Cognitive Radio oriented wireless networks: Challenges and solutions

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Cognitive Radio Oriented Wireless Networks: Challenges and Solutions

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***Abstract*—Existing wireless networks are unable to fulfill the insatiable demand of radio spectrum by emerging wireless services and applications. To address the current spectrum scarcity problem, next generation wireless networks are required to be comprising of intelligent and reconfigurable radios (popularly known as Cognitive Radios (CRs)) that can interact with their continuously changing environment to capture real time spectrum awareness and avail any spectrum usage opportunity. Dynamic and opportunistic spectrum access is identified as an enabling technology for Cognitive Radio Oriented Wireless Network (CROWN) wherein low-priority secondary users (CRs) are allowed to communicate over licensed frequency bands when the legacy users of that spectrum are not fully utilizing it. As most of the spectrum is already allocated to primary users with exclusive legacy rights of the frequency bands, the key challenge for CROWN is to reuse/share licensed spectrum without interfering with primary transmissions. This paper highlights fundamental challenges in getting multi-dimensional spectrum awareness under practical constraints and provides viable solutions. Furthermore, limitations of both transmitter detection based non-cooperative spectrum sensing techniques and cooperative sensing strategies are discussed, open research challenges are investigated and possible solutions are presented.**

***Keywords*–cognitive radio; spectrum sensing; cooperative sensing; noise uncertainty; receiver uncertainty; sensing duration; sensing frequency; cooperation overhead; sensing delay**.

I. INTRODUCTION

Recent studies [1] on spectrum utilization reveal that actual spectrum usage varies from 15% to 85% with wide variance in time and space indicating that the root cause of current spectrum scarcity is the inefficient fixed spectrum allocation. Cognitive Radio (CR) has emerged as a promising solution to poor spectrum efficiency problem by fully exploiting the under-utilized spectrum wherein unlicensed (secondary) users are allowed to opportunistically access the un-used licensed spectrum without interfering with primary users with legacy rights to that spectrum. The key component of CR technology is the ability to sense and ultimately adapt to the continuously updating radio's operating environment. The most crucial task of CR in this regard is to track Primary User (PU) activity in the spectrum of interest with an aim to reliably identify currently un-occupied frequency bands, popularly known as *spectrum hole(s)*, across multiple dimensions like time, space, frequency, angle and code etc. With an objective to benefit from this spectrum usage opportunity, CR adjusts its transmission parameters e.g. modulation, frequency, access technique etc on the fly and uses the available band until the licensed user of that spectrum resumes its transmission. In that case, CR which behaves like a low priority Secondary User (SU), must move to another spectrum hole if available or to reconfigure itself (by changing its transmission power, modulation scheme etc) to avoid presenting any noticeable interference to PU.

The most critical concern for the establishment of Cognitive Radio Oriented Wireless Network (CROWN) is that the secondary transmissions over specific licensed frequency band must remain transparent to legacy users of that spectrum. This requirement is necessary to avoid any harmful interference to licensed users and has to be met under scattering rich RF environment. As a result, SUs must detect primary transmissions at very low SNR with high probability of detection within very short period of time. On the other hand, secondary users would not be able to exploit spectrum usage opportunity efficiently if they falsely identify any PU activity in the scanned band when the spectrum is actually free. This demands the probability of false alarm to be maintained at minimum. In this way, Spectrum Sensing (SS) performance is crucial to both primary and secondary networks. For these reasons, various standards related to dynamic spectrum access (e.g. IEEE 802.22, IEEE 802.11h, IEEE 802.11y and IEEE 802.16h) require high sensing performance for the actual deployment of CROWN which make practical spectrum sensing a very challenging task. For example, IEEE 802.22 standard allows Wireless Regional Area Network (WRAN) secondary devices to transmit over TV *white spaces* if they can detect digital TV signal at -21 dB SNR while maintaining at least 90% probability of detection and maximum 10% probability of false alarm [2].

Facing these challenges,the main functionality of CR lies in efficient and reliable spectrum sensing techniques. Variety of spectrum sensing approaches ranging from very simple energy detection based on periodogram to quite advanced approaches based on cyclostationary feature detection, pilot based coherent detection using correlation and matched filtering concept and covariance based blind detection are reviewed in [3]. Here, our objective is to highlight limitations of these sensing schemes subject to practical constraints and propose viable solutions to the fundamental challenges in SS. For in-depth

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comparative survey of sensing techniques along with other aspects of SS, the interested readers are referred to [4].

The organization of this paper is as follows. Section II introduces the system model for primary transmitter detection and identifies the key detection performance metrics. Fundamental challenges associated with spectrum sensing based on local, non-cooperative detection of spectrum activity are discussed in Section III and possible solutions are provided. In Section IV, cooperative sensing concept is presented and an insight into the cooperation overhead as the cost of achievable cooperative gain is highlighted as the fundamental challenge in cooperative detection. Finally, conclusions are drawn in Section V.

II. System Model for Primary Transmitter Detection

Spectrum sensing is the task of obtaining awareness of spectrum usage. The most efficient approach to identify spectrum opportunity with low infrastructure requirement is to detect the presence of a primary receiver within coverage area of CR. Practically, however, it is not feasible as CR cannot locate PU receiver due to absence of signaling between them. Hence, CR bases its decision about the presence or absence of PU on locally observed weak primary transmitter signal which can be formulated as a binary hypothesis problem as follows [3].

$$x(t) = \begin{cases} n(t), & 0 < t \leq T \quad H_0 \\ hs(t) + n(t), & 0 < t \leq T \quad H_1 \end{cases} \tag{1}$$

where x(t) is the signal received by CR during observation window *T*, *n(t)* represents the Additive White Gaussian Noise (AWGN) with mean 0 and variance σ^2, *s(t)* represents the PU transmitted signal which is to be detected and *h* is the channel gain. This is a classic binary signal detection problem in which CR has to decide between two Hypothesis, H_0 and H_1. H_0 corresponds to the absence of primary signal in scanned spectrum band while H_1 indicates that some licensed user is occupying the frequency of interest. The performance of detection algorithm is gagged with its *sensitivity* and *specificity* [5] which are measured by two metrics: probability of detection P_d,which denotes the probability of correctly detecting the PU signal present in the considered frequency band, and probability of false alarm P_f, which represents the probability that the detection algorithm falsely decides that PU is present in the scanned frequency band when it actually is absent. Thus, we target at maximizing P_d while minimizing P_f. Another important probability of interest in analyzing the performance of detection algorithm is probability of missed detection P_m which is the complement of P_d. Total probability of making a wrong decision on spectrum occupancy is given by the weighted sum of P_f and P_m. Hence the key challenge in PU transmitter detection based SS approach is to keep both P_f and P_m under maximum allowed limit as high P_f corresponds to poor spectrum utilization/exploitation by CR and high P_m results in increased interference at primary receiver.

Extensive literature exists on SS techniques [3]-[7]. Our contribution in this paper is in reference to challenges associated with spectrum sensing schemes where we identify number of factors that may significantly compromise the sensing results and present possible solutions to achieve targeted detection performance.

III. Challenges In Spectrum Sensing

This section features key research challenges in spectrum sensing and provides feasible solutions to them while giving references to key publications for in-depth reading.

A. Optimal threshold setting

As indicated in Section II, SS in essence is a binary detection problem in which setting the right threshold value is of critical importance. The key problem in this regard for the case of Energy Detector (ED) based sensing is illustrated in Figure 1 which shows probability density function of received signal with and without active PU. If Γ represents the test statistics (energy content of the received signal in this case), sensing algorithm differentiates between the two hypotheses H_0 and H_1 by comparing Γ with threshold voltage V_t as:

$$\begin{array}{lll} \Gamma \geq V_t & => & H_1 \\ \Gamma < V_t & => & H_0 \end{array} \tag{2}$$

Hence if V_t is kept too low,

$$Pr(\Gamma \geq V_t/H_0) \text{ increases} \tag{3}$$

increasing P_f which results in low spectrum utilization.

On the other hand, if V_t is kept unnecessarily high,

$$Pr(\Gamma < V_t/H_1) \text{ increases} \tag{4}$$

corresponding to increased P_m which makes the CR susceptible to interfere with active PU. Hence, a careful trade off has to be considered while setting the threshold. In practice, if a certain spectrum re-use probability of unused spectrum is targeted, P_f is fixed to a small value (e.g $\leq 5\%$) and P_d is maximized. This is referred to as Constant False Alarm Rate (CFAR) detection principle [4]. However, if the CROWN is required to guarantee a given non-interference probability, P_m is set at a minimum value (or equivalently P_d is fixed to a high value (e.g. $\geq 95\%$)) and P_f is minimized. This requirement is known as Constant Detection Rate (CDR) principle [4].

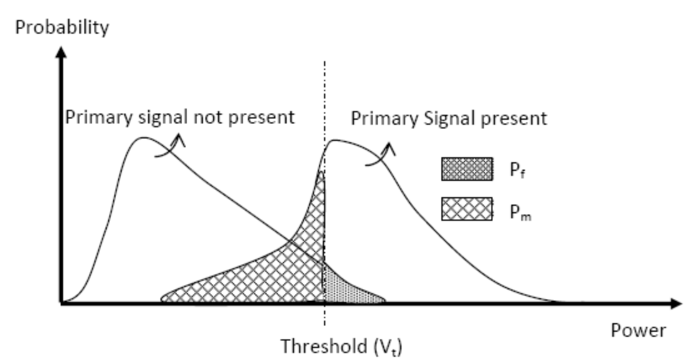

Fig. 1. Threshold setting in SS: trade off between P_m and P_f

B. Noise uncertainty problem

Another challenge related to threshold setting is noise power uncertainty as the value of threshold strongly depends on the actual noise variance which may change with time and location. Figure 2 indicates the performance degradation of energy detector based SS under noise uncertainty for different sample size. These curve indicate the presence of SNR wall [8] defined as the minimum SNR below which the performance of ED remains unreliable even for infinite sensing duration (unlimited sample size).

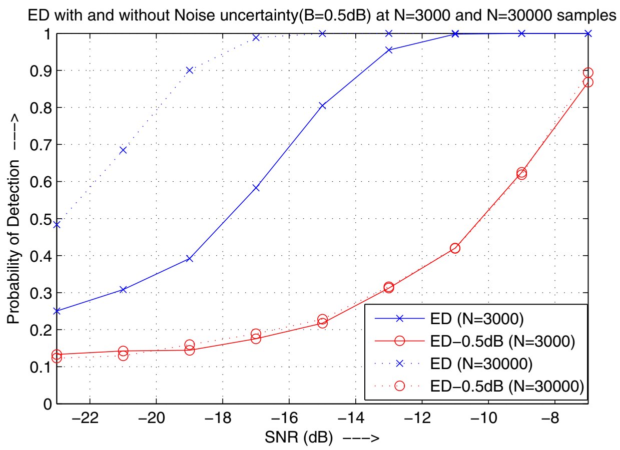

Fig. 2. Performance of ED based spectrum sensing under noise uncertainty

Reliability of spectrum sensing under noise uncertainty is studied in [9] where the authors have proposed cooperative sensing to increase the detection reliability with increasing number of cooperating sensors. Cooperative sensing and associated challenges in increasing the number of cooperating nodes are addressed in Section IV.

C. Primary receiver uncertainty problem

PU transmitter detection based sensing approach is simple but it cannot detect PU activity when CR lies outside the primary transmitter range. As a result, CR creates unavoidable interference to primary receivers particularly when CR lies close to them. This situation called *primary receiver uncertainty problem* as depicted in Figure 3a is a crucial challenge to meet in sensing.

D. Detecting hidden primary transmitter

A situation similar to receiver uncertainty problem may arise even when the CR lies inside the primary transmitter range but experiences heavy shadowing or deep fading. This situation is called *hidden primary transmitter problem* and depicted in Figure 3b. In this case, primary receiver becomes vulnerable to harmful interference by secondary communications as shadow fading makes CR blind to pick up ongoing primary transmissions. Cooperation among CRs is a promising solution to mitigate multipath fading and shadowing based on the underlying rationale that spatially distributed secondary users are unlikely to experience same channel conditions. Cooperative sensing is discussed in detail in Section IV.

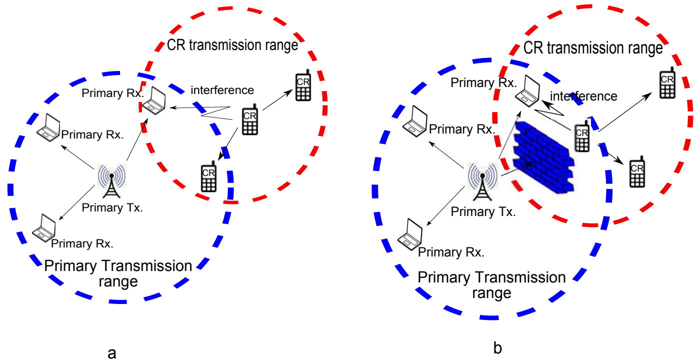

Fig. 3. (a) Receiver uncertainty prob. (b) Hidden primary transmitter prob.

E. SS in multiuser environment

Usually, CRs reside in a multiuser environment consisting of users with and without exclusive rights for frequency spectrum. In addition, CRs can be co-located with other secondary networks competing for the same spectrum resource. Under these situations, SUs may interfere with each other making PU detection a difficult task. The presence of a second secondary network affects the detection capability of a CR in two ways:

- A secondary signal may be detected as a primary signal
- A secondary signal may mask the primary signal thus deteriorating the PU detection capability of CR

Multiuser problem can be addressed using cooperative sensing which is discussed along with its own challenges in Section IV.

F. Detecting spread spectrum primary signals

PUs employing spread spectrum signaling spread their transmitted power over wide frequency range. This may be a single band in the case of Direct Sequence Spread Spectrum (DSSS) or multiple bands for Frequency Hopping Spread Spectrum (FHSS). In both the cases, SS becomes difficult and needs some *apriori* information regarding frequency hopping patterns and synchronization pulses to successfully detect such primary transmissions.

G. Exploiting spectrum usage opportunity in angle dimension of spectrum space

With the recent advances in multi-antenna technology and signal processing, PUs instead of emitting radio waves over air interface in all directions may confine their transmissions within an angle targeting particular primary receivers present in specific direction. In such cases, different users can simultaneously transmit over shared frequency, time, space and code resources. Such users employ highly directional antennas or use signal processing techniques like beamforming to avoid interference with neighboring users. In CR technology, this means that primary and secondary users can share the same frequency band in the same time slot and in same area if the secondary transmissions can be directed in directions other than the primary transmission directions. To benefit from this new dimension of spectrum space, CR must estimate the Angle of Arrivals (AoAs) of the primary transmissions along with the occupied frequency band which is a challenging task and needs yet to be explored in depth for its practical feasibility.

H. Sensing duration and sensing frequency

The key to efficient spectrum utilization is rapid and reliable spectrum sensing. However, sensing time reduction is always traded off with sensing reliability. Similarly, sensing frequency (i.e. how often spectrum sensing is performed) is another design parameter that must be selected very carefully. Optimum value of sensing frequency depends on CR capabilities and PU temporal characteristics in the radio environment. An important thing to note is that a channel that is being used by SU cannot be used for sensing. This requires SU to interrupt their data transmission for possible PU identification on that channel. As a result, spectrum efficiency of the overall system is decreased. To combat this situation, a method known as Dynamic Frequency Hopping (DFH) has been proposed in [10]. DFH is based on the assumption of having more than one channel. During operation on a *working channel*, *intended channel* is sensed simultaneously and if its availability is reported, the *intended channel* becomes the *working channel*. However, this requires apriori knowledge of hopping pattern which might be difficult to obtain. Furthermore, some of the time would still be wasted in sensing the *intended channel* which can otherwise be used for secondary transmissions.

I. Sensing at extremely low SNR

Detection of low-power primary signals (e.g. wireless microphone signal with typical transmission power level below 17 dBm) in itself is an arduous job which becomes challenging under uncertain channel conditions. This problem can be handled using cooperative sensing approach which exploits spatial diversity to increase the reliability of PU detection. Cooperative SS and associated challenges are elaborated later in Section IV.

J. Sensing with limited information

CRs need to sense their multidimensional radio environment with limited available information. Possible enhancement of sensing capability might be through cooperative communication between secondary users but this may not be always feasible and simple along with possible delays and other overheads. Cooperative sensing and cooperation overhead are discussed in Section IV.

K. Physical constraints for practical wideband sensing

In principle, CRs are required to sense relatively large frequency band for identifying spectrum holes. The large operating bandwidth imposes stringent requirements on RF front end of cognitive radio including wideband antennas and power amplifiers. Different approaches have been suggested in literature to combat CR hardware requirements. In [11], authors have proposed two different SS architectures based on single radio and dual-radio chains. In single radio sensing architecture, CR itself is responsible for sensing the radio environment. In this approach, limiting sensing time not only results in degraded reliability of spectrum occupancy decision rather it also decreases the overall spectrum efficiency as some portion of the time slot (sensing period) is used in SS while remaining time (transmission period) is used for data transmission. The obvious advantage is simplicity and low cost. In the dual radio setup, one radio chain is dedicated for spectrum monitoring while the other radio chain transmits and receives secondary data. In this way, disadvantages of single radio architecture are overcome at the cost of increased power consumption and hardware cost and complexity.

L. Security

In CROWN, legitimacy of PU is an important aspect to consider. In this regard, Primary User Emulation (PUE) attack wherein a selfish or malicious SU may mimic a PU is investigated in [12]. To combat security issues, a public key encryption based security mechanism is also proposed but it has its own requirements and limitations.

IV. Cooperative Sensing and Associated Challenges

As compared to simple primary transmitter detection which relies on the sensing by single CR, cooperative detection refers to SS methods where multiple CRs cooperate in a centralized or decentralized manner to decide about the spectrum hole. Each cooperating node in CROWN may apply any sensing method locally, and then share its raw/refined sensing information with other senor(s), depending on a selected cooperation strategy. A comprehensive survey on Cooperative Spectrum Sensing (CSS) discussing cooperation models, information fusion approaches, control channel and reporting concerns and user selection etc is available in [4],[13]. Here, we present an insight into the achievable cooperative gain and associated cooperation overhead.

Cooperative detection provides enormous *cooperation gain* by mitigating multipath fading and shadowing effects which are the key issues in spectrum sensing. This is depicted in Figure 4 which highlights the performance enhancement through CSS with 10 cooperating CRs. The figure shows the complementary Receiver Operating Characteristics (ROC) (plot of P_m vs. P_f) of ED under rayleigh fading and log-normal shadowing (with 6dB spread) for time-bandwidth product = 5 and average received SNR of 10 dB [14].

However, the practically achievable cooperation gain may diminish when cooperating CRs are blocked by the same obstacle resulting in correlated shadowing. Sensing performance degrades further when more and more spatially correlated CRs participate in reaching a cooperative decision [14]. In addition to gain-limiting factors, CSS can incur *cooperation overhead* in terms of cooperative sensing delay, increased energy requirements and more vulnerability to security attacks.

Hence, the key challenge in cooperative sensing is to achieve optimal cooperation gain without being compromised by the associated cost. In the following, we discuss some of the

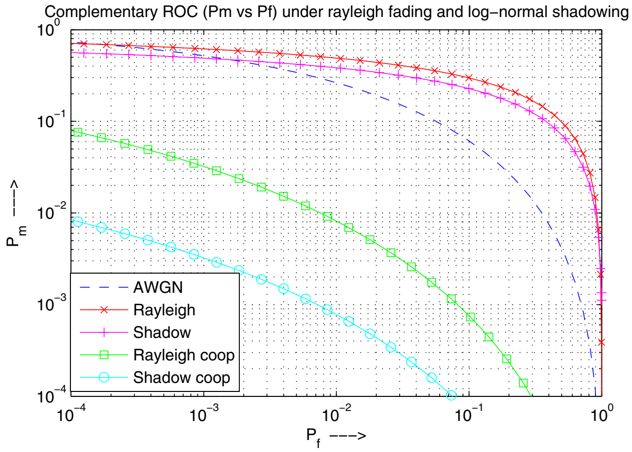

Fig. 4. Sensing performance enhancement through cooperation

fundamental challenges in CSS and present possible solutions to meet these challenges in an efficient manner.

A. Cooperative sensing delay

As opposed to non-cooperative spectrum sensing, CSS involves sharing local sensing information to achieve a unified global cooperative decision. As a result, the total sensing time in cooperative detection must include reporting time along with the conventional local sensing time. Following three factors play a critical role in deciding about the overall reporting time:

- amount of reporting data,
- number of cooperating secondary users and
- reporting channel access scheme.

Synchronization among the cooperating CRs is also taken as an underline assumption in many typical cooperative sensing schemes such as ED based CSS. Such schemes, being blind or semi-blind suffer from the lack of the capability to distinguish between primary and secondary transmissions and hence require all CRs to halt their transmissions for simultaneous sensing operations. Also, most of the cooperative sensing techniques assume that the sensing results become available for combining not only instantly but also concurrently. In such cases, the delay for synchronization also needs to be taken into account while analyzing the cooperative sensing delay.

Moreover, the cooperative decision results from an iterative process in distributed cooperation and thus *convergence rate* of distributed cooperation algorithm also affects the overall sensing time in CSS.

Therefore, it is evident that cooperative sensing delay is influenced by multiple factors which must be carefully analyzed in order to determine practically achievable throughput of CROWN employing cooperative detection.

B. Spatially correlated shadowing and optimal user selection

Cooperative sensing is most efficacious when cooperating nodes witness independent fading and shadowing. Correlated shadowing results in increased probability of missed detection, degrading the overall sensing performance of CROWN which has been analyzed in [14]. In this paper, It is also shown that a small number of cooperating CRs over a large geographical area may outperform comparatively large number of cooperating CRs over a smaller area. Hence, the key challenge to mitigate correlated shadowing lies in *optimal user selection* ensuring that all cooperating CRs experience independent observations under practical fading and shadowing conditions. Careful user selection in CSS also improves the reliability and security of CROWN. Furthermore, optimal user selection offers increased network efficiency both in terms of throughput and energy requirements. Optimally choosing the number of cooperating CRs is another challenge which has been studied in [15]. It has been shown that CRs with high PU's SNR give optimum sensing performance rather employing all SUs in CROWN to cooperate. The Binary Particle Swarm Optimization (BPSO) algorithm to find suitable cooperative nodes is applied in [16] to show improved sensing performance when compared with the case that all neighboring nodes participate in sensing.

C. Information fusion criterion

Finding an efficient information sharing approach is another challenge in CSS. This problem in itself is multifarious and becomes very critical when the number of CRs in CROWN become large, requiring prohibitively large control channel band width along with added computational complexity and reporting delay. Optimum decision combining approach is analyzed for both soft and hard combining at FC in [17] and a genetic-based soft combining algorithm is proposed to improve cooperative decision provided SNRs of all cooperating CRs and channel conditions are known while combining. More recently, in [18], the optimal value of k for k out of N decision fusion rule is derived using completely blind, learning automata based, voting rule optimization approach.

D. Energy efficiency

The energy consumption in CSS is proportional to number of cooperating CRs and amount of sensing information that is shared among CRs. Optimal user selection and decision fusion approaches are generally invoked to deal with the increased energy consumption overhead in CSS. The key challenge in this regard is to let only those CRs sense and report (i.e. consume energy) which do participate in final cooperation. In this regard, a combination of *censoring* and *sleeping* policies is proposed for the cases of known and unknown PU activity in [19]. Authors have shown that applying this technique in large sensor networks, overall energy consumption of the network is reduced significantly and becomes independent of the number of cooperating nodes.

E. PU and CR mobility

Mobility of primary and/or secondary users in CROWN is a unique challenge for cooperative detection as it may boost or diminish the achievable cooperative gain in CSS. For example, if we consider stationary PU, moving CRs may observe independent or correlated shadowing at different times depending on their direction and speed. In this way, cooperation throughput changes with the movement of cooperating CRs. Problem analysis becomes more challenging if PU also starts to move simultaneously with secondary users in CROWN. Impact of mobility on sensing is addressed in [20] though such studies are still in their very primitive phase.

F. Data falsification and Security attacks

Security plays a critical role in CSS. The risk of involving malfunctioning and malicious secondary users increases proportionally with the increasing number of cooperating CRs. Such unwanted secondary users may intentionally corrupt or send unreliable sensing information to influence the cooperative decision in their favor. PU emulation attacks and control channel jamming are examples of security attacks where legitimate CRs are forced to vacate the acquired frequency band for attackers. To address security problems, all cooperating users are authenticated [21] which puts additional overhead in cooperative detection. The key challenge in this regard is to ensure security during cooperation under the constraint of minimum incurred overhead.

V. Conclusions

Acquiring reliable spectrum awareness is the core requirement of cognition-based future wireless networks for efficiently resolving the conflict between spectrum congestion and under-utilization. In this paper, we examined various challenges in obtaining multi-dimensional spectrum awareness and proposed viable solutions to tackle these problems. Specifically, spectrum sensing with limited information and sensing at extremely low SNR were found to be most critically affecting the overall system throughput. Cooperative sensing was identified as a promising solution to meet high performance requirements imposed by dynamic spectrum access standards for the practical deployment of CROWN. The critical trade-off between achievable cooperative gain and incurred cooperation overhead was analyzed in detail. Optimal user selection and decision fusion approach were shown to be most dominantly dictating the cooperative detection performance in terms of sensing delay, control channel bandwidth and energy efficiency. Mobility of primary and secondary users in CROWN and security concerns in ad-hoc heterogenous networks were pointed out as open research challenges that are still needed to be adequately addressed before the establishment of CROWN.

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