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 consider the feasibility of designing such a sensor network. We show that such a senor network for sensing the primary is only feasible if the primary is large in scale with respect to the secondary system. When this is not the case (the scales of the two are comparable), each radio should be equipped with a sensor and location device.**

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 [3]. 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 [4]. 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[5], [6], [7]. 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 [8]. 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) 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 [8].

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 [9], [10]. While some of these noise uncertainties are from within the devices themselves or from unintentional emitters nearby [11], 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 [3].

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 [3]. If individual cognitive radios have a fixed transmit power, the tradeoffs can be expressed in terms of the existence of a *minimum coordination radius* [12]. In essence, this minimum radius can be used to rule out very local schemes [12].

Thus, even if a 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 [12]. 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.

II. INFRASTRUCTURE DENSITY REQUIREMENTS

In a large secondary 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.

A. Infrastructure Density Requirements for Requests

The infrastructure must be dense enough 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.

The density requirements on the infrastructure to accept admission requests can be calculated by first calculating the radius of a typical cell (R_{ar}). R_{ar} is the maximum value of r that satisfies the following link budget equation:

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

where P_2 is the power of single secondary user, α_{22} is the path loss exponent for secondary-to-secondary transmissions, δ is the sensitivity requirements at the infrastructure node (eg. 5dB SNR), Δ is the fading margin (eg. 10dB) and f is the overlap factor (eg. 20%). The overlap factor is typically used in cell planning to ensure coverage.

The corresponding infrastructure density (ID_{ar}) for admission requests can be calculated as:

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

This density does not depend on the density of the secondary nodes; it only depends on the power of the secondary user at the edge of the cell.

B. 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 infrastructure nodes.

In [**?**], we have seen that the difference between the protected radius (r_p) and the no talk radius (r_n), imposes a limit on the secondary power density (measures in units of $Watts/m2$) that can be supported. We call this maximum density D_{crit}. D_{crit} is the maximum D such that:

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

where α_{21} is the primary-to-secondary decay exponent, $K(\alpha_{21})$ is a constant that is dependent on the path loss exponent (see [7] for details) and μ is the protection margin ([7]).

If we are trying to support a lower density of secondary users ($D < D_{crit}$), then we have some slack that can be used to overcome location uncertainty. Hence for a given D, if r'_n was the required no talk radius, then the slack is $r_n - r'_n$. If we make the assumption that an infrastructure node can only distinguish between cognitive radios inside and outside its footprint, we can calculate the admission control radius of an infrastructure cell as,

$$R_{ac} = r_n - r'_n$$

Hence the required infrastructure density to guarantee admission control is:

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

C. Numeric Examples

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

In the first case we consider a large primary system. Such a system has large protection and no talk radius (for example $r_p = 55km$ and $r_n = 60km$). For such a system, there is a lot of slack in the system for secondary densities of interest and hence a very sparse admission control infrastructure is required (See Figure 1). The infrastructure requirements are solely dictated by admission request considerations.

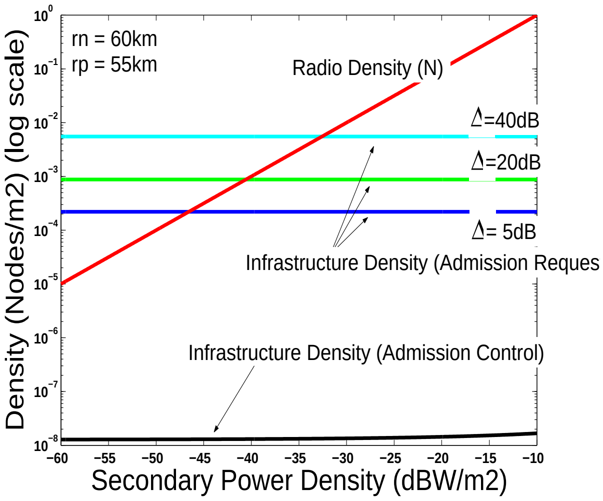

Fig. 1. For a large legacy system (large r_n and r_p) infrastructure density requirements are dictated by admission request constraints. Infrastructure density requirements from admission control are very relaxed and it makes sense to have a sensing infrastructure.

In the second case we consider a small scale secondary system. Such a system has small protection and no talk radius (for example $r_p = 950km$ and $r_n = 1km$). For such a system, the maximum density that can be supported is very small ($D_{crit} = -43dBW/m2$) and hence the admission control infrastructure must be able to locate secondary nodes exactly. (See Figure 2). In this case it makes sense to have each cognitive radio equipped with its own location awareness device.

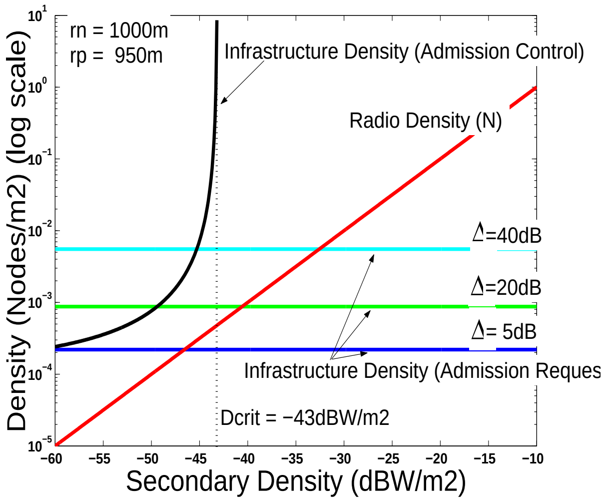

Fig. 2. For a small primary system (small r_n and r_p) infrastructure density requirements are dictated by admission control. The two spatial scales are very close. In this case it makes sense to have radios perform their own sensing within their own ad-hoc network or to have radios equipped with location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

III. CONCLUSIONS

Whether to establish a sensor network to sense the primary user or to instruct each cognitive radio to perform its own sensing and equip it with a location device, is an important question for the service provider. In this paper we show that the answer of this question is based on the scale of the primary as compared to the scale of the secondary. For a large scale primary system, a sensing infrastructure is feasible and can lead to reduced costs. On the other hand, for a small scale primary it is prudent to equip each radio with a sensor and a location device.

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