Spectrum Sensing in Cognitive Radio Networks: Requirements, Challenges and Design Trade-offs

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ABSTRACT

Opportunistic unlicensed access to the (temporarily) unused frequency bands across the licensed radio spectrum is currently being investigated as a means to increase the efficiency of spectrum usage. Such opportunistic access calls for implementation of safeguards so that ongoing licensed operations are not compromised. Among different candidates, sensing-based access, where the unlicensed users transmit if they sense the licensed band to be free, is particularly appealing due to its low deployment cost and its compatibility with the legacy licensed systems. The ability to reliably and autonomously identify unused frequency bands is envisaged as one of the main functionalities of *cognitive radios*. In this article we provide an overview of the regulatory requirements and major challenges associated with the practical implementation of spectrum sensing functionality in cognitive radio systems. Furthermore, we outline different design trade-offs that have to be made in order to enhance various aspects of the system's performance.

INTRODUCTION

Driven by consumers' increasing interest in wireless services, demand for radio spectrum has increased dramatically. Moreover, with the emergence of new wireless devices and applications, and the compelling need for broadband wireless access, this trend is expected to continue in the coming years.

The conventional approach to spectrum management is very inflexible in the sense that each operator is granted an exclusive license to operate in a certain frequency band. However, with most of the useful radio spectrum already allocated, it is becoming exceedingly hard to find vacant bands to either deploy new services or enhance existing ones.

On the other hand, as evidenced in recent measurements, the licensed spectrum is rarely utilized continuously across time and space [1]. Figure 1 shows spectrum utilization in the frequency bands between 30 MHz and 3 GHz averaged over six different locations [2]. The relatively low utilization of the licensed spectrum suggests that spectrum scarcity, as perceived today, is largely due to inefficient fixed frequency allocations rather than any physical shortage of spectrum. This observation has prompted the regulatory bodies to investigate a radically different access paradigm where secondary (unlicensed) systems are allowed to *opportunistically* utilize the unused primary (licensed) bands, commonly referred to as *white spaces*. In particular, the Federal Communications Commission (FCC) has already expressed its interest in permitting unlicensed access to white spaces in the TV bands [3]. This interest stems in part from the great propagation characteristics of the TV bands and their relatively predictable spatiotemporal usage characteristics. Building on this interest, the IEEE has formed a working group (IEEE 802.22) to develop an air interface for opportunistic secondary access to the TV spectrum. In order to protect the primary systems from the adverse effects of secondary users' interference, white spaces across frequency, time and space should be reliably identified. Table 1 lists a variety of approaches that may be employed for this purpose.

The first two approaches charge the primary systems with the task of providing secondary users with current spectrum usage information by either registering the relevant data (e.g., the primary system's location and power as well as expected duration of usage) at a centralized database or broadcasting this information on regional beacons [4]. While leading to simplified secondary transceivers, these methods require some modifications to the current licensed systems and, as such, are incompatible with legacy primary users. Moreover, their deployment is costly and requires positioning information at

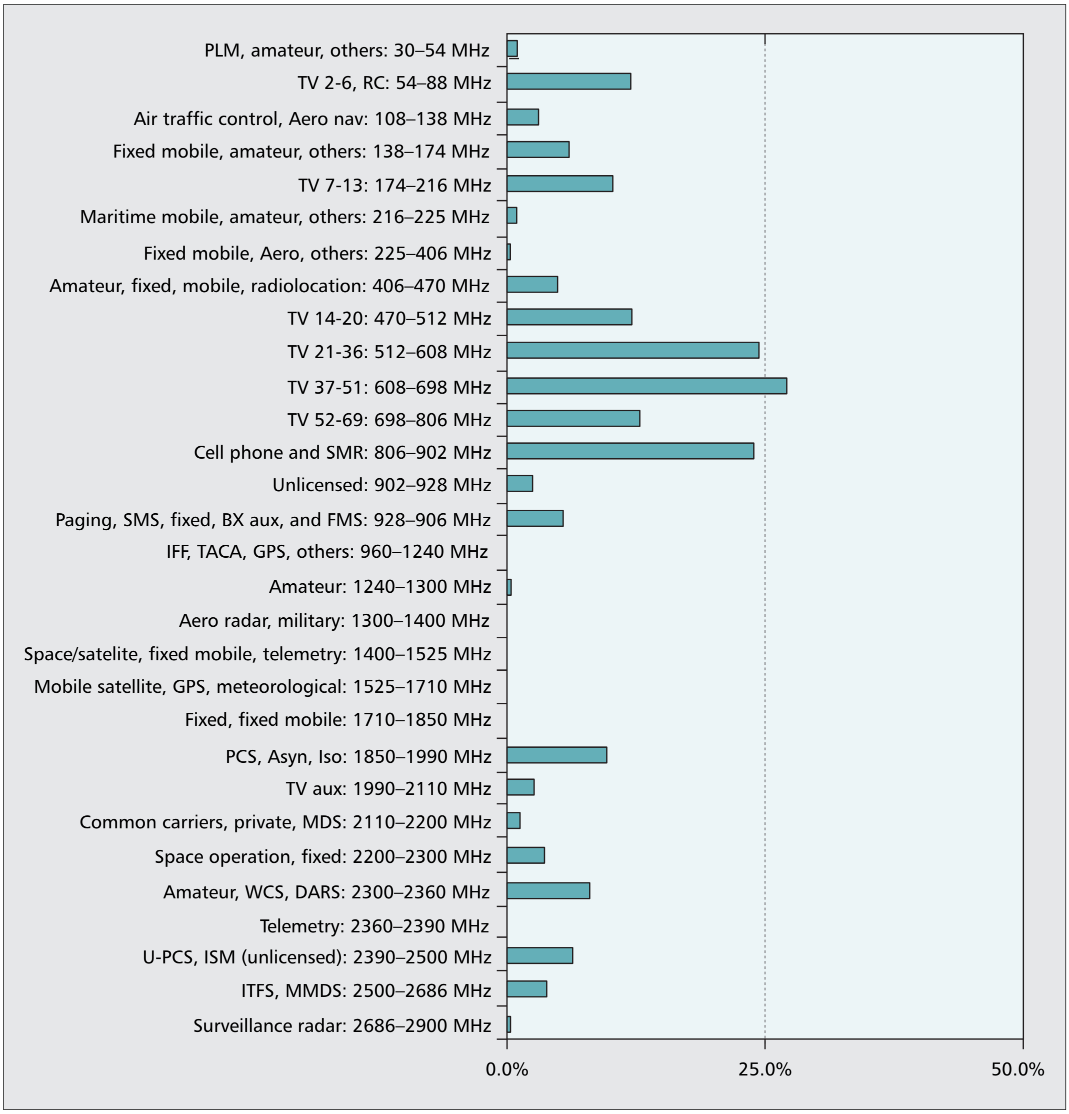


Figure 1. *Spectrum usage measurements averaged over six locations [2].*

Thanks to its relatively low infrastructure cost and its compatibility with the legacy primary systems, spectrum sensing has received more attention compared to other candidates and is being considered for inclusion in the IEEE 802.22 standard.

the secondary users in addition to either a ubiquitous connection to the database or a dedicated standardized channel to broadcast the beacons.

Spectrum sensing, on the other hand, solely relies on the secondary system to identify white spaces through direct sensing of the licensed bands. In this case the secondary system monitors a licensed frequency band and opportunistically transmits when it does not detect any primary signal. Thanks to its relatively low infrastructure cost and compatibility with legacy primary systems, spectrum sensing has received more attention than other candidates and is being considered for inclusion in the IEEE 802.22 standard.

Due to their ability to autonomously detect and react to changes in spectrum usage, secondary users equipped with spectrum sensing capability may be considered a primitive form of cognitive radio [5]. Indeed, enabling dynamic spectrum access seems to be the first and foremost commercial application of cognitive radio [6]. This article provides an overview of different issues associated with the implementation of spectrum sensing functionality in secondary systems. In particular, practical challenges in reliable identification of white spaces along with technical solutions are discussed. Furthermore, major trade-offs involved in the design and optimization of spectrum sensing from the end user's point of view are characterized.

Spectrum Sensing Techniques

If the structure of the primary signal is known, the optimal detector in stationary Gaussian noise is a matched filter followed by a threshold test. This type of coherent detection may be a viable approach for early cognitive radio deployments where the secondary system is limited to operate in a few primary bands. However, with more primary bands being opened for opportunistic access, the implementation cost and complexity associated with this approach will increase prohibitively since a cognitive radio will need dedicated circuitry to achieve synchrony with each type of primary licensee as required for coherent detection [7].

A simpler alternative for the detection of a primary signal in noise is to employ energy

	Infrastructure cost	Legacy compatibility	Transceiver complexity	Positioning	Internet connection	Continuous monitoring	Standardized channel
Database registry	High		Low	X	X		
Beacon signals	High		Low	X			X
Spectrum sensing	Low	X	High			X	

Table 1. *Classification of white space identification methods.*

detection. An energy detector simply measures the energy received on a primary band during an observation interval and declares a white space if the measured energy is less than a properly set threshold. While compared to matched filtering energy detection requires a longer sensing time to achieve a desired performance level, its low cost and implementation simplicity render it a favorable candidate for spectrum sensing in cognitive radio systems.

The main drawback of the energy detector is its inability to discriminate between sources of received energy (the primary signal and noise), making it susceptible to uncertainties in background noise power, especially at low signal-to-noise ratio (SNR) [8]. If some features of the primary signal such as its carrier frequency or modulation type are known, more sophisticated *feature detectors* may be employed to address this issue at the cost of increased complexity. These detectors rely on the fact that, unlike stationary noise, most communication signals exhibit spectral correlation due to their built-in periodicities (features) such as carrier frequency, bit rate, and cyclic prefixes. Since the spectral correlation properties of different signals are usually unique, feature detection allows a cognitive radio to detect a specific primary signal buried in noise and interference.

In practice, a combination of different techniques may be needed in order to handle different situations. For instance, energy detection may be used to perform a quick but coarse scan of a wide range of frequencies to identify a few *possibly free* bands. The white spaces among these candidate bands may then be discovered through more accurate feature detection. Regardless of the underlying detection technique, sensing performance may be improved by sensing (observing) the band for a longer time, thereby increasing signal processing gain. However, as we shall shortly describe, regulatory constraints imposed on sensing time limit such improvements.

Regulatory Constraints

Realization of the opportunistic spectrum access paradigm is contingent on satisfactory protection of primary systems from harmful interference. Consequently, sensing performance is subject to certain regulatory constraints, which are characterized in what follows.

Sensing Periodicity

While utilizing a white space, the secondary system should continue to *periodically* sense the band (e.g., every T_p) in case a primary user starts to transmit. The sensing period, T_p, determines the maximum time during which the secondary user will be unaware of a reappearing primary user and hence may harmfully interfere with it. Therefore, the sensing period determines the delay, and thus the quality of service (QoS) degradation, incurred by the primary users in accessing the band. In general, T_p will depend on the type of the primary service (e.g., delay sensitivity of the primary application) and has to be set for each licensed band by the regulator. For instance, one expects T_p to be very small for the public safety spectrum, while less frequent sensing may be allowed for the TV spectrum where the spectrum usage varies over a much larger timescale.

Since it is not possible to transmit on a licensed band and sense it simultaneously, sensing has to be interleaved with data transmission. While from the regulator's perspective it suffices for the secondary system to monitor the band and make a decision about the presence of the licensee once every T_p s, from the secondary system's point of view it is desired to maintain the sensing time *well below* T_p in order to maximize the time available for data transmission.

Detection Sensitivity

Interference due to a cognitive radio network is deemed harmful if it causes the signal-to-interference ratio (SIR) at any primary receiver to fall below a certain threshold, Γ, supplied by the regulatory bodies. This threshold depends on the receiver's robustness toward interference and varies from one primary band or service to another. Some examples include 34 dB for analog TV and 23 dB for digital TV [3]. It should, however, come as no surprise that this threshold in general may depend on the characteristics of the interfering signal (e.g., signal waveform, continuous vs. intermittent interference) as well [9], which in turn may influence a cognitive radio's choice of transmission waveform in certain licensed bands.

Building on the above definition, the *interference range* of a secondary transmitter may be defined as the maximum distance from a primary receiver at which the incurred interference is still considered harmful. As such, the interference range depends not only on the secondary user's transmitted power, but also on the primary user's interference tolerance. Let P_p and P_s denote the transmitted power of the primary and secondary users, respectively. We also denote by R the maximum distance between a primary transmitter and its corresponding receiver. Thus, R may be the maximum length of a point-to-point microwave link or the coverage radius of a TV station, as shown in Fig. 2. The interference range of the secondary user, D, is then determined by the following condition:

$$\frac{P_p L(R)}{P_s L(D)+P_b}=\Gamma, \tag{1}$$

where P_b is the power of background interference at the primary receiver and $L(d)$ denotes the total path loss (including shadowing and multipath fading effects) at a distance d from the transmitter. Since path loss varies with frequency, terrain characteristics and antenna heights, these parameters should be taken into account in the evaluation of D.

The condition in Eq. 1 ensures that a primary receiver, even if located at the edge of its service area, is still protected from harmful interference if it is not within the interference range of the secondary user. Consequently, in a sensing-based system, the cognitive radio has to be capable of detecting any active primary transmitters within a radius of $R + D$ to ensure that no primary receivers are operating within its interference range. Defining the *detection sensitivity*, $\gamma_{\min}$, as the minimum SNR at which the primary signal may still be accurately (e.g., with a probability of 0.99) detected by the cognitive radio, this regulatory requirement may be expressed as

$$\gamma_{\min}=\frac{P_p L(D+R)}{N}, \tag{2}$$

where N is the noise power. In order to determine the required detection sensitivity, in addition to Γ, P_p and R should also be supplied by either the regulator or the corresponding primary system.

It may be seen from the preceding development that there is a strong dependency between the detection sensitivity of a cognitive radio and the maximum power it is allowed to transmit in a certain licensed band. This notion may be generalized to cognitive radio networks. Intuitively, a network with more users and/or higher transmitted powers impacts primary systems located further away. Therefore, a spectrum management scheme should be in place to manage the total interference according to the network's detection sensitivity (e.g., by coordinating transmissions or setting limits on the transmitted power of users).

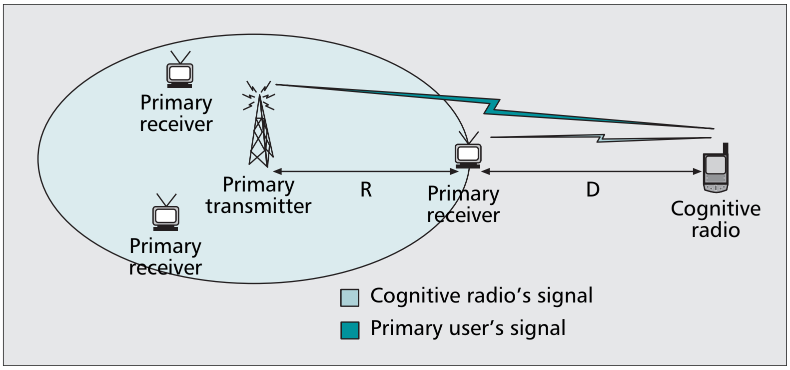


Figure 2. *Interference range of a cognitive radio.*

Spectrum Sensing Challenges

Spectrum sensing in cognitive radio networks is challenged by several sources of uncertainty ranging from channel randomness to device-level and network-level uncertainties. Since spectrum sensing should perform robustly even under worst case conditions, such uncertainties usually have implications in terms of the required detection sensitivity, as discussed below.

Channel Uncertainty

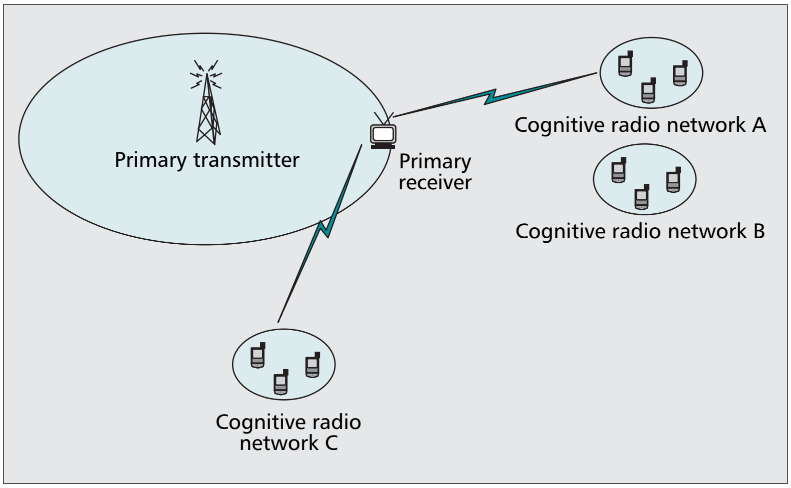
Under channel fading or shadowing, a low received signal strength does not necessarily imply that the primary system is located out of the secondary user's interference range, as the primary signal may be experiencing a deep fade or being heavily shadowed by obstacles. Therefore, spectrum sensing is challenged by such channel uncertainty since cognitive radios have to be more sensitive to distinguish a faded or shadowed primary signal from a white space. Indeed, it may be seen from Eq. 2 that any uncertainty in the received power of the primary signal translates into a higher detection sensitivity requirement.

Under severe fading, a single cognitive radio relying on local sensing may be unable to achieve this increased sensitivity since the required sensing time may exceed the sensing period, T_p. As we shall illustrate later, this issue may be tackled by having a group of cognitive radios share their local measurements and collectively decide on the occupancy state of a licensed band.

Noise Uncertainty

In order to calculate the required detection sensitivity in Eq. 2, the noise power has to be known. Such a priori knowledge, however, is not available in practice, and N has to be estimated by the receiver. Unfortunately, calibration errors as well as changes in thermal noise caused by temperature variations limit the accuracy with which noise power can be estimated. Since a cognitive radio may violate the sensitivity requirement due to an underestimate of N, $\gamma_{\min}$ should be calculated with the worst case noise assumption, thereby necessitating a more sensitive detector.

Spectrum sensing is further challenged by noise uncertainty when energy detection is used as the underlying sensing technique. More specifically, a very weak primary signal will be indistinguishable from noise if its SNR falls below a certain threshold determined by the level of noise uncertainty [8]. Feature detectors, on the other hand, are not susceptible to this limitation due to their ability to differentiate between signal and noise.



■ **Figure 3.** *The operation of network A forces network B to move to another band; however, the aggregate interference of networks A and C may still be harmful.*

Aggregate-Interference Uncertainty

With widespread deployment of secondary systems in the future, there will be increased possibility of multiple cognitive radio networks operating over the same licensed band. As a result, spectrum sensing will be complicated by uncertainty in aggregate interference (e.g., due to the unknown number of secondary systems and their locations). In particular, even though a primary system may be out of any secondary system's interference range, the aggregate interference may turn out to be harmful. This uncertainty calls for more sensitive detectors as a secondary system may harmfully interfere with primary systems located beyond its interference range, and hence should be able to detect them.

The requirement for higher detection sensitivity may be relaxed by using energy detection. In this case nearby cognitive radio networks (e.g., networks A and B in Fig. 3) detect each other and therefore refrain from occupying the same band simultaneously, thereby reducing the aggregate interference. However, as illustrated in Fig. 3, cognitive radio networks located further apart may still be oblivious to each other and simultaneously transmit.

Alternatively, system-level coordination among different cognitive radio networks enables them to overcome the above uncertainty at increased implementation cost. For instance, different secondary systems can negotiate access and manage aggregate interference through a standardized common control channel. This approach starts to move the spectrum sensing solution closer to the other alternatives listed in Table 1. We note, however, that the uncertainty levels arising from initial deployments may still be addressable by increasing the detection sensitivity without resorting to system-level coordination, thereby maintaining the cost advantage of the spectrum sensing solution.

Cooperative Spectrum Sensing

As discussed earlier, under fading or shadowing, a cognitive radio requires higher detection sensitivity in order to overcome the uncertainty introduced by channel randomness. The resultant sensitivity requirement may end up being too stringent as the cognitive radio has to maintain its sensing reliability even under worst case fading or shadowing.

On the other hand, multipath fading effects vary significantly depending on the receiver's location, and users placed more than a few wavelengths apart are expected to experience independent fading. Therefore, the uncertainty due to fading may be mitigated by allowing different users to share their sensing results and cooperatively decide on the licensed spectrum occupancy. The diversity gain achieved through such cooperative spectrum sensing improves the overall detection sensitivity without imposing higher sensitivity requirements on individual cognitive radios [10].

The improved sensitivity, however, comes at the cost of additional communication overhead. More specifically, local measurements should be collected at a *band manager* (e.g., an access point or simply another secondary user) to be processed into a decision regarding the occupancy state of the primary band. This decision in turn should be broadcast to all users of the secondary system. As such, a control channel is needed to enable the exchange of information between the cooperating cognitive radios and the band manager. In order to minimize the communication overhead and hence the bandwidth required for this control channel, users may only report their final 1-bit decisions (i.e., white space or occupied) rather than the actual measurements. The band manager then declares a white space only if none of the cooperating users has detected a primary signal.

The effect of cooperation on the required detection sensitivity of individual users is illustrated through the following example where we have implemented the low-overhead cooperation scheme described above along with simple energy detection as the local detection scheme. We assume an analog TV station with a transmitted power of 10 kW and a coverage radius of 100 km. We also assume a maximum secondary transmitted power of 20 mW and a sensing bandwidth of 1 MHz. The path loss exponent and thermal noise power spectral density are 4 and –174 dBm/Hz, respectively. Applying Eqs. 1 and 2, it may be shown that an overall detection sensitivity of –20 dB is required under these conditions. The resulting local sensitivity levels under independent Rayleigh fading and log-normal shadowing (dB spread = 3 dB) are plotted in Fig. 4.

Evidently, cooperative sensing enables users to employ less sensitive detectors. A less stringent sensitivity requirement is particularly appealing from the implementation point of view due to the reduced hardware cost and complexity. We note, however, that realizing such potential cost savings demands some flexibility in terms of access policies. In particular, opportunistic spectrum access for a network of cooperating secondary users should be regulated based on their capabilities as a group rather than individual users. In that sense a group of cognitive radios should be permitted to *cooperatively* access a licensed band otherwise restricted to any of them individually.

Compared to multipath fading, shadowing effects tend to be correlated over a much larger distance, thereby reducing the diversity gain achievable through short-range cooperation. This is depicted in Fig. 4. In fact, it has been shown that under spatially correlated shadowing, the cooperation gain is fundamentally limited by the distance spread of the cooperating users [11]. This limitation has practical implications in terms of protocol design as having fewer users cooperate over a large distance may be more effective than a dense sensing network confined to a small area.

Another challenge in the implementation of cooperative sensing is the issue of user reliability. For instance, a single malicious user may prevent a cognitive radio network from accessing a white space by sending false reports to the band manager. In order to deal with this issue, further research needs to be done on the design of efficient trust management systems in cognitive radio networks.

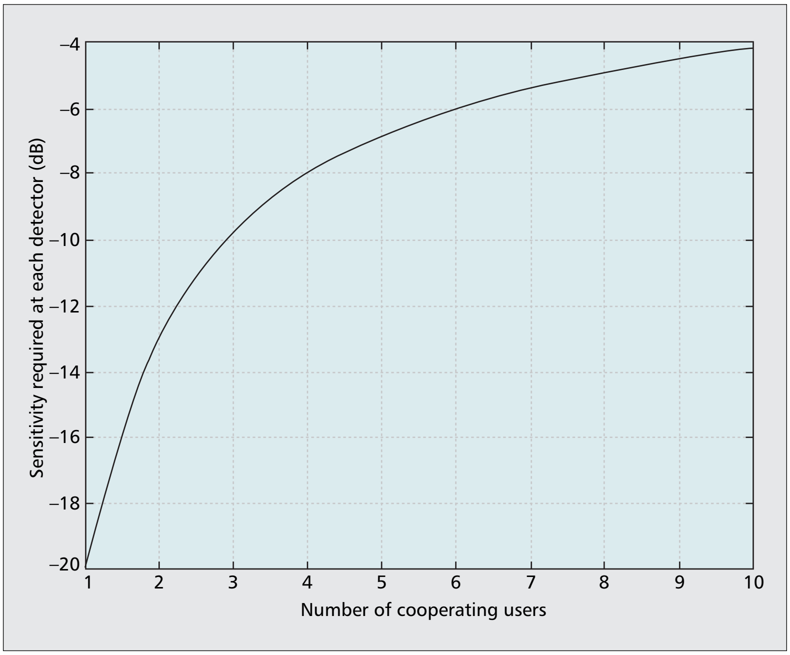


Figure 4. *Required sensitivity of individual cognitive radios to achieve an overall detection sensitivity of –20 dB under Rayleigh fading vs. the number of cooperating users.*

DESIGN TRADE-OFFS

In this section we outline the major trade-offs involved in the implementation of spectrum sensing functionality in the cognitive radio networks. The system designer should balance these trade-offs according to the application-specific requirements, hardware cost and complexity, and available infrastructure (e.g., to coordinate sensing and access) among other considerations.

COOPERATION-PROCESSING TRADE-OFF

As outlined previously, with increasing the number of cooperating users, a target detection sensitivity may be achieved by having less sensitive detectors at the individual users. Given a certain detector, a relaxed sensitivity requirement is translated into a shorter sensing time and hence less local processing. This phenomenon is depicted in Fig. 5, where the sensing time of local energy detectors, required to achieve an overall detection sensitivity of –20 dB (with 99 percent accuracy), is plotted as a function of the number of cooperating users under independent Rayleigh fading. Furthermore, communication among users is assumed to be error-free and the channel bandwidth is set at 1 MHz.

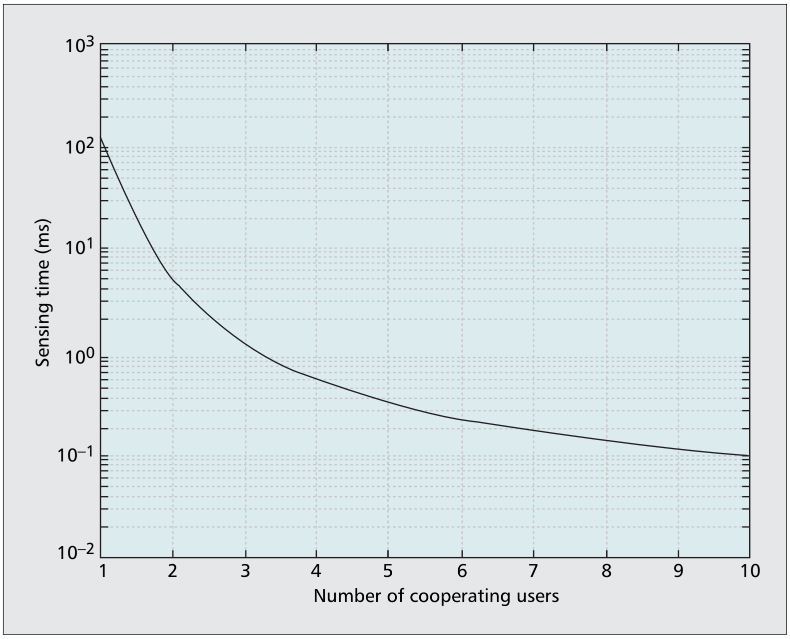


Figure 5. *Cooperation-processing trade-off under Rayleigh fading.*

The observation above, however, raises a natural question: how much (local) processing and cooperation is needed, respectively, in order to achieve a certain performance level? In particular, the cooperation overhead generally increases with the number of cooperating users due to the increased volume of data that needs to be reported to and be (centrally) processed by the band manager. Therefore, there exists a trade-off between the local processing overhead and the cooperation overhead as they both add to the total sensing time. This trade-off may be balanced by finding the optimum levels of processing and cooperation, minimizing the total sensing overhead [12].

Intuitively, the optimum number of cooperating users depends on the efficiency of the underlying cooperation protocol. For instance, a simple way to collect sensing data is for the band manager to poll the cognitive radios one by one. However, the communication overhead associated with this method increases linearly with the number of users. A more efficient technique has been proposed in [13] where all sensing data is collected simultaneously, thereby allowing a higher cooperation level at the cost of increased protocol complexity. Moreover, the cooperation level should be adapted to the fading characteristics. In particular, as the fading becomes less severe (e.g., if there is a line of sight to the primary user), the optimum trade-off between local processing and cooperation will be tilted more toward processing. Informally speaking, this is

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due to the fact that in such cases it is less likely for a secondary user to experience a deep fade. As such, the diversity gain achieved through cooperative sensing is diminished and may not be adequate to compensate for higher cooperation overheads.

Reactive vs. Proactive Sensing

Spectrum sensing schemes may be broadly categorized as reactive and proactive, depending on the way they *search* for white spaces. Reactive schemes operate on an on-demand basis where a cognitive user starts to sense the spectrum only when it has some data to transmit. Proactive schemes, on the other hand, aim at minimizing the delay incurred by cognitive user(s) in finding an idle band by maintaining a list of one or more licensed bands currently available for opportunistic access through periodic sensing of the spectrum. Of course, the enhanced responsiveness toward data transmission requests comes at the cost of increased sensing overhead.

Therefore, choosing the appropriate sensing mode involves a trade-off between the periodic sensing overhead and the on-demand sensing overhead. Intuitively, delay-sensitive applications favor proactive sensing as the delay associated with reactively finding an idle band may be significant (e.g., when searching over a crowded region of the spectrum with a relatively small number of white spaces available). On the other hand, energy efficiency concerns along with the delay tolerance of the application may warrant the selection of reactive sensing. As such, to maintain optimum performance, a cognitive radio has to adapt its sensing mode to the varying spectrum usage, available resources, and application characteristics.

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Rate-Reliability Trade-off

Opportunistic access to the licensed spectrum is *interruptible* in the sense that cognitive users have to cease transmission immediately and relocate to a new band as soon as the primary user appears. While the delay associated with such relocations may be reduced through proactive sensing, cognitive users will still face abrupt QoS degradation as communication peers need to coordinate the frequency transition, and many parameters across the protocol stack have to be reset to match the characteristics of the new frequency band. Therefore, cognitive radio links built on top of a licensed band are inherently unreliable unless the corresponding primary users access their band very sporadically.

Communication reliability may be enhanced by distributing data transmission over a number of independent licensed bands as opposed to a single one. In this case a primary user reclaiming one of these licensed bands only affects a fraction of the cognitive link's bandwidth, thereby reducing the detrimental impact on the cognitive user's QoS. Consequently, frequency chunks from several unreliable primary bands may be grouped together to form a more reliable cognitive radio link. In practice, this may be realized by employing orthogonal frequency-division multiplexing (OFDM) as the underlying modulation scheme thanks to its inherent flexibility in using noncontiguous frequency bands.

The drawback of transmitting over multiple licensed bands rather than a single one, however, is that the regulatory constraints on spectrum sensing now have to be fulfilled for each and every individual frequency band. In particular, additional temporal/spectral resources, otherwise available for data transmission, have to be allocated to periodic sensing of these extra frequency bands, resulting in reduction of the effective data rate of the cognitive user. Therefore, assuming a fixed operating bandwidth for the cognitive radio system, choosing the appropriate number of independent licensed bands for data transmission involves a trade-off between the effective data rate and the reliability/stability of the cognitive user's link.

Obviously, information from the upper layers regarding the application-specific QoS requirements should be taken into account in order to optimally balance the above trade-off. For instance, with a live video streaming application it is more essential to stabilize the link, while for a file transfer session the user may be willing to sacrifice link stability for a higher data rate. As such, the spectrum sensing component should work in conjunction with the upper-layer protocols to optimize the end user's perceived QoS.

Conclusion

With the increasing demand for radio spectrum on one hand and inefficient usage of the licensed bands on the other, a reform of the spectrum access policy seems inevitable. Opportunistic spectrum access is envisioned to resolve the spectrum scarcity by allowing unlicensed users to dynamically utilize white spaces across the licensed spectrum on a noninterfering basis. Cognitive radio networks offer a low-cost backward-compatible implementation of this novel paradigm thanks to their ability to autonomously identify white spaces and react to variations in spectrum usage and operation environment.

In this article we investigate the main issues associated with the design of spectrum sensing functionality for cognitive-radio-based dynamic spectrum access. Performance limitations raised by the uncertainties at various levels of operation are discussed, and it is argued that these challenges may be overcome by a proper combination of local signal processing, user-level cooperation among cognitive radios, and system-level coordination among different cognitive radio networks.

Research on spectrum sensing thus far has mainly focused on meeting the regulatory requirements for reliable sensing. An important venue for further research is the interplay of spectrum sensing and higher-layer functionalities to enhance the end user's perceived QoS. In this respect we outline some of the major cross-layer trade-offs involved in spectrum sensing; however, the list is by no means exhaustive.

Finally, spectrum sensing is a multifaceted problem demanding coordinated efforts of the regulatory and technical sides. One particular example is the case of cooperative sensing, which requires a flexible policy, regulating the dynamic access to spectrum based on the behavior and capabilities of a cognitive radio network as a whole rather than individual users.

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BIOGRAPHIES

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