handoff schemes for mobility enhancement and channel utilization etc. In this paper after an overview of CR and spectrum sensing a detailed review of possible techniques which can be used for energy efficient CR models has been presented. Factors affecting the energy consumption on CR functions such as spectrum sensing, management and hand off, allocation and sharing have been discussed in detail.

Keywords- Cognitive radio; spectrum sensing techniques; Energy efficient CRN

INTRODUCTION

The rapid ongoing multiplicative growth of wireless users is forcing to make utmost use of available spectrum. Increasing efficiency of the spectrum usage to an optimum level would be a compulsion in future of telecommunication. The conventional fixed allocation policy which assigns spectrum bands to licensed users irrespective of geographical and temporal variations has inadvertently contributed to the spectrum scarcity as revealed in Federal Communications Commission (FCC) report**.** FCC estimates that the variation of use of licensed spectrum in the band below 3GHz is from 15-85% [1], even if all bands are allocated. This inefficient spectrum utilization brings in operational challenges to most of wireless devices such as, Wi-Fi, wireless sensor network, cordless phones, Bluetooth and hence arise the need for a fundamental change from the conventional spectrum allocation policy to intelligent and more flexible spectrum access management. Due to recent technical advances in Software Defined Radio (SDR), wideband transceivers, digital signal processors, etc it has now become possible to employ intelligent transceivers, for utilizing the available spectrum in a highly dynamic and adaptive manner.

The concept of Cognitive Radio (CR) first coined by Mitola in late 1990s [2], is based on the ability to sense the idle frequencies in the spectrum and allow Secondary User (SU) to use them without affecting Primary User (PU). A cognitive radio can change its transmitter parameters based on interaction with the environment in which it operates [1]. This interaction involves active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio. The concept of CR can be realized only by integrating multidimensional different issues e.g. smart antennas, signal processing, networking, communication, hardware architecture with software defined radio (SDR), information theory etc to achieve its envisioned goals.

For coexistence of the licensed and unlicensed wireless systems, CR has to make use of wide variety of techniques and architectures with basic idea of SDR [2] and provide opportunities to find its applications ranging from terrestrial services like in Television White Spaces (TVWSs) [3] to space communication services like satellite communications [4], [5]. For its commercial viability several industry players and regulatory bodies are putting significant efforts towards the realization of CR technology [6] involving different forms of cognitive cycles [2], [7].

Several survey papers exist in the context of CR communications covering a wide range of areas such as spectrum occupancy measurement [33], spectrum sensing [18] [31] [32] [34], cognitive radio under practical imperfections [35], spectrum management [36], emerging applications for cognitive radios [37], spectrum decision [38], spectrum access strategies [39], and CR networks [40]. Even though there is lots of available literature under ideal conditions, but [35] provides an overview of the enabling techniques for CR communications under various practical imperfections. In [41] sensing as a driving technology for the interweave model is highlighted.

This paper presents a review on the practical implementation aspects of the spectrum sensing techniques particularly on energy efficiency aspects. In spectrum sensing main issues involved are accuracy, complexity and sensing time. It is difficult to design an algorithm which can be called optimum in all respect as multifactor trade-offs are involved. Therefore enhancing the current algorithms to obtain near-optimum accuracy and reasonable complexity and sensing time is generating interest in research groups [42].

Rampant surge in traffic over wireless networks, is increasing the energy consumption globally and presently 3% of the worldwide energy is consumed by the Information and Communication Technology (ICT) infrastructure that causing about 2% of worldwide CO_2 emissions [43]. Since wireless communication account for half of the total energy consumption in ICT, energy efficiency becomes an important aspect and there is a need to lower energy consumption in future wireless radio. Energy efficient policies are becoming more important to achieve green communication standards to reduce CO_2 emissions to protect the environment.

Thus spectrum scarcity and green communication are two serious challenges that nowadays wireless industry is facing. Cognitive radio though initially designed to cope with spectrum scarcity, makes it ideal for green communication as well, due to its inherent properties like strict energy constraint and opportunistic spectrum sharing with primary users without causing harmful interference. Energy efficiency also emphasizes on enhancing the battery lifetime of wireless devices and reducing replacement cycles which is again an increment friendly move. [44].

With a special focus on energy efficient CRN the paper is organized as follows. In section 2 we provide a brief overview of Cognitive Radio. Spectrum sensing techniques are discussed in detail in section 3. In section 4 we explain the factors affecting the energy consumption in functions of CRN i.e. spectrum sensing, spectrum management, handoff and sharing and conclude the paper in section 5.

COGNITIVE RADIO

The most common and basic functions in all the proposed cognitive cycles are (i) spectrum awareness, (ii) analysis & decision, and (iii) spectrum exploitation (adaptation). Spectrum awareness capability helps a CR to acquire information about the spectral opportunities dynamically while spectrum exploitation capability assists a CR to exploit the available spectral opportunities efficiently.

The Institute of Electrical and Electronics Engineers (IEEE) has released many standards concerning secondary operation, and among those is 802.22 [9]. This standard regulates the deployment of Wireless Regional Area Network (WRAN) in TVWS. More such IEEE standards for secondary operation have either been released or under preparation such as IEEE 1900 group of standards which is responsible for standardizing the new technologies for next generation radio and advanced spectrum management [10]. A detailed survey on the IEEE standards in CR and issues in coexistence can be found in [11].

Types of CR

Depending on the set of criteria taken into account when deciding on the changes in transmission and reception, there are two main types of CR:

Full CR (Mitola radio): In which every possible parameter observable by a SU is taken into account [2].

Spectrum Sensing CR (Haykin radio): In which only the radio frequency spectrum is considered [7].

Mitola radio is not expected to be completely implemented before 2030, until the whole SDR hardware become available in a suitable size [12].

Types of CR in terms of the parts of the spectrum available are:

Licensed band CR: used in the bands that are used and sold by license. The IEEE 802.22 standard defines a system for a WRAN that uses spectrum holes within the TV bands between 54 and 862 MHz. To achieve its aims, the 802.22 standard utilizes CR technology to ensure that no undue interference is caused to television services using the television bands [9], [13].

Unlicensed band CR: can only utilize unlicensed parts of the radio frequency spectrum. There is one system in the IEEE 802.15 Coexistence Task Group 2 (TG2), which focuses on the coexistence of WLAN and Bluetooth [16].

In CR domain, PUs also called as licensed users or incumbent users are defined as the users who have legacy rights on the use of a specific part of the spectrum. On the other hand, SUs also called as unlicensed users or cognitive users; optimize this spectrum utilization in such a way that they do not provide interference to the PU's operation. The SU with CR capabilities acquire information about its operating environments and adapts its radio parameters accordingly in order to optimize the underutilized part of the spectrum.

Approaches for enhancing the spectral efficiency

There are two commonly used approaches for enhancing the spectral efficiency of current wireless systems (i) by utilizing opportunistic spectrum access, called Dynamic Spectrum Access (DSA), and (ii) by sharing of the available spectrum between primary and secondary systems, called Spectrum Sharing (SS).

In DSA, network consists of a pair of PU and a pair of SU which operate at the same frequency band. The PU has higher priority accessing the spectrum. The SU has to sense the spectrum and communicate only if it identifies a spectrum hole. If miss detection by SU occurs it will cause interference to the PU.

In SS, multiple independent entities access spectrum simultaneously in a specific geo-location at a specific time using mechanisms other than the multiple access techniques. SS systems are further classified in two categories [45].

Horizontal sharing: In horizontal sharing, different entities share the spectrum and can coexist simultaneously and this type of sharing is possible in both licensed and unlicensed spectrum. An example of licensed spectrum horizontal sharing is, different mobile stations (MS) accessing the uplink cellular spectrum. Another example of horizontal unlicensed spectrum sharing is, Wi-Fi access point sharing a portion of the 2.4 GHz, Industrial, scientific and medical, (ISM) band.

Vertical sharing: Here, multiple sharing entities have different rights to access the spectrum. In vertical sharing framework, the spectrum is owned by the licensed PU and can be shared by a SU. Unused spectrum can be dynamically allocated within the licensed frequency band according to SU's requested quality of service (QoS) specifications. SUs have to assure PU protection such as the transmission power limits while sharing the spectrum.

Access Techniques Classification

There are four ways of accessing the spectrum by SUs :-

(i) Interweave technique
(ii) Underlay technique
(iii) Overlay technique
(iv) Hybrid technique

Interweave technique: Interweave communication avoids interference using opportunistic techniques in which SUs communicate opportunistically using spectral holes (SH) in space, frequency, and time which are not occupied by the PUs[46]. Also Polarization [47], [48] and angular [49] domains can be considered as additional dimensions for spectrum exploitation. SH and approaches to find SH are discussed in detail in following sections.
Underlay technique: Underlay technique allows the coexistence of primary and secondary systems, only if the interference caused by Secondary Transmitters (STs) to the Primary Receivers (PRs) can be efficaciously controlled and managed [50]. The STs utilizing the shared band must ensure that their transmissions added to the existing interference must not exceed the interference threshold at the PR as defined by FCC spectrum policy task force [51].
Overlay technique: In Overlay technique, the SU transmits the PU signal along with its own signal and the interference caused by the ST to the PR can be offset with the help of advanced coding and transmission strategies at the STs [46]. The cognitive transmitter should have knowledge of the PU's channel gains, codebooks and possibly its messages as well. In practice, this paradigm is difficult to implement due to a high level of cognition required between primary and secondary systems.
Hybrid technique: This technique uses a hybrid form of interweave and underlay techniques to overcome some of their drawbacks. Since, the Spectrum sensing approach does not allow the SUs to transmit in a particular frequency band when the PU is active in that band while on the other hand; the underlay approach is not able to detect the activity or inactivity of the PUs in a particular band and hence does not utilize the idle bands efficiently. [52], [53], [54]. Here, a CR accesses the PU channel with its full power in case of an idle channel and also accesses the channel with the controlled power in case of the occupied channel.

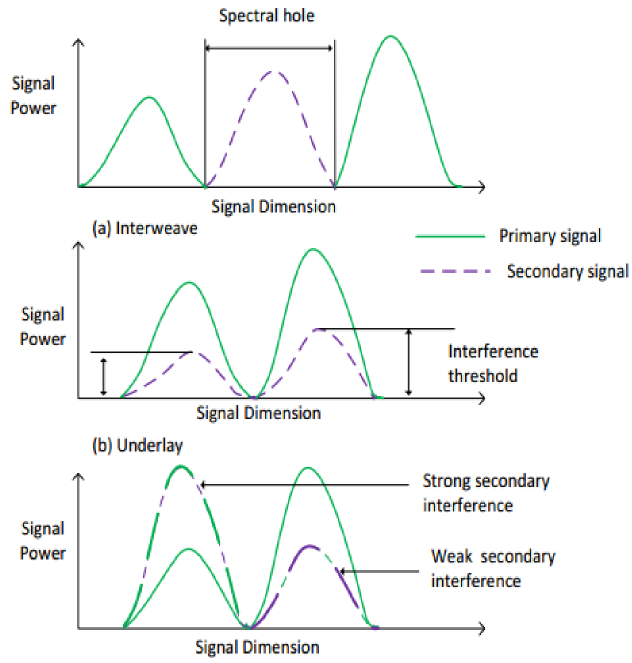

Figure 1: Different Access techniques [8]

Spectrum Hole

Since spectrum is initially assigned to license PUs, the key task is to share the spectrum without harmful interference to PUs. To search and utilize the unused spectrum is the final objective of CR. This means that CR introduces intelligence to conventional radio such that it searches for a spectrum hole defined as "a licensed frequency band not being used by an incumbent at that time within a selected area" [7]. Fig.2 shows the concept of spectrum hole.

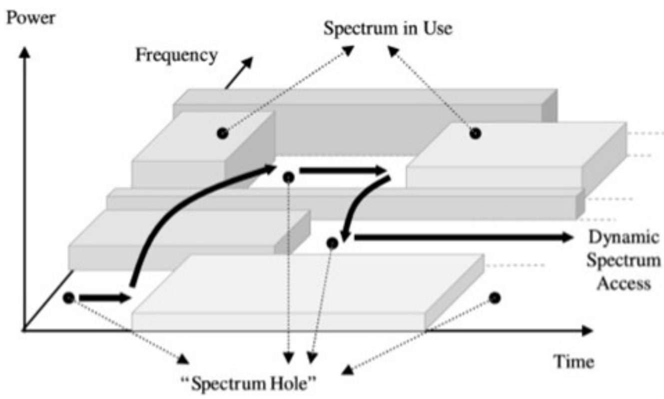

Figure 2: Spectrum hole concept [7]

Usually spectrum holes are categorized into **temporal spectrum holes** and **spatial spectrum holes**. A temporal spectrum hole is unoccupied by the PU during the time of sensing. Hence, this band can be used by SUs in the current time slot. Spectrum sensing of this kind does not require complex signal processing. A spatial spectrum hole is a band which is unoccupied by the PU at some spatial areas; and therefore can be occupied by SUs as well outside this area. Spatial sensing of a PU needs complex signal processing algorithms [15], [16]. In terms of power spectra of incoming RF, the spectrum holes are classified into three broadly defined types [17]

Black spaces, which are dominated by high-power "local" interference at some of the time.

Grey spaces, which are partially dominated by low-power interference.

White spaces, which are free of RF interference except for white Gaussian noise. Among these three, white spaces and grey spaces can be used by unlicensed operators if accurate sensing technique is designed, and Black spaces cannot be used because usage of this space will cause interference to the PU.

Finding spectrum hole

Three approaches are used to find the spectrum opportunities [19], spectrum sensing, geo-locations databases and beacon signals.

Spectrum sensing: SU scans across the usable spectrum and identifies the spectrum holes using one of the many spectrum sensing techniques available [18, 20] with different complexity and reliability.

Geo-location databases: Spectrum opportunities with their associated constrain is reported in an accessible database by SUs. The geo-location databases based spectrum opportunities are suitable when the PU usage pattern is fixed or varies slowly over time [21]. For example, the TV broadcasting and the radar systems are potential PUs to adopt the geo-location databases for spectrum opportunities [22–28]. The main concern when building the geo-location databases spectrum opportunities is protecting the PU from harmful interference [29].

Beacon signals: Beacons are radio signals that indicate the proximity or location of a device. Beacon signals also carry several critical, constantly changing parameters such as location, power-supply information, signal strength, available bandwidth resources and also atmospheric temperature and pressure. To determine the spectrum opportunities using the beacon signals method, SUs detect PUs' signatures through receiving a beacon signal from that PUs [30]. Beacon signals based spectrum opportunities approach attracts less attention since it costs burden on PUs and requires more resources in terms of standardized channel.

Spectrum sensing, geo-location databases and beacon signals have been compared on different concerning aspects. Table 1 summarizes the comparison [19]:

Table 1: Spectrum sensing, geo-location database and beacon signals comparison [19]

	Spectrum sensing	Geo-location Database	Beacon signals
Main responsibility	SU	PU	PU
Infrastructure cost	Low	High	High
Transceiver complexity	High	Low	Low
Positioning (Fixed)	No	Yes	No
Internet connection	No	Yes	No
Standardized channel	No	No	Yes
Continuous monitoring	Yes	No	No

Spectrum sensing is used as an enabler of finding spectrum holes. After identification of Spectrum hole, CR exploits the opportunity as long as no spectrum activity is detected by PU. If this band is re-acquired by PU, CR being low-priority secondary user must either vacate the band or adjust its transmission parameters to accommodate the PU or, if available/possible, shift to another spectrum hole.

SPECTRUM SENSING (SS)

The SS is actually a problem found in detection theory to distinguish between presence and absence of PU. Using the binary hypotheses, H_0 (noise only hypothesis) and H_1 (signal plus noise hypothesis) respectively it is formulated as [55]

$$y[n] = z[n] \qquad :H_0 \qquad (1)$$

$$y[n] = h\, s[n] + z[n] \qquad :H_1 \qquad (2)$$

where s[n] denotes the transmitted signal at the nth sampling instant, h indicates the channel coefficient, z[n] denotes the Additive White Gaussian Noise (AWGN) and y[n] denotes the received signal at the CR at the nth sampling instant. In order to test the above hypothesis, we need to find a decision statistic whose distribution sufficiently differs under the H_0 and H_1 hypotheses. A test statistic T(y) is a function of the received signal, which is compared against the threshold (λ) and gives the decision statistic, Z, which decides between the two hypotheses about presence or absence of PU. The binary hypothesis model in terms of decision statistic is described as:

$$Z=\begin{cases} T(y) \le \lambda : H_0 \\ T(y) \ge \lambda : H_1 \end{cases} \qquad (3)$$

Hypothesis testing criteria: There are two basic hypothesis testing criteria in spectrum sensing:

Neyman-Pearson (NP) test: aims at maximizing P_d (or minimizing Pm) under the constraint of $P_f \le \alpha$, where α is the maximum false alarm probability.

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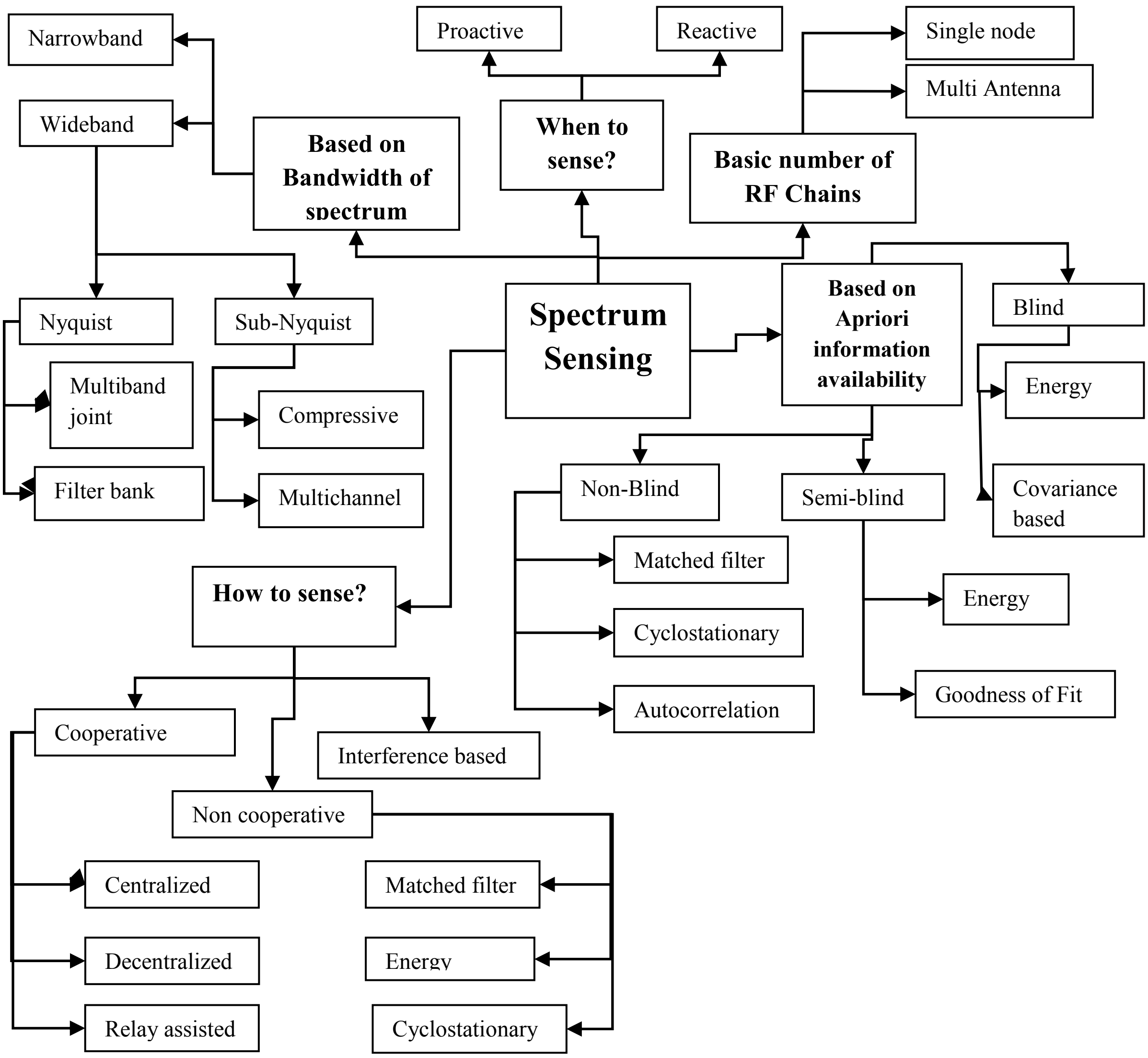

Figure 3: Operative space of SS techniques

The Bayes test: minimizes the average cost and can be conducted simply by calculating the likelihood ratio Λ(R) and comparing it to the threshold.

In Fig.3, we present the operative space of SS techniques depicting the multi-dimensional concerns and involved their possible addressing approaches. While focusing on responsibility of sensing the spectrum at a node in the network, spectrum sensing techniques can be broadly categorized as Non Cooperative and Cooperative.

Non-cooperative (Local) spectrum sensing techniques

SS exploits the SHs in several domains such as time, space, frequency, angular and polarization domains. Different local spectrum sensing techniques have been proposed to identify SHs and protect PU transmission.

Energy Detection: It is also called as a radiometer. It is a non coherent, blind detection method used to detect the PU signal. In energy detection method, received signal energy is compared to a predefined threshold value over an observational interval [56] [57]. If the received signal is greater than threshold, it indicates the presence of PU otherwise absence is indicated. It is one of the most popular and simplest detector as it has less computational and implementation complexity, less delay, relative to other methods. If the noise power is known, energy detector is a good choice, but can't discriminate between primary signal and noise in low SNR and hence vulnerable to noise uncertainty. [58-60].

Matched Filter (MF): is an optimal method for detection of PUs when transmitted signal is known [61]. MF is a linear filter designed to maximize the output SNR for a given input signal [63].

The matched filter operation can be defined as:

$$y[n] = \sum_{k=-\infty}^{\infty} h[n-k]x[k] \quad (4)$$

Where x is the unknown received signal (vector) and is convolved with the impulse response of the filter, h matching to signal transmitted. Hence, cognitive radio has a prior knowledge of the PU Signal at both physical and MAC layer, such as frequency, bandwidth, and modulation type to demodulate received signals. The sensing device has to achieve coherency by using pilot patterns (or symbols) and demodulate PU signal. For examples; TV Signal has narrowband pilot for audio and video carriers; CDMA system have dedicated spreading codes for pilot and packet acquisition. However, the constraint with MF is that CR needs a dedicated receiver for every type of primary user.

Feature based Detection: Primarily cyclostationary features of received signals can be used in Cyclostationary Detection (CD) technique to detect the PU presence [63]. Cyclostationary features are caused by the periodicity in the signal or in its statistics like mean and autocorrelation or they can be intentionally induced to assist spectrum sensing. Modulated signals are generally coupled with different pulses such as sine wave carrier, pulse trains, cyclic prefixes etc., during signal transmission, resulting in built-in periodicity in statistics [64]. Cyclostationary detection can be done even without the prior knowledge of the primary signal [65-67].

Some other feature detection techniques such as blind standard recognition, feature vectors based detection have also been introduced [68, 69]. Blind Standard Recognition Sensor (BSRS) technique has been introduced in [70, 71] which is based upon the fusion of information from several sensors. In [72], a blind feature learning algorithm has been proposed along with a feature template matching using learned features.

Autocorrelation based Sensing: Presence of RF channel guard bands and the use of practical modulation schemes lead to the higher autocorrelation of the signal which further leads to the difference between the signals and noise spectrum over a particular bandwidth. This difference is exploited by the autocorrelation based detectors [73] by using both energy and correlation parameters assuming that correlation is real and further extend it to the scenario with the knowledge of correlation distribution information [74].

Covariance based Sensing: is based on the sample covariance matrix of the received signal at the CR node and exploits the difference in the statistical covariance of the received signal and the noise. The performance of Covariance detector and cyclic autocorrelation detector can be improved further using the estimated autocorrelation of the received signal as suggested in Constant False Alarm Rate (CFAR) detection algorithm [75]. Covariance absolute value and generalized covariance based detection algorithms for a CR [76] and distribution of the test-statistic for the covariance based detection is studied in [77] and authors proposed analytical expressions for calculating detection and false alarm probabilities.

Eigenvalue based Detection: To enhance the SS efficiency in wireless fading channels several diversity enhancing techniques have been introduced such as multi-antenna and oversampled techniques [78-81]. Using the Random Matrix Theory the properties of the eigenvalues of the received signal's covariance matrix have been considered to find test statistics. Some of the Eigenvalue based SS techniques do not require any prior information of the PU's signal and they outperform ED techniques, especially in the presence of noise covariance uncertainty. The existing Eigenvalue based approaches are Maximum Eigenvalue (ME) [82], Signal Condition Number (SCN) [83], Energy with Minimum Eigenvalue (EME) [78], Scaled Largest Eigenvalue (SLE) [84], Spherical Test (ST) Method and John's Detection (JD) Method [79].

Waveform based Sensing: It is also known as coherent sensing. It is only applicable to systems with known signal patterns such as preambles, midambles, regularly transmitted pilot patterns and spreading sequences. This type of sensing can be performed by correlating the received signal with a known copy of itself. In [85], it is found that waveform-based sensing requires short measurement time and its performance is susceptible to synchronization errors.

External sensing: Another technique for detecting the presence of the active PU is external sensing, where an external agent does the sensing and transmits the channel occupancy information to the CRs. The Primary advantage of external sensing is to detect hidden PU and to overcome the uncertainty due to shadowing and fading. Moreover, spectrum efficiency is increased as the sensing is done by the external agent and not CR. Other alternative spectrum sensing methods include information theoretic based spectrum sensing, fast sensing, radio identification based sensing, multi-taper spectral estimation, and wavelet transform based estimation, Hough transform, and time-frequency analysis [32].

Performance metrics for evaluating sensing: sensing performance is evaluated on two criteria, detection probability based performance and transmission efficiency based performance, first being statistical and second non-statistical in nature. Detection performance is characterized by the probabilities of detection, (P_d), and false-alarm (P_f). Based on P_d, the probability of miss-detection P_m can be obtained by $P_m = 1 - P_d$. Receiver operating characteristics (ROC), the plot of P_d against P_f is a powerful tool to judge the sensitivity and specificity of the detector. The coordinate [0, 1] at upper left portion of the ROC curve represents perfect classification and for the SU closeness to this portion denotes high probability of detection and low probability of false alarm. Transmission efficiency (η) is the fraction of time during which a SU is utilizing a free channel between two sensing instances. Transmission efficiency is formulated assuming that SUs can perform one task at a time either sensing or transmitting. Hence, transmission efficiency is found as $\eta = T/(T + t_s)$ where T is transmission time and t_s is the sensing time required to collect the samples and perform the sensing. Sensing time is often used as a measure for sensing complexity.

These performance metrics reflecting reliability, accuracy and system complexity, however do not form the sole basis for comparison of different sensing techniques. The various spectrum sensing methods including Likelihood ratio test (LRT) [34], Energy detection (ED) method [86], Matched filtering (MF)-based method [87], Cyclostationary detection method [88], Multitaper spectrum estimation[89], Wavelet transform based estimation [90] and Support Vector Machine (SVM) [91] have been studied for detection of PUs. Each of the mentioned methods has different requirements together with advantages or disadvantages. LRT is proven to be optimal but difficult to use, as it requires exact channel information and distributions of the source signal and noise which are difficult to obtain practically. The MF-based method requires perfect knowledge of the channel responses from the primary user to the receiver and accurate synchronization. This is possible only if the primary users cooperate with the secondary users else leads to degradation in the performance of MF-based method [91]. The cyclostationary detection method is used for OFDM-signals detection based on multiple cyclic frequencies [88]. Also in [92] [93], cyclostationary based detection is applied for OFDM-based digital TV-signals for the IEEE 802.22 WRAN standard. But cyclostationary detection method requires the exact knowledge of the cyclic frequencies of the primary users, which is not possible practically for many spectrum reuse applications. Also this method demands excessive analog-to digital (A/D) converter requirements and signal processing capabilities. Multi-taper spectrum estimation [89] shown to be an approximation to maximum likelihood Power Spectrum Density (PSD) estimator, and it is nearly optimal for wide band signals. Although the complexity of this method is smaller than the maximum likelihood estimator, it is still computationally rather demanding. Wavelets [90] are used for detecting edges in the PSD of a wideband channel. Once the edges, which correspond to transitions from an occupied band to an unoccupied /vacant / empty band or vice versa, are detected, the powers within bands between two edges are estimated. Using this information and edge positions, the frequency spectrum can be identified as vacant or occupied. In [94], a Support Vector Machine (SVM), which is a data mining method, is applied for detection of PU signal. It shows superior performance compared to energy detection. Based on these advantages and disadvantages different techniques can be compared as shown in table 2.

Table 2: Comparison of different sensing techniques [95]

Sensing Technique	Narrowband(NB)/ Wideband(WB) Sensing	Prior signal information	Reliability & accuracy	Computational Complexity	Sensing time	Cost	Power consumption
Energy Detection	NB/WB	No	Very very poor	Very very Low	Very very less	Very very low	Very very low
Matched Filter	NB	Yes	Very good	Very low	Very less	Very low	Medium
Waveform based	NB	Yes	poor	Medium	Medium	Low	Very low
Eigen value based	NB	Yes	Very poor	Low	Less	Medium	Low
Wavelet Based	WB	Yes	Medium	Very high	Very large	Very high	Very high
Cyclostationary	NB	Yes	Good	High	Large	High	High

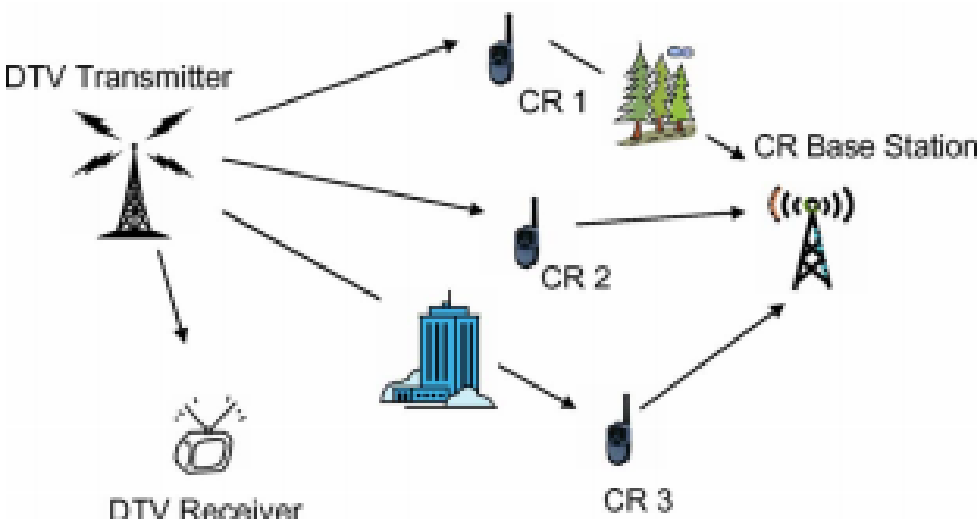

Figure 4: Cooperative spectrum sensing scenario [102]

Cooperative Spectrum Sensing (CSS)

Wireless channels have fundamental characteristics as noise uncertainty, multipath fading, and shadowing which affect the performance of the local spectrum sensing techniques. The concept of cooperative spectrum sensing emerged to overcome the limitations in local spectrum sensing. In Cooperative spectrum sensing, several nodes cooperate with each other in order to enhance the overall sensing performance by exploiting the observations captured by spatially located CR users as depicted in Fig.4

Steps involved in CSS

Local Sensing: Local sensing is performed by each SU individually. Different methods to sense the spectrum already discussed can be used. Among them Energy detection is the most popular method. Each SU needs to find a way to represent its result. There are two well known schemes for this: soft-based scheme and hard-based scheme. In soft-based scheme [96], the local result is reported as it is, e.g. while using energy detection method the result is in the form of received signal energy. On the other hand, hard-based scheme is based on comparing the local result to a predefined threshold in order to make a local binary decision that can be transmitted via a single bit.

Reporting: In this step local results/decisions are reported to a common receiver, called fusion center (FC) which processes them for making a global decision of the spectrum occupancy. The reporting of the results can be done through a common control channel (CCC) either using centralized time-division multiple access (TDMA) [97] or through a random access [98]. In a centralized TDMA, each SU reports its local result on its own time slot, while in a random access reporting scheme the SUs randomly transmit their results without any coordination.

Decision Making: The results received from different SUs are processed at the FC by employing a specific fusion rule (FR) to finally make a global decision. The results received in soft-based CSS schemes are weighted and summed up and the sum is compared against a threshold to make a global decision.

Classification of FRs for soft-based scheme can be done according to the weights used, such as equal-gain combining (EGC), where the weights of the all SUs are identical, maximal ratio combining (MRC) [96], where each SU is weighted by its SNR and likelihood-ratio test (LRT) [99], where the likelihood ratio statistical test is used to obtain the most likely decision of the spectrum availability.

The general rule for classification of FRs for hard-based CSS schemes is called *K-out-of N* rule [100], where the number of SUs that detect a signal is compared to a threshold (K), where N is the total number of SUs. Depending on K, several rules can be derived for the *K-out-of-N* rule, such as the OR rule ($K = 1$), the AND rule ($K = N$) [101] and majority-logic rule ($K = N/2$).

Types of CSS

Based on the cooperation among various SUs, CSS can be implemented in the following three ways [103]:

Centralized Spectrum Sensing: In this central FC collects results from sensing devices, identifies the unused spectrum, and transmits this information to other cognitive radios or directly controls the cognitive radio traffic.

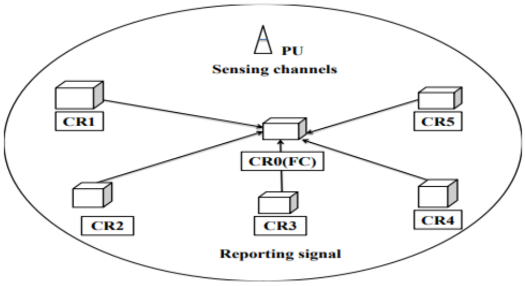

Figure 5: Centralized Sensing [103]

Distributed Sensing: In distributed sensing, there is no FC involved and SU share its information with other SUs to decide as to which part of the spectrum they can use. This technique requires regular update of the spectrum information table hence large storage and computation is required [18].

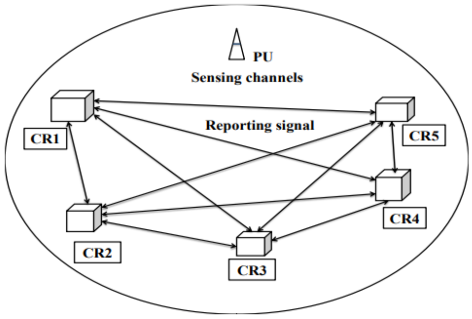

Figure 6: Distributed sensing [103]

Relay assisted sensing: Relay-assisted approach emerged, as centralized and distributed cooperative schemes both were not that perfect. In this scheme, a CR user with a strong sensing channel and a weak report channel can cooperate with a CR user observing a weak sensing channel and a strong report channel in order to improve the overall sensing performance. A detailed survey on existing cooperative SS approaches can be found in [103], [104].

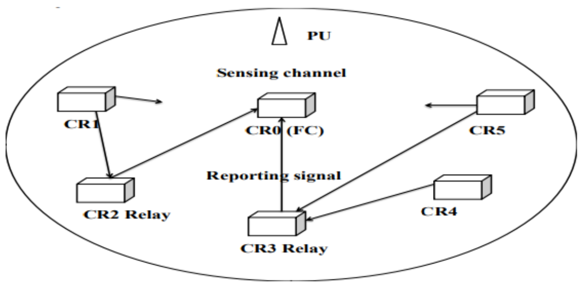

Figure 7: Relay assisted sensing [103]

While using CSS technique, hidden node problem which is a main drawback of local sensing techniques is sufficiently reduced and false alarm rate is also reduced. Due to this signal detection is more accurate in CSS than non-CSS techniques.

Challenges in CSS

In CSS, it is difficult to establish a CCC in the beginning of the sensing stage and also the regular change in CCC as PU's activities affects it and this increases the complexity. A selective-relay based CSS scheme without common reporting control channels has been proposed in [105]. The other problem in CSS is Synchronization as practically all the SU are placed at different places resulting in problem for data fusion. To overcome this problem a probability based combination method has been proposed by taking time offsets of SUs into account [106].

ENERGY EFFICIENT CRN

The design and implementation of most wireless communication networks suffers from the major constraint namely Energy Efficiency (EE). The EE is defined as the ratio of the average transmitted bits to the average consumed energy [107]. The network comprises the number of nodes, Base Station (BS) and various backbone networks. The network lifetime is decided by energy consumption of BS and nodes. Hence, the primary ingredient of network lifetime improvement is the reduction of energy consumption during transmission, reception and related cognitive processes. The optimum energy consumption with maximum spectrum efficiency is considered a critical task in CRN modeling. The provision of balancing between the sensing and transmission accuracies achieves the high-energy efficiency. To ensure the Quality of Service (QoS) optimizing the energy efficiency is crucial step which not only reduces the environmental impacts but minimizes the overall network cost effectively. If performance of the CRN be represented by single metric combining overall energy consumption, achievable throughput and detection accuracy, EE is most appropriate criterion. Energy efficiency metrics are discussed in [108].

Parameters which govern the energy efficiency in a CRN model are:

1. Transmission energy: The consumption of energy while the idle state frequencies are not allotted
2. Circuitry Power : The power consumption by the electronic circuits
3. Channel switching energy: Energy consumption with hardware configuration
4. Idle energy: Energy consumption during the absence of CR selection

The overall energy efficiency in CR depends on energy efficiency achieved in its three basic functions namely, spectrum sensing & analysis, spectrum management & handoff, and sharing & allocation. All three functions are discussed along with energy consumption optimization strategies in following sections.

Spectrum Sensing and Analysis:

Energy efficiency of the spectrum sensing algorithms depends not only on the sensing performance but also on power consumption. Most commonly five algorithms for spectrum sensing are compared on power consumption as shown in table 2. Based on binary hypothesis testing the relationship between different parameters to sensing performance is defined as [109]:

$$P_d = \text{prob } \{f(t_s,\gamma)>\lambda_d|H_1\} \quad (5)$$

$$P_f = \text{prob } \{f(t_s,\gamma)>\lambda_f|H_0\} \quad (6)$$

P_d increases with sensing time t_s and SNR γ and decreases with λ_d, detection threshold whereas P_f decreases with t_s, γ and λ_f the false alarm threshold.

Power consumption in sensing power P_S and reporting power P_R can be expressed as:

$$P_S=F_S(t_S) = F_S(N_S) \quad (7)$$

$$P_R=F_R(N_C, D) \quad (8)$$

Where F_S and F_R are the sensing and reporting power functions respectively, N_S is number of collected samples and N_C is number of SUs, and D is transmission distance.

Sensing performance can be increased by increasing sensing time and SNR but sensing power P_S is reduced with reducing the sensing time t_S and number of collected samples. The reporting power P_R is reduced by reducing the number of SUs, N_C and transmission distance D.

Factors affecting energy consumption in non-CSS

Local spectrum sensing can give good sensing performance if the PU signals are sufficiently strong. The parameters which affect the energy consumption are **channel sensing time** and **sensing order** for channel access. The cognitive transmission frame is divided in sensing and transmission frames. If the sensing time is more, less time is left for secondary transmission and vice versa. A minimum value of sensing time is required to achieve acceptable false alarm probability. Increasing the sensing time increases the sensing performance but at the cost of higher energy consumption and decrease in time left for secondary transmission and lowering the transmission efficiency. Hence tradeoff between the sensing time and energy efficiency as well as transmission efficiency is possible. Some of the sensing time/period optimization approaches are presented in [110-112]. In [110], an adaptive sensing period is obtained based on the past spectrum occupancy pattern. Switching of SU into non-sensing mode during the presence of PU is studied in [111]. Joint optimization of the sensing and transmission durations is studied in [112] with the condition under which SU has to strike a balance in energy consumption between sensing and transmission via appropriate idling.

Sensing order means the order of channels to be sensed, which also affects the energy consumption. If the SU learns the transmission channel quality, statistics and decides sensing order accordingly then it can prevent excessive energy consumption. In [113] joint design of channel sensing order and sensing access strategies are presented, the optimal sensing allows the SU to transmit only if the current channel condition is good enough. The optimal access strategy, i.e., the optimal power allocation strategy, has a water-filling structure. The optimal sensing order is to choose to sense the channel from the set of remaining channels associated with the maximum expected future net reward. In [114] energy allocation problem for a wideband cognitive radio network with limited available frame energy is discussed and showed that higher gain is achieved by excluding from the sensing order the number with poor channel conditions or high occupancy probability..

Factors affecting energy consumption in CSS

In the case of weak PU signal and harsh channel conditions the CSS gives better sensing performance over non-CSS. Above stated two factors in local spectrum sensing should also be optimized in cooperating scenario. A number of approaches have been proposed to improve EE in CSS during all of its three stages.

Local sensing stage: In CSS the sensing resource is not only the sensing time but also the number of SUs participating in cooperation. Thus, energy consumption in the sensing stage can be reduced in two different ways by:

(i) optimizing the number of sensing users (ii) optimizing the sensing time.

Optimizing the number of sensing users

The energy consumption in CSS depends on the number of sensing users. This implies that reduction in the number of sensing users would lead to a reduction in all the preceding stages. Many algorithms have been proposed to optimize the number of SUs [115-120]. A study on satisfying predefined constraints on the detection and false-alarm probabilities, considering a limited frame length by minimizing the number of sensing SUs is presented in [115]. In [116], a dynamic algorithm is presented which continuously checks a binary indicator which further ensures the satisfaction of the desired detection accuracy by allowing only the minimum number of SUs to participate in the sensing process. The mathematical description of detection and false alarm probabilities are described in [117], using the minimum number of sensing SUs. In [118], the SUs are divided into non-disjoint subsets such that only one subset senses the spectrum while the other subsets enter a low power mode. In [119] an algorithm is proposed that divides the SUs into subsets. Sensing is done by the subset that has a lowest cost function and guarantees the desired accuracy. Distributed approach is proposed [120] for selecting the participating SUs. Here expected energy consumption by each SU is pre-estimated. If it is lower that the desired threshold, the SU will participate otherwise not.

Optimizing the sensing time

A two stage sensing which reduces the sensing time but leads to extra energy consumption in reporting stage is proposed in [121]. The sensing time is optimized by maximizing the difference between the achievable throughput (revenue) and the consumed energy (cost) in [122] and an iterative algorithm is presented in [123] to solve the joint optimization of the number of sensing users, the sensing time, the transmit power and the local detection threshold jointly and individually. In [124], the difference between achievable throughput and consumed energy is maximized by joint optimization of sensing time and number of sensing users. The golden section search algorithm is used to find the optimal sensing time [125]; however no closed form expression is given.

Reporting stage: It is the second stage of CSS, where SUs transmit their local sensing results to the FC. Wherein Power consumed in reporting is higher as compared to the sensing power, but since the sensing time is normally longer than the reporting time, the energy consumed in the reporting stage may be comparable to the energy consumed during the sensing stage.

Optimizing the report form

The local sensing results are reported to the FC by either soft based or hard based schemes which have been discussed earlier. Although many works have compared them under different setups and assumptions [126–131], none of them has investigated the resulting energy consumption or energy efficiency.

To reduce the reporting power following approaches have been suggested.

Censoring: The energy consumption during transmission is high as the SUs provide informative as well as non-informative results to FC. Censoring [32,132] is basically restricting reporting of non-informative results to FC thus saving energy.

Sleeping: It is another power saving technique where sensing device of each CR is turned off randomly with a probability, known as sleeping rate. This technique is also known as on/off technique [32,132]. This technique is advantageous as sleeping CR does not consume any energy while in censoring all CR consume energy on sensing. Hence it is beneficial to apply sleeping technique along with censoring.

Sequential detection: Sequential detection is used to reduce the average number of sensors which are needed to reach a decision [32,132]. This technique has been used to reduce the sensing time in single radio spectrum sensing as well as cooperative or distributed sequential detection. They provide the ability to significantly reduce the energy consumption of the overall system. In this detection by minimizing the average sensing time sensing energy is minimized. Every sequential sensing scheme has a stopping rule and a terminal decision rule. The decision when to stop collecting observations is given by stopping rule and after the sequential test has stopped which decision has to be made is decided by the terminal decision rule.

Confidence Voting: In Confidence voting [133], SU votes only if they are confident about their results and refrain themselves from sending unreliable information. If their results are with the consensus, it gains confidence, else lose it. The transmission of results is stopped, if SU confidence level drops below a threshold, and restarts when it regains its confidence level. Hence energy is saved as unnecessary transmission is stopped. In this scheme, the sent-out information can be either hard decision or soft decision.

Cluster Collect Forwarding: In Cluster Collect Forward scheme [134], nearby SUs form a cluster based on their geometric location and one of them is chosen as a cluster-head on random basis who also works as Local vote-collector (LVC). Each user transmits their result to LVC after spectrum sensing. LVC adds its vote to the received votes and forward the final result (total no of votes or scores) to the central vote-collector (CVC). Every LVC takes turn to work as CVC increasing total lifetime. CVC announces the total vote count after collecting and counting the votes and sends them back to LVCs. The final result is then forwarded to each member by the LVC.

Decision-making stage: The last stage of CSS is decision making about spectrum occupancy. Decision arrives by applying a specific FR after processing of the local results. The decision is based on the predefined fusion threshold. The optimization of fusion threshold of *K-out-of-N* FR for maximizing energy efficiency without constraints is shown in [135]. Energy efficiency is maximized with a constraint on resulting interference represented by the missed detection probability and throughput of CRN is maximized by optimizing fusion threshold with constraints on the consumed energy per SU and the overall detection probability [136]. Three popular FRs namely LR, MRC and EGC are compared in [137] based on limited time assumption and in terms of the consumed energy and the achievable detection probability at a given false alarm probability threshold where EGC has a better performance among all.

Spectrum Management and Handoff:

Spectrum management: In order to meet the communication requirements of the users it captures the best available spectrum. The functions of the spectrum management are important for the CRs. These management functions can be classified
as follows: **Spectrum analysis** and **spectrum access** [138]. **Spectrum analysis**: In this the characteristics of spectrum holes detected through spectrum sensing are analyzed. In spectrum access, the decision whether to access or not is derived by identifying the best available channel. The energy used in the data transmission depends on the channel characteristics (mostly channel capacity). Hence, energy efficiency is important in the design of the spectrum management mechanism. **Spectrum Access:** For efficient spectrum management an option for SU can be given to keep idle on the channel with poor fading condition without sensing and transmission in order to save energy. The Partially Observable Markov Decision Process (POMDP) framework indicates that the optimal sensing decision and access strategy uses a threshold structure in terms of channel free probability and channel fading condition [139]. In this, SU will sense the channel when conditional probability that the channel is idle in the slot is above threshold and will access the channel if the fading condition of idle channel is better than a certain threshold.

Spectrum Mobility: As availability of spectrum varies over time and space, the concept of mobility which refers to mobile users traversing across cells can be imitated to spectrum mobility in any dimension, wherein SU moves from one spectrum hole to another on the reappearance of PU to avoid interference with it incurring in CR network. This requires handoff strategies similar to adopted in mobile communication scenario. There are two types of spectrum handoffs wherein SU continues transmission even when current channel gets busy by switching to another vacant channel [140,141].

Reactive sensing spectrum handoff- Here another spectrum hole is sensed or selected only after the spectrum handoff request is made for the present channel. Hence SU consumes more time to ensure accuracy of the targeted channel.

Proactive-sensing spectrum handoff- Here target spectrum hole is predetermined prior to handoff request. Hence it saves sensing time at the cost of accuracy.

Practically, it is more advantageous for energy saving when SU waits for the current channel, however it affects service quality. Hence Handoff strategy needs to take a prior decision whether handoff request is to be made or not.

Spectrum Sharing and Allocation:

The existing solutions for spectrum sharing based on the coordination between the PUs and SUs can be classified into three major categories [142]:

Spatial spectrum sharing, e.g., spectrum underlay, always allows secondary users to access the spectrum subject to interference temperature (IT) constraint, which is the threshold of interference impairing the PU receiver.

Temporal spectrum sharing, e.g., spectrum overlay, allows secondary users to utilize the spectrum only when it is idle.

Hybrid spectrum sharing, in which SUs initially sense for the status (active/idle) of a frequency band (as in the temporal spectrum sharing) and adapt their transmit power based on the decision made by spectrum sensing, to avoid causing heavy interference (as in spatial spectrum sharing) [143]. Since SUs might be competing for the resource or cooperating to improve efficiency and fairness of resource sharing. In [144] a novel receiver and frame structure for spectrum sharing cognitive radio networks is proposed and derived the optimal power allocation strategy that maximizes the throughput. For energy efficient designs diversity of SUs power budgets, channel condition and quality of service requirements are very important to the spectrum sharing and allocation algorithms [145]. A game theoretic approach for solving spectrum sharing problem in unlicensed band is studied in [146] where multiple systems coexist and interfere each other. For energy efficient underlay CRs, dynamic resource allocation techniques have great importance, which include spectrum sharing with power control, bit rate and antenna beam allocation. To access the same spectrum SUs provide incentive to compensate for additional interference induced to PUs; this can be in form of spectrum trading. In [147] the distributed and iterative algorithm has been shown to achieve the equilibrium of spectrum trading in a time-varying cognitive wireless networking environment.

CONCLUSIONS

This paper presented the fundamental concept of cognitive radio and its functions in brief and as spectrum sensing is the main complex part of CRN this is reviewed in detail. Energy efficient CRNs are being proposed to address energy conservation issues in current wireless communications as inefficiency in the spectrum usage and in energy both becoming vital issues. The discussion provided in this review identifies and addresses the factors affecting the energy consumption in non cooperative and cooperative spectrum sensing. Research contributions so far strongly suggest that by optimizing the number of secondary users and choosing appropriate sensing time the CRN can improve its energy efficiency. Also, by using appropriate techniques for reporting energy efficiency can be improved further. This article also reviewed spectrum allocation and sharing, management and hand off functions of CR in the context of energy efficiency.

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