Sensing for communication: the case of cognitive radio

(Invited Paper)

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***Abstract*— Sensor networks and communication usually intersect with the communication being used by the network to communicate sensed information for some application's purposes. Cognitive radio provides an interesting twist: the sensed information is used to benefit the communication network, by collectively identifying and allocating the communication degrees of freedom that can be used by the network itself. In this paper, we explore how space, time, and knowledge interact to make this a fundamentally challenging task.**

I. BACKGROUND

Rather than reviewing the entire background in depth, we merely cite references to some of our earlier work on this topic. The reader is directed there for additional references as well as detailed explanations of the results.

Under the current system of spectrum allocation, rigid partitioning has resulted in vastly underutilized spectrum bands, even in urban locales [1], [2]. In order to increase utilization of this spectrum, new approaches to spectrum sharing are needed that bridge the vast gulf in time and space scales between regulation and potential use [**?**]. However, any such approach must also maintain robust performance guarantees for existing legacy systems. Cognitive radios have been proposed as a way to exploit this underutilized spectrum in an opportunistic manner by sensing spectrum opportunities and then communicating over them [3]. Architectural questions are key here. This paper addresses the core question of whether this requires a *sensor* or a *sensor network* perspective?

In order to guarantee non-interference with the legacy user, cognitive radios must detect very weak legacy signals because of random fading [4]–[6]. Because fading — especially shadowing – models are also inaccurate, robustness also requires the sensing system's performance to be made insensitive to the model uncertainty — particularly uncertainty to the tail of the fading distribution [7]. This *requires* cooperation and taking a sensor network perspective. The sensor network perspective also helps reduce the required sensitivity from individual sensors, although once again the limits of trust (or confidence in the model) again introduces a limit on both how insensitive we can be to the tail model of the fading distribution as well as how much the sensitivity can be reduced [7].

Fading and path-loss are not the only inaccurate parts of any model. Uncertainties in the noise+interference level induce limits on how weak signals individual sensors can detect [8], [9]. While some of these noise uncertainties are from within the devices themselves or from unintentional emitters nearby [10], a major component is potential interference from other opportunistic spectrum users. Because these uncertainties are not stochastic in nature, mere aggregation of sensor data cannot overcome them. Instead, coordination among nearby cognitive radios is required to control this uncertainty. While this coordination can take a form similar to a traditional MAC protocol for data communication, its role is different in that it aims to *reduce the uncertainty about interference* rather than just reducing the interference itself [?].

The degree of coordination required varies with the complexity of the sensors and the extent of their knowledge of the legacy signals. The simplest sensing strategies end up needing the most coordination, while more complex strategies involving adaptive coherent processing and interference prediction can be individually more robust and thereby reduce the need for coordination [?]. If individual cognitive radios have a fixed transmit power, the tradeoffs can be expressed in terms of the existence of a *minimum coordination radius* [11]. In essence, this minimum radius can be used to rule out very local schemes [11].

Thus, even if cognitive radio system itself only wants to support very short range communication (WLAN, PAN, etc.), the sensor network supporting it must extend beyond if it is to operate fairly and with high efficiency [11]. So far, our model has implicitly considered a local sensor network that has a total extent that is large enough to enable independent realizations of the shadowing/fading, but is essentially small when compared to the legacy system's radio footprint. It is natural to consider sensor networks that exist on a spatial scale that is comparable to the legacy systems themselves. In such cases, the coupling between communication and sensing can be significantly weakened and there is a strong case that spectrum sensing should be considered as infrastructure in support of communication rather than a required function of communicating nodes themselves. In such a large network, we assume that some sensor nodes are close enough to the legacy transmitter so as to determine their service area and the corresponding no-talk zones. The only question is how dense the infrastructure must be in order to properly accept/reject requests from cognitive radios wishing to use the frequency in question.

II. INFRASTRUCTURE DENSITY REQUIREMENTS FOR REQUESTS

The infrastructure must be dense able to accept radio requests to join the network. Being able to accept requests involves being able to hear the cognitive radio that wants to contact the infrastructure. Some diversity is required to account for possible fading between the sensing infrastructure and the cognitive radios wanting to use the band.

- Key parameters:
  - P_2 - Power of single secondary user
  - α_{22} - Path loss exponent for secondary-to-secondary transmissions
  - δ - Required Sensitivity (eg. 5dB SNR)
  - Δ - Fading margin (eg. 10dB SNR)
  - f - Overlap Factor (eg. 20%)
- Compute R_{ar} as maximum r that satisfies:

$$10\ \log_{10}(\frac{P_2 r^{-\alpha_{22}} 10^{-\Delta/10}}{\sigma^2}) \geq \delta$$

- Compute Infrastructure Density (ID_{ar}) for Admission Requests as:

$$ID_{ar} = \frac{1+f}{\pi R_{ar}^2}$$

III. INFRASTRUCTURE DENSITY REQUIREMENTS FOR ADMISSION CONTROL

The infrastructure must also be dense enough to as to disambiguate the positions of cognitive radios. After all, it must determine whether or not they are within the no-talk radius or outside of it. We assume that the cognitive radios do not have any other positioning technology and that furthermore, the environment is richly scattering enough or the architecture is simple so that no triangulation is possible. Positioning accuracy is therefore limited by the density of secondary nodes.

- Key parameters:
  - N - Node Density of secondary users (e.g. $1/m^2$)
  - D - Power Density of secondary users ($D = N \times P_2$)
  - α_{21} - Path loss exponent for secondary-to-primary transmissions
  - r_n - No Talk Radius
  - r_p - Protected Radius
  - μ - Protection Margin (e.g. 5dB)
- For a given value of $r_n - r_p$, there exists a certain critical density (D_{crit}) above which protection margin cannot be ensured.
- Calculate D_{crit} as maximum D such that:

$$D\,K(\alpha_{21})\,(r_n - r_p)^{-\alpha_{21}+2} \leq (10^{\frac{\mu}{10}} - 1)\,\sigma^2$$

- For $D < D_{crit}$, we have some slack which can be used to overcome location uncertainty.
- Hence for a given D, if $r_n' - r_p'$ were is required values, then slack = $r_n - r_p - (r_n' - r_p')$.
- Since an infrastructure node can only distinguish between nodes inside and outside its footprint, we have

$$R_{ac} = r_n - r_p - (r_n' - r_p')$$

The required infrastructure density to guarantee admission control is:

$$ID_{ac} = \frac{1}{\pi\,R_{ac}^2}$$

IV. NUMERIC EXAMPLES

In this section, we have two simple examples that illustrate the qualitative effect.

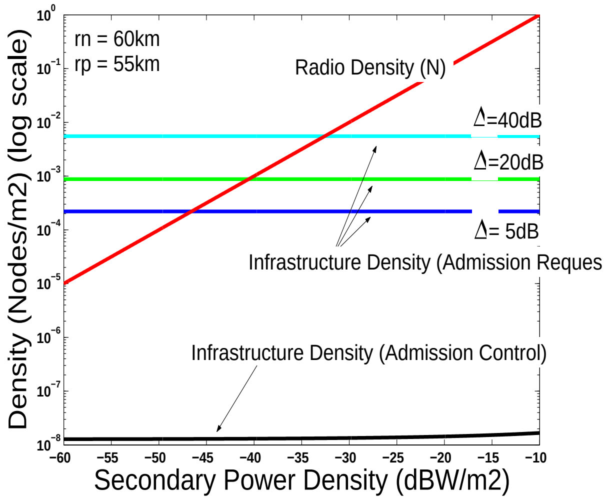

Fig. 1. For a large legacy system (large r_n and r_p) infrastructure density requirements are dictated by admission request constraints. Infrastructure density requirements from admission control are very relaxed and it makes sense to have a sensing infrastructure.

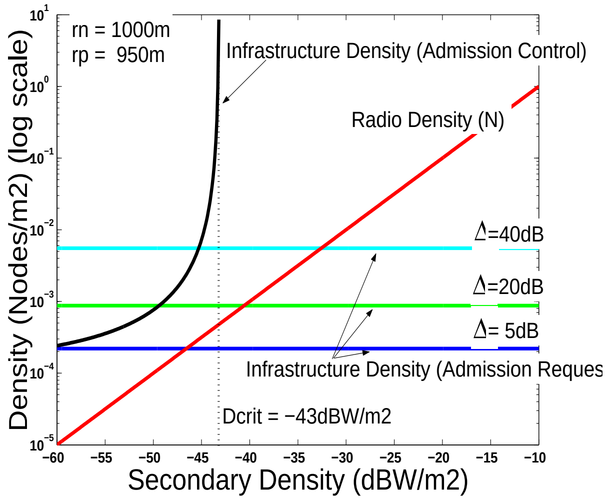

Fig. 2. For a small primary system (small r_n and r_p) infrastructure density requirements are dictated by admission control. The two spatial scales are very close. In this case it makes sense to have radios perform their own sensing within their own ad-hoc network or to have radios equipped with location awareness devices.

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