Cooperative Shared Spectrum Sensing for Dynamic Cognitive Radio Networks

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***Abstract*—Cooperative spectrum sensing for cognitive radio networks is recently being studied to simultaneously minimize uncertainty in primary user detection and solve hidden terminal problem. Sensing wideband spectrum is another challenging task for a single cognitive radio due to large sensing time required. In this paper, we introduce a technique to tackle both wideband and cooperative spectrum sensing tasks. We divide the wideband spectrum into several subbands. Then a group of cognitive radios is assigned for sensing of a particular narrow subband. A cognitive base station is used for collecting the results and making the final decision over the full spectrum. Our proposed algorithm minimizes time and amount of energy spent for wideband spectrum scanning by a cognitive radio, and effectively detects the primary users in the wideband spectrum thanks to cooperative shared spectrum sensing.**

***Index Terms*—shared spectrum sensing, cooperative spectrum sensing, cognitive radio**

I. Introduction

Cognitive radio, a paradigm originated by Mitola, has emerged as a promising technology for maximizing the utilization of the limited bandwidth while accommodating the increasing amount of services and applications in wireless networks [1]. A cognitive radio (CR) transceiver is able to adapt to the dynamic radio environment and the network parameters to maximize the utilization of the limited resources while providing flexibility in wireless access [2]. By detecting particular spectrum holes and exploiting them rapidly, the CR can improve the spectrum utilization significantly. To guarantee a high spectrum efficiency while avoiding the interference to the licensed users, the CR should be able to adapt spectrum conditions flexibly.

Literature Review: To make the CR systems practical, several cognitive networks must be able to coexist. However, the coexistence of multiple cognitive users generates interference to each others, leading to the hidden terminal problem. This problem occurs usually when the CR is shadowed, in severe fading or with high path loss while a primary user (PU) is in vicinity [2]–[4]. In order to deal with the hidden terminal problem in cognitive networks, cognitive users can cooperate to sense the spectrum as well as share the spectrum without causing harmful interference to the PU. Thus, one of the most critical components of the CR is spectrum sensing and accordingly, detection of PUs. However, the communication model adopted in the cooperative spectrum sensing literature assumes noise-free communication between the CRs and cognitive base station (CBS) [2]–[7], which is clearly not the case in realistic cooperative spectrum sensing scenarios and might lead to misleading performance result interpretations that are crucial to the development of cooperative CR systems. Only very recently, this model has been extended to admit imperfect channels for the *soft decisions* case operating *only* with energy detectors [8]. Of note is that *all* these works consider the detection of a PU in a particular *narrow* band.

Although the cooperative spectrum sensing in narrow band among multiple CRs has a rich literature [2]–[7], [9], the studies for wideband spectrum sensing are limited [10]–[13]. A multiband joint detection have been proposed in [10] which jointly detects the primary signals over multiple frequency bands rather consider one band at a time. In [11] and [12], the wavelet approach was investigated by estimating the average power spectrum density (PSD) level within each identified subband. However, they proposed to use only one CR for scanning all subbands. For scanning such wide bandwidth by only one node is time consume. In order to solve the problem, on our knowledge one literature point out the issues by grouping the cognitive nodes to detect different frequency bands [13]. However, their grouping was based on the geographical location. The drawback of this approach is that if both systems, primary and secondary, are dynamic one group might miss the primary signals cause relative location.

Summary of Main Contributions: In this paper we extend cooperative spectrum sensing model to admit noisy channels and develop algorithms that are able to operate with *any* hard decision based algorithm. Moreover, our technique forms a number of groups each sensing a small portion of the wide spectrum to be sensed. The nodes belonging to the same group cooperate amongst themselves to decide the occupancy in the particular subband that they are measuring. This allows the system to balance between sensing accuracy and the amount of network and terminal resources involved into sensing. We also present the complex optimal and an hardware friendly suboptimal detector with near-optimal performance. Moreover, we present simulation results evaluating the performance of the proposed technique. We, thus, present the “cooperative shared spectrum sensing” framework designed to minimize uncertainty in PU detection while maintaining control over time and energy spent for spectrum sensing by CRs.

Paper Organization: The rest of the paper is organized as follows: Section II presents the core of the proposed approach on shared spectrum sensing and the cooperative spectrum sensing detection mechanisms; Section III analyzes the performance of the shared spectrum sensing approach with an example and simulation results, finally Section IV draws some concluding remarks.

II. Cooperative Shared Spectrum Sensing

Cooperative shared spectrum sensing becomes quite feasible when there are sufficient number of CR nodes present within the network covering the desired geographical area. The model that we present here is valid especially if the CR nodes are close to each other.

A. Shared Spectrum Sensing

Shared spectrum sensing concept is to divide the wide bandwidth $f = [f_1, f_{M+1})$ to be scanned into M disjoint small bands or sub-bands

$$f^m = [f_m, f_{m+1}), \ f = \bigcup_{m=1}^{M} f^m. \tag{1}$$

Then a group of CR-nodes the indexes of which are denoted as $C^m \in \mathcal{C} = \{1, 2, \ldots, N\}$ such that

$$C^m \cap C^n = \varnothing, \ \mathcal{C} = \bigcup_{m=1}^{M} C^m \tag{2}$$

is assigned to perform scanning only that particular single sub-band f^m instead of scanning the full bandwidth f. Thus, we consider a set of $\{d_m : m = 1, 2, \ldots, M\}$ many CRs cooperating to decide on the spectrum occupancy for each frequency band $\{f^m : m = 1, 2, \ldots, M\}$. The cooperation and its execution at the CBS for each subband is detailed in the following.

B. Cooperative Spectrum Sensing

We consider a CR network with $d_m = |C^m|$ secondary users in each *cluster*. The binary hypothesis test for spectrum sensing at the t'th time instant, for each cluster, is formulated as follows:

$$H_0^m : x_j^m(t) = v_j^m(t) \tag{3}$$
$$H_1^m : x_j^m(t) = s(t) + v_j^m(t) \tag{4}$$

where $j = 1, 2, \ldots, d_m, \ m = 1, 2, \ldots, M, \ t = 1, 2, \ldots, T_i$ (T_i is determined by the time-bandwidth product), $s(t)$, $x_j^m(t)$ denote the signal transmitted by the PU and the received signal at the j'th secondary user in the i'th cluster. The signal $s(t)$ is corrupted by zero-mean white (possibly nonGaussian) *sensing* noise $v_j^m(t)$ with variance σ_v^2. Moreover, we assume that $s(t)$ and $\{v_j^m(t)\}$ are independent of each other $\forall m, j, t$.

Moreover, we define the spectrum sensing SNR as $\gamma_S \triangleq 1/\sigma_v^2 1/T_0 \int_0^{T_0} |s(t)|^2$ where T_0, σ_n^2 denote the signal duration and the power of the sensing noise, respectively.

Given the observed signal, the CR makes a local decision and determine if the PU is present in a particular band by utilizing a local decision function $\Gamma : \mathbb{C}^{T_0+1\times 1} \rightarrow \{0, 1\}$. This local decision can be based on energy detection [8], coherent detection [2], cyclostationary [14] and wavelet-based [11] feature detection. We denote the local spectrum sensing decision of the CR as b_j^m where

$$\Gamma(\{x_j^m(t)\}_{t=0}^{T_0}) \Rightarrow H_i ; b_j^m = i \tag{5}$$

where $i \in \{0, 1\}$ and H_1 implies that PU is detected and H_0 implies that the band of interest is not occupied by a PU. We utilize a generic probabilistic model given by

$$P_{ij} = \Pr\{b_j^m = H_i | H_j\}, \ i, j \in \{0, 1\} \tag{6}$$

to characterize the performance of the local spectrum detection algorithm.

We further extend this model to include realistic channel models by incorporating amplification factor and communication noise. The transmission of the decisions from all the CRs to the CBS can be seen as a multiuser access protocol which can be based on TDMA or FDMA. Thus, to incorporate the imperfections in the communication mediums between the CRs and the CBS, we consider communications channels corrupted with additive white noise, *i.e.*, the received signal, in the baseband, is given by

$$y_j^m = A h_j^m + w_j^m, \ \text{where } h_j^m = 2b_j^m - 1 \tag{7}$$

and y_j^m, w_j^m and A represent the signal received at the CBS, the corrupting additive white Gaussian noise between the k-th CR and CBS, and the amplification factor, respectively. Given the received signal set $\{y_j^m : j = 1, 2, \ldots, d_m; m = 1, 2, \ldots, M\}$, the CBS's goal is to determine if any PU is present in the wideband spectrum. Clearly, the SNR of the communication channels is given by $\gamma_T \triangleq A^2/\sigma_w^2$ where σ_w^2 denote the variance of the communication noise.

Although we consider i.i.d. case to simplify the presentation, of note is that one can further generalize this model to admit CR dependent amplification factor and communication noise variance.

In the following, we first present the optimal likelihood ratio test (LRT) detector and we briefly discuss a computationally attractive, hardware friendly and effective suboptimal PU detector operating at the CBS for each subband f^m, namely the *two-step* detector that we have recently proposed [15] and analyzed [16]

1) Optimal Detector: The LRT for the considered model, $L(\mathbf{y}^m) = f(\mathbf{y}^m|H_0)/f(\mathbf{y}^m|H_1)$, after which utilizing the fact that the samples are conditionally independent reduces to

$$L(\mathbf{y}^m) = \frac{\prod_{j=1}^{d_m} f_w(y_j^m - A; 0, \sigma_w^2)P_{10} + f_w(y_j^m + A; 0, \sigma_w^2)P_{00}}{\prod_{j=1}^{d_m} f_w(y_j^m - A; 0, \sigma_w^2)P_{11} + f_w(y_j^m + A; 0, \sigma_w^2)P_{01}} \tag{8}$$

where $f_w(x;q,z)$ denotes the transmission noise density function with mean q and variance z. subsequently a decision θ is made as following:

$$\theta^m = \begin{cases} H_1, & L(\mathbf{y}^m) \le \delta \\ H_0, & L(\mathbf{y}^m) > \delta \end{cases} \tag{9}$$

where δ is the decision threshold allowing trade-offs in the performance of the LRT detector. The optimal LRT detector unfortunately requires the knowledge of the local CR detector performance parameters, *i.e.*, P_{ij}, values which are dependent on the existence/non-existence probabilities of the PU and the performance of the local CR detector that are clearly not available at the CBS. To overcome this drawback, we propose the following suboptimal two-stage detector.

2) Suboptimal Detector: We consider a two-step based information fusion algorithm at the CBS after collecting the data from the CRs. The CBS, after collecting the data from the CRs, performs the following two tasks consecutively:

1) Detect the transmitted $\{b_j^m\}_{j=1}^{d_m}$, values utilizing an optimal maximum a posteriori (MAP) detector.
2) Fuse the detected $\{\hat{b}_j^m\}_{j=1}^{d_m}$, values to determine the occupancy of the spectrum.

After fusing the estimated local decisions, the CBS transmits back the final decision to the CRs.

Let us define the following quantities:

$$P_i^m \triangleq \Pr\{h_j^m = 2i-1\} = \Pr\{b_j^m = i\} \tag{10}$$

where $i \in \{0,1\}$. Then, the optimal MAP detector for the additive white Gaussian noise (AWGN) channel is given by

$$\hat{h}_j^m = \mathrm{sgn}\{y_j^m - \lambda_{TS}^m\} \Rightarrow \hat{b}_j^m = \frac{1}{2}(\hat{h}_j^m + 1). \tag{11}$$

where

$$\lambda_{TS}^m = \frac{\sigma_w^2}{2A}\log\left(\frac{P_0^m}{P_1^m}\right). \tag{12}$$

Of note is that the MAP detector also minimizes the probability of detection error [17]. Clearly the MAP optimal detector requires the knowledge of P_i^m, $i \in \{0,1\}$ and $m = 1,2,\ldots,M$ values that might be unknown at the CBS. In the following, we present a computationally attractive and effective estimator of these probabilities in case they are unknown at the CBS [15], [16]:

$$\hat{\lambda}_{TS}^m = \frac{\sigma_w^2}{2A}\log\left(\frac{A-\Delta(\mathbf{y}^m)}{A+\Delta(\mathbf{y}^m)}\right) \tag{13}$$

where for $\mathbf{u} \in \mathbb{R}^{N\times 1}$, $\Delta(\mathbf{u}) = 1/N\sum_{k=1}^{N} u_k$.

Now, let θ^m denote the decision statistic at the CBS for the frequency band f^m, given the estimated $\{\hat{b}_j^m\}$ values –using λ_{TS}^m ($\hat{\lambda}_{TS}^m$) if the priors are (un)known–, the CBS decision statistic is obtained as in the following:

$$\theta^m = \begin{cases} H_0, & \Delta(\hat{\mathbf{b}}^m) \le \phi \\ H_1, & \Delta(\hat{\mathbf{b}}^m) > \phi \end{cases} \tag{14}$$

where ϕ denotes the decision threshold utilized at the CBS. This decision statistic is then broadcasted to the CRs. Of note is that we adopted the averaging concept as it is generally adopted for the corruption-free model. However, given the detected CR local detection results, one can utilize a different decision fusion processing based on a different criteria such as the "OR" logic [2]. We have recently shown that the suboptimal detector is more attractive then the global solution due to its simplicity, amount of information it requires and close-to-optimal performance [16].

C. Topology Model

We define a graph $G = (\mathcal{V})$ consisting of a set $\mathcal{V}$ with $|\mathcal{V}| = N$ vertices, where $|\cdot|$ denotes the cardinality. The vertices are uniformly distributed over the graph and represent the CR nodes in the network. We consider the cases where the nodes are (possibly) dynamic and move around the given area, thus we consider (possibly) dynamic topologies.

Random dynamic topology which is the result of random CR nodes placement/movement inside the cell area, addresses the problem of PUs' mobility. Indeed, accuracy of detection of a PU which is able to change its location (or direction of signal emission) rapidly in unpredictable manner depends on the cell region the detection is performed. As a result, solutions with rather uniform distribution of CRs are preferred over solutions where CRs tend to cluster.

D. Frequency Distribution

In our system, the frequency band f^m that a node is measuring is periodically updated with period Δt. At the beginning of each scanning cycle, the node chooses a frequency band f^m uniformly from the frequency set $\{f^m : m = 1,2,\ldots,M\}$ which is coordinated by the CBS by knowing which CR node scans which band. Let f_j for $j = 1,2,\ldots,N$ denote the frequency band sensed by the j'th node, then $\Pr\{f_j = f^m | t = t_0 + k\Delta t\} = 1/M$, for $k \in \mathbb{N}$.

Random sub-band selection is designed to further reduce location bias of the CRN topology. It becomes especially relevant in case of static or CRN with low mobility which ensures the nodes scanning the same frequency band will not be grouped in any region of the cell for more than one scanning cycle avoiding the problem occuring in [12], [13].

III. Performance Analysis

The performance of the shared spectrum sensing approach is presented here considering the proposed cooperative detection algorithm. We provide an example for the proposed method exhibiting its advantage, and present the cooperative detection performance of the shared spectrum sensing approach.

A. Shared Spectrum Example

We consider Ultra Wide Band (UWB) based Orthogonal Frequency Division Multiplexing (OFDM) as an example of a CR in our proposed shared subband cooperative algorithm. However, such methodology is applicable to any radio systems. There are two basic UWB standards to be mentioned: high data rate (European Computer Manufacturers Association, ECMA 386) and low data rate IEEE 802.15.4a. In ECMA standard, a UWB device operates with a number of

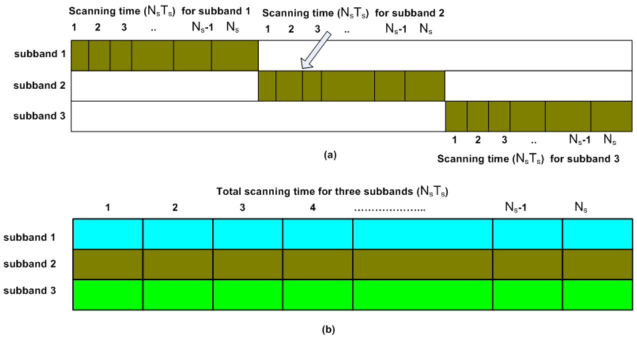

Fig. 1. (a) Cooperative scanning with $M = 3$: The time required to scan the spectrum (subband) is $N_S T_S$ μsec, (b) Non-cooperative scanning: The time required to scan is $M N_S T_S$ μsec, using one node

subbands, M (= 3) and each subband is about B_s wide (for example B_s = 528MHz). That means one single UWB device may operate with total of MB_s (MHz) bandwidth depending on the hopping technique. In such cases a single device may require to scan a large portion of the bandwidth which is an extremely time and power consuming process.

The main concept is that a group of CR-nodes will be assigned to perform spectrum sensing only within a particular subband B_s instead of scanning entire bandwidth. Figure-1 illustrates the ideas and compares the advantages considering UWB as an example of a CR. Suppose if a device sets its scanning duration to N_S OFDM symbols and each OFDM symbol is of T_S μsec long, then the UWB node spends $N_S T_S$ μsec of time to scan one single subband of bandwidth B_s. Since the UWB-CR needs to scan the entire bandwidth, the total scanning during becomes $M N_S T_S$ μsec. Now if we calculate the scanning time for the network forming with N numbers of UWB-CR nodes, then the network will be busy for $M N_S T_S N$ μsec of time scanning the spectrum. We compare the required scanning time for the same cell by spreading the task amongst the CR nodes assuming that a group of nodes should scan only a single subband for N_S symbols of duration. Meanwhile, the other subbands are also being scanned simultaneously by the other members of the group (i.e. by other UWB-CR nodes). Therefore in essence, the entire frequency band is scanned within the time period of $N_S T_S$ μsec. Considering this aspect, the cell requires only $N_S T_S N$ μsec of time to perform the scanning process. Therefore, the proposed algorithm improves the scanning time by a factor of M.

B. Detection Performance and Simulation Results

In this section we analyze the detection performance of the cooperative shared spectrum sensing approach in terms of the probability of miss detection and the probability of false alarm. We consider the *two-step* sub-optimal detector described in Section-II in our analysis. Let, B_w be the PU's transmission bandwidth, W be the total observation bandwidth of the CR node, Δ be the time duration between successive transmissions of the PU, τ be the transmission duration of the PU for a particular transmission, and T_w be the total time to **linearly** sweep the observation bandwidth W. In our model, we consider a Poisson arrival process for the traffic generated by the PU [18], where Δ then follows an exponential distribution with a mean time between transmission of Δ_m, and τ is assumed to be an exponentially distributed random process with a mean transmission duration of τ_m.

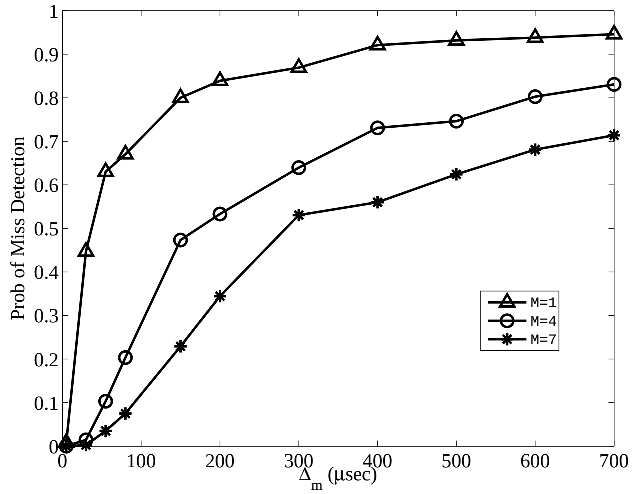

Fig. 2. Prob of miss detection for shared cooperative spectrum sensing approach wrt the mean time between transmission Δ_m, with $d_m = 5$, $T_w =$ 0.7msec, $\tau_m = 5\mu$sec, $\gamma_S = 10$dB, $B_w = 50$MHz, and $\gamma_T = 10$dB

A spectrum scanning process of a single CR node over a bandwidth of $W = 7GHz$ ($3GHz$ to $10GHz$) is considered linearly at a rate of W/T_w. When a PU transmits, the CR detects the transmission during its m^{th} scan only within the time slot from $t = t_0 + m f_1 T_w / W$ and $t = t_0 + m f_2 T_w / W$, where, f_1 and f_2 are the edge frequencies of the transmission bandwidth of the PU with $f_1 < f_2$, and t_0 is a constant. Given that the PU is detected by the CR, it decides upon hypothesis H_1 (PU detected) for the entire period of the scan before re-initializing it back to hypothesis H_0 (PU not detected) for the next scan (i.e. $(m+1)^{th}$ scan) until it is detected again. There are four possible cases in the detection, given by, Case-0 (C_0): case of $H_0|H_0$, Case-1 (C_1): case of $H_0|H_1$ (miss detection), Case-2 (C_2): case of $H_1|H_0$ (false alarm), and finally Case-3 (C_3): case of $H_1|H_1$. We see that when T_w reduces, or equivalently when the scanning frequency band is reduced per CR node, the occurrences of C_1 reduces, and hence reducing probability of miss detection in the system. This is the main advantage claimed in the shared spectrum sensing approach.

The system model was simulated and the results are presented here. Figure-2 shows the probability of miss detection with respect to the mean time between transmissions Δ_m for the PU. The system was simulated for the following parameters; B_w = 50MHz, W = 7GHz, T_W = 0.7msec, $\tau_m = 5\mu$sec, γ_S = 10dB, γ_T = 10dB and d_m = 5. The figure shows the performance improvement in terms of the probability of miss detection for the shared spectrum sensing approach when the cluster size M is increased. As expected the the probability of miss detection degrades when Δ_m is increased and at the same time improves when M is increased.

Figure-3 shows the probability of miss detection with respect to the transmission signal to noise ratio γ_T. As we see

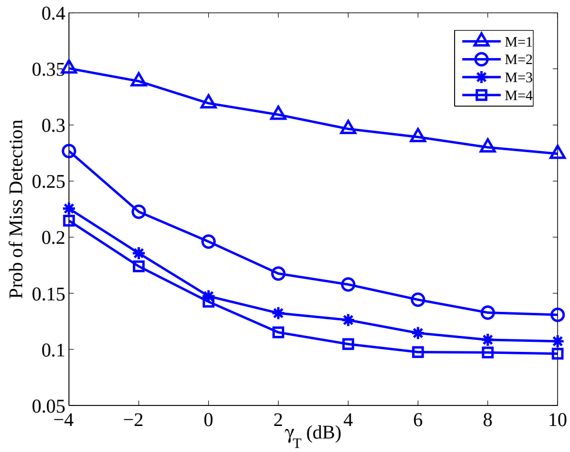

Fig. 3. Prob of miss detection for the shared cooperative spectrum sensing approach as a function of the transmission SNR γ_T, for $d_m = 5$, $\Delta_m = 40\mu$sec, $T_w = 0.7$msec, $\tau_m = 10\mu$sec, $B_w = 50$MHz, and $\gamma_S = 5$dB

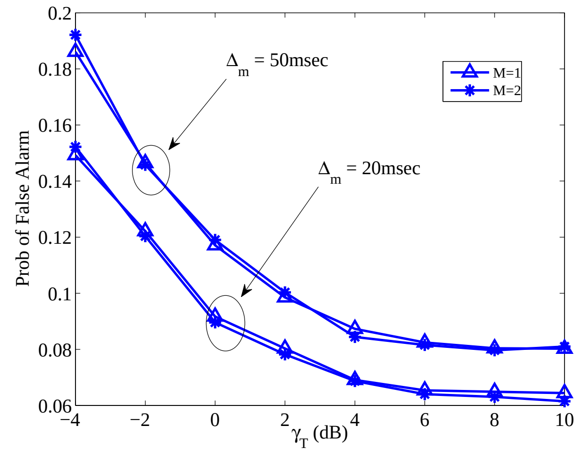

Fig. 4. Prob of false alarm for the shared cooperative spectrum sensing approach as a function of the mean time between transmission Δ_m, for $d_m = 5$, $T_w = 0.7$msec, $\tau_m = 10\mu$sec, $B_w = 50$MHz, and $\gamma_S = 0$dB

from the figure, the transmission channel noise greatly affects the cooperative detection performance at the CBS, the figure also shows the improvement using the shared spectrum sensing approach. We also notice that the detection performance at the CBS reaches a lower bound as γ_T increases which is bounded by the noise at the CR nodes during the spectrum sensing process. The probability of false alarm for the shared spectrum sensing approach is depicted in Figure-4. The probability of false alarm occurs due to the additive noise presence through out the sensing process when the PU is not transmitting. In Figure-4 we see that the probability false alarm does not depend on whether the spectrum sensing is shared or not, as expected, but mainly depends on the transmission and sensing SNR γ_S, γ_T, as well as Δ_m for a given observation time.

IV. Concluding Remarks

This paper addresses the problem of wideband spectrum sensing by the network of cognitive devices. When the system is wide band solutions currently available in the literature propose either continuous scanning using a single radio device which is time consuming or using a multi-band receiver which makes energy the constraint by scanning multiple bands in parallel. In this paper we propose a framework designed to minimize uncertainty in primary user detection while maintaining control over the time and the amount of energy spent for spectrum sensing by cognitive terminals. Specifically, it arranges the nodes into groups each sensing a disjoint small band of the spectrum (shared spectrum sensing) while the nodes within the group produce cooperative decision.

Acknowledgments

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