Coexistence with primary users of different scales

Shridhar Mubaraq Mishra
Department of Electrical Engineering
and Computer Science
University of California
Berkeley, California 94704
Email: smm@eecs.berkeley.edu

Rahul Tandra
Department of Electrical Engineering
and Computer Science
University of California
Berkeley, California 94704
Email: tandra@eecs.berkeley.edu

Anant Sahai
Department of Electrical Engineering
and Computer Science
University of California
Berkeley, California 94704
Email: sahai@eecs.berkeley.edu

***Abstract*— Opportunistic radio systems aim to exploit 'spectrum holes' by finding bands and transmission characteristics that will not cause harmful interference to the primary users of that band. This paper explores whether it is harder/easier to peacefully coexist with primary systems that operate at different scales in terms of their coverage area and transmission power. When sensing a large scale primary, a small scale secondary user can make its own decision about transmission based on the sensing results from its neighborhood. This assumption fails when the scale of the primary is comparable to the scale of the secondary user. In this scenario, we need to decouple sensing from admission control – a sensor network is required to perform the sensing. For small primaries, the environment over which the sensing results are valid is small which imposes certain minimum density requirements for sensor nodes.**

Collective sensing is used to localize the primary while a separate admission control algorithm decides on which secondaries can safely transmit. Location information of the primary and secondary users is key for such an admission control algorithm to operate successfully. In the case of a large primary, location uncertainty did not impact results significantly since decisions are made about a primary that is very far as compared to the inter-sensor distances. This is no longer valid for a small primary and hence more exact location information is paramount. With location uncertainty of primary and secondary users, the effective primary user footprint can increase significantly.

We focus our discussion around a toy model of the Part 74 'wireless microphone users' that are a concern to the IEEE 802.22 Working Group.

I. INTRODUCTION

Measurements indicating low spectrum utilization bring to the forefront the inefficiency of the current regulatory regime [1], [2], [3]. Regulation specifies spectrum usage on the spatial scale of countries and continents and on temporal scales of years to decades. This leads to poor utilization of spectrum, since the large allocation scale is too conservative and does not coincide well with realities on the ground – wireless systems can operate on much smaller spatial and temporal scales than regulation can efficiently specify. Like sand and pebbles poured into the gaps between larger rocks, small scale devices can reuse these spatial and temporal gaps and hence greatly improve our overall spectrum utilization. Cognitive radios have been proposed to reuse unutilized spectrum in a opportunistic manner by sensing the primary user and using the spectrum only if the frequency band is deemed empty [1].

This view is seeing a concrete embodiment in the reuse of TV spectrum for wireless services by the IEEE 802.22 Working Group [4]. The main aim is to reuse TV spectrum while ensuring that passive TV receivers at the edge of the coverage area are not interfered with. The important thing to note is the scale of the primary system relative to the secondary system. TV transmitters are mounted on large towers, are high power devices (100kW) and have huge coverage radii (50-60km). IEEE 802.22 transmitters on the other hand are supposed to be roof mounted and are medium power devices (1W transmit power). While TV transmitters are the main primary users in this frequency range, wireless microphones (part 74 devices) also need to be protected [4]. These devices are low power devices (50mW-250mW) that have small coverage areas (100m). So what does it take for IEEE 802.22 devices to protect wireless microphones? Or in a general case, what does it take for secondary devices to coexist with similar sized primary users? Metaphorically, can pebbles coexist with other pebbles?

Three aspects of the problem change when we move from a large scale primary to a small scale primary:

- Radios cannot make individual decisions about their transmission when a primary is not found. An admission control network is needed to decide on which users can transmit.
- Sensing results are valid in a small area around the primary (due to the footprint of the primary). This requires a minimum sensing density to achieve the required diversity during sensing. These density requirements could be relaxed by either limiting the number of simultaneous users per cell or by improving the sensitivity of each radio by employing coherent detection.
- With large primary systems, decisions were made about a primary that was very far away from the secondaries. Hence location uncertainty of the primary/secondary did not impact results in [5]. This is not the case for small scale primaries – location uncertainty can lead to very conservative estimates about the area where transmissions

can occur.

Demonstrating the above aspects of the problem forms the core of this paper. We start in Section II by providing a summary of the background material needed to analyze this problem. In Section III, we seek to answer the question of whether primary and secondary users of the same scale can coexist. In this section we establish the need to decouple sensing from admission control. Admission control is analyzed in detail in Section IV. In this section we also establish gains from having location awareness devices on each secondary transmitter.

II. BACKGROUND AND RELATED RESEARCH

The unique features of cognitive radios (as opposed to traditional radios) is the need to sense the primary users and make changes to transmission parameters in order to protect them. Sensing is needed to answer the question, '*Is the primary present nearby?*'. If the primary is not present, the cognitive radio must decide whether it can transmit. If the primary is present, the cognitive radio must decide on what changes it needs to make to its transmission parameters in order to protect the primary user.

In order to reliably sense the primary user, cognitive radios must detect very weak legacy signals because of random fading [6], [5]. Because fading (especially shadowing) models are also unreliable, robustness also requires the net sensing performance to be made insensitive to the model uncertainty – particularly uncertainty in the tail of the fading distribution[1] [7]. This requires cooperation and taking a network perspective [7], [8]. The network perspective also helps reduce the required sensitivity from individual sensors, though limits of trust (or confidence in the model) again introduce a limit on both how insensitive we can be to the tail model of the fading distribution [7]. Fading and path-loss are not the only inaccurate parts of a wireless channel model. Uncertainties in the noise+interference level and the coherence time induce limits on how weak signals individual sensors can detect [6], [9][2]. While some of these noise uncertainties are from within the devices themselves or from unintentional emitters nearby, 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 [10]. 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 [6]. 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. Both these aspects of sensing (gains from cooperation and the SNR wall) have been verified experimentally in [11].

When a secondary user transmits, it also needs to know the impact of its transmission on the primary receivers. This task is rendered difficult since the transmitter does not know its channel to the primary receivers; hence in general it needs to budget for the worst case e.g. its transmission has a line of sight to the primary receiver. This worst case budgeting can be avoided by placing a sensor near the primary receiver [12]. The sensor can feedback the channel information to the secondary transmitter which can then estimate the shadowing to the primary receiver.

In the sensor network scenario, [13] has also considered the required density of a sensor network performing distributed sensing. However the key constraint is the power density of the sensor network to relay the information back to the fusion center. In this context, the appropriate question is 'Is it better to have few high power sensors or many smaller sensors?'.

Uncertainties fall into two categories: either they can be modeled and we can take expectations over these models in a meaningful way or they are unknown but bounded. In the latter, we must budget for the worst case to achieve robust performance. Multipath models are well known and have been studied extensively [14]. Shadowing models are less reliable and we would prefer not to trust their tail distributions [7]. In this paper, radio placement is not considered a stochastic process and hence we need to budget for worst case placements.

III. CAN SECONDARY USERS PROTECT SIMILAR SCALE PRIMARY USERS?

The key question to answer is, '*What should a secondary device do when it does not hear the primary user?*'. If the secondary device chooses to transmit, it must ensure that its transmission will not interfere with the primary receiver. This situation is depicted in Figure 1(a) along with relevant notation – the secondary sensor must detect the primary transmitter while the secondary transmitter must ensure that the primary receiver is not interfered with. Figure 1(b) shows the scenario that we focus on first: the secondary sensor and transmitter are co-located (we will revisit this assumption at the end of this section) while the primary receiver is as close to the secondary as possible. Table I lists the relevant parameters, their description and their typical values for wireless microphones and IEEE 802.22 Customer Premise Equipment (CPE).

The sensitivity of a wireless sensor is limited by noise uncertainty [6]. Noise uncertainty imposes a SNR wall -

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[1] If the target probability of detection is high, we need to account for the tail probability governing deep fades. These tail probabilities are not well modeled and hence we need to be robust to these tails. We achieve robustness by employing diversity through multiple cooperating sensors.

[2] This limit on the minimum power level of the signal (called the SNR wall) cannot be overcome even with very large sensing times. Hence, from a system design perspective we need to ensure that the received power at some sensor within the sensing area is above this fundamental limit.

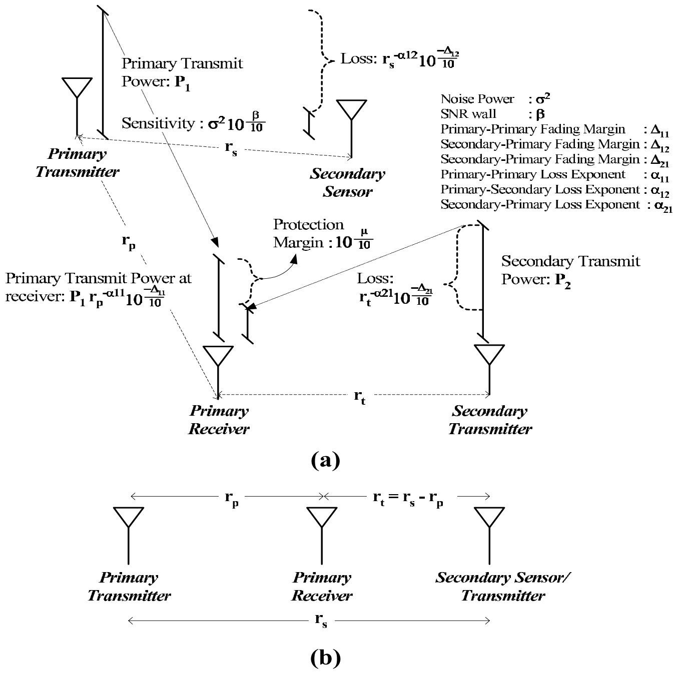

Fig. 1. (a) Sensing and interference scenario where we must ensure that the received energy at the sensor is above the sensing sensitivity. Further, we must ensure that interference to the primary receiver must be below the SINR requirements of the receiver. (b) Typical sensing scenario where the secondary sensor and transmitter are co-located and the primary receiver is at its worst case location with respect to interference.

a minimum SNR level below which the signal cannot be detected irrespective of the sensing time. We would like to determine if the received signal at the sensor will be above the SNR wall (β dB – see Table I). (1) states this in equation form requiring the received SNR ($\frac{P_1 r_s^{-\alpha_{12}} 10^{\frac{-\Delta_{12}}{10}}}{\sigma^2}$) of the primary transmitter at the secondary sensor be above the SNR wall.

$$\frac{P_1 r_s^{-\alpha_{12}} 10^{\frac{-\Delta_{12}}{10}}}{\sigma^2} \geq 10^{\frac{\beta}{10}} \tag{1}$$

We also require the Signal-to-Interference-And-Noise Ratio (SINR) at the primary receiver to be above the receiver's Desired/Undesired ratio requirements (specified as a protection margin of μ dB – see Table I). The secondary signal at the primary receiver is $P_2 * (r_s - r_p)^{-\alpha_{21}} 10^{\frac{-\Delta_{21}}{10}}$ which acts as interference (recall that $r_t = r_s - r_p$ for the case that the secondary sensor and transmitter are co-located). The primary signal at its own receiver is $P_1 r_p^{-\alpha_{11}} 10^{\frac{-\Delta_{11}}{10}}$. These SINR requirements are stated in (2). These conditions for non interference are further explored in [5].

$$\frac{\sigma^2 + P_2 * (r_s - r_p)^{-\alpha_{21}} 10^{\frac{-\Delta_{21}}{10}}}{P_1 r_p^{-\alpha_{11}} 10^{\frac{-\Delta_{11}}{10}}} \leq \frac{1}{10^{\frac{\mu}{10}}} \tag{2}$$

We analyze this non-interference question starting with a very simple case where the primary receiver is co-located with the transmitter and complete reciprocity holds between the primary transmitter-secondary sensor channel and the secondary transmitter-primary receiver channels. We develop this story using the wireless microphone as the primary transmitter and the IEEE 802.22 CPE as the secondary sensor and transmitter. We gradually move to more realistic scenarios quantifying the effect of each change. These scenarios are depicted in Figure 2 which examines if the received power at the primary receiver can be above the desired sensitivity in each case.

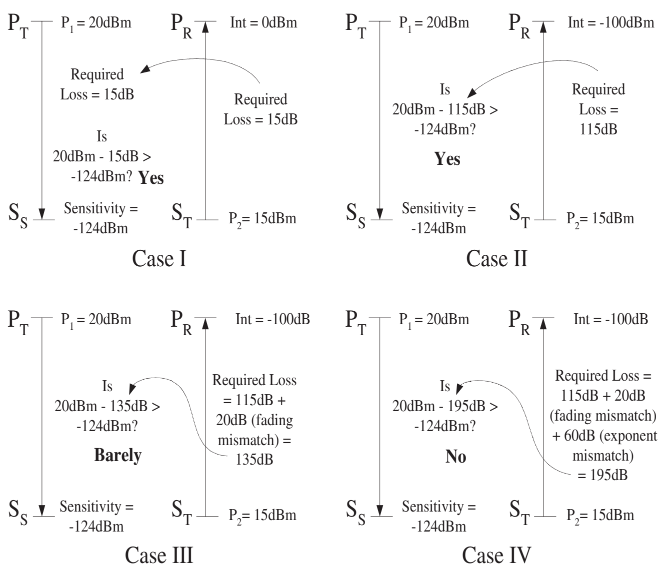

Fig. 2. (Case I) Complete reciprocity ($\alpha_{21} = \alpha_{12} = \alpha_{11}$ and $\Delta_{12} = \Delta_{21}$); primary transmitter is co-located with the primary receiver ($r_p = 0$ and $\Delta_{11} = 0$). (Case II) Primary receiver is r_p distance away from the primary transmitter. (Case III) $\Delta_{12} - \Delta_{21}$ = 20dB. (Case IV) $\alpha_{12} - \alpha_{21}$ = 3.

Case I: Complete reciprocity, primary receiver co-located with primary transmitter

At the edge of the sensing region, (1) becomes an equality and we can express the sensing radius (r_s) as:

$$r_s^{-\alpha_{12}} = \frac{\sigma^2}{P_1} 10^{\frac{\beta+\Delta_{12}}{10}} \tag{3}$$

To obtain a bound on the secondary power (P_2) from a secondary transmitter at the edge of sensing region, we assume that the interference term in (2) dominates the noise power and that the sensing radius is very large as compared to the protected radius ($r_s \gg r_p$). Furthermore, since the primary transmitter and primary receiver are co-located, $\Delta_{11} = 0$. Our reciprocity assumptions also imply that $\alpha_{12} = \alpha_{21}$ and that $\Delta_{12} = \Delta_{21}$. Under these assumption and substituting (3), in (2) we get:

$$P_2 \leq \frac{P_1^2}{\sigma^2} 10^{\frac{-\beta-\mu}{10}} \tag{4}$$

Parameter	Description	Typical values
P_1	Power of primary transmitter	100mW in 200kHz
P_2	Power of secondary transmitter	1W (30dBm) in a 6MHz band 15dBm in 200kHz
σ^2	Noise power	-121dBm (200KHz)
r_p	Protected Radius	100m
β	SNR wall (for radiometer sensor)	-3dB
Δ_{12}	Fading from primary transmitter to secondary sensor	0 - 50dB
Δ_{21}	Fading from secondary transmitter to primary receiver	0 - 50dB
Δ_{11}	Fading from primary transmitter to primary receiver	0 - 50dB
α_{12}	Path loss exponent from primary transmitter to secondary sensor	2 - 5
α_{21}	Path loss exponent from secondary transmitter to primary receiver	2 - 5
α_{11}	Path loss exponent from primary transmitter to primary receiver	2 - 5
μ	Protection margin (Desired to Undesired ratio/SINR)	20dB
D	Transmission Density of the Secondary users (Watts/km^2)	
N_w	Number of secondary radios around a primary receiver (worst case)	16
R	Length of a secondary cell (assuming a square cell)	10-33km
H	Number of secondary cells between the primary transmitter and the sea of users	5-15

TABLE I

RELEVANT PARAMETERS, THEIR DESCRIPTION AND TYPICAL VALUES FOR WIRELESS MICROPHONES AS PRIMARIES AND IEEE 802.22 CPES AS SECONDARIES.

In the log domain, this translates into,

$$P_2(dB) \quad \leq \quad 2\,P_1(dB) - \sigma^2(dB) - \beta - \mu \tag{5}$$

Figure 2 illustrates this case for the wireless microphone. Since the D/U ratio for the microphone is around 20dB, the maximum interference at the primary receiver can be as high as 0dBm. Since the secondary signal only needs to decay by 15dB, complete reciprocity implies that the primary signal power at the secondary sensor will also be very high (20dBm - 15dB = 5dBm). This is must larger than the target sensitivity (-124dBm) and hence the IEEE 802.22 CPE can sense the microphone and does not risk interfering with the receiver.

Case II: Complete reciprocity, primary receiver is 100m away from the primary transmitter

For this case we assume that primary transmitter and receiver pair is separated by a distance of r_p meters. In this case, (2) at the edge of the sensing radius (assuming $\frac{r_s}{r_p} \gg 1$) takes the following form,

$$P_2 \quad \leq \quad r_p^{-\alpha_{12}} \frac{P_1^2}{\sigma^2} 10^{\frac{-\beta-\mu}{10}} \tag{6}$$

Again in the log domain, this translates into,

$$P_2(dB) \leq 2\,P_1(dB) - \sigma^2(dB) - 10\alpha_{12}\,\log_{10}(r_p) - \beta - \mu \tag{7}$$

This the same as (5) except for the term $10\alpha_{12}\,\log_{10}\,r_p$ which could be as large as 100dB for the wireless microphone (α_{12} = 5, r_p = 100m). With this additional term, the interference at the primary receiver has to be limited to -100dBm (20dBm (primary power) - 100dB (distance loss) - 20dB (D/U ratio) = -100dBm). This requires the loss from the secondary transmitter to be larger (115dB as see in Figure 2). With complete reciprocity this implies that the primary power at the secondary sensor is still large enough (20dBm - 115dB) and hence above the sensing sensitivity.

Case III: Primary receiver is 100m away from the primary transmitter, fading is not reciprocal

Since the primary transmitter-receiver pair are more than a wavelength wavelength apart, the multipath at both these places is essentially independent. Shadowing on the other hand could be highly correlated since the primary transmitter-receiver pair are very close as compared to the secondary. In this case, (2) at the edge of the sensing radius takes the following form,

$$P_2 \quad \leq \quad 10^{\frac{\Delta_{21}-\Delta_{11}-\Delta_{12}}{10}}\, r_p^{-\alpha_{12}} \frac{P_1^2}{\sigma^2} 10^{\frac{-\beta-\mu}{10}} \tag{8}$$

In the log domain, the above equation is the same as (7) except for the difference between fading margins ($\Delta_{21} - \Delta_{11} - \Delta_{12}$). We are interested in the case (worst case) where the fading between the secondary transmitter and the primary receiver is less than the fading between the primary transmitter and the secondary sensor ($\Delta_{12} > \Delta_{21}$)[3]. In [7], is has been shown that the multipath variability can be as high at 20dB for reasonable detection probability. Hence we budget 20dB for this mismatch.

Case IV: Primary receiver is 100m away from the primary transmitter, fading is not reciprocal, path loss exponents are unequal

Inequality between exponents can arise from the physical configuration of the transmitters. In the case of wireless

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[3] In this case we are assuming that Δ_{11} = 0.

microphones, the wireless microphone transmitter may be on the ground while the wireless microphone receiver may be mounted on a truck. The IEEE 802.22 transmitter may be mounted in the roof top. Here the propagation between the microphone and the secondary sensor is worse than the propagation between the secondary transmitter and the primary receiver. For this scenario, (2) at the edge of the sensing radius (assuming $\frac{r_s}{r_p} \gg 1$) takes the following form,

$$P_2 \le \frac{r_p^{(\alpha_{12}-\alpha_{11})}}{r_s^{(-\alpha_{21}+\alpha_{12})}} 10^{\frac{\Delta_{21}-\Delta_{11}-\Delta_{12}}{10}} r_p^{-\alpha_{12}} \frac{P_1^2}{\sigma^2} 10^{\frac{-\beta-\mu}{10}} \quad (9)$$

Again, this is the same as (8) except for the factor $\frac{r_p^{(\alpha_{12}-\alpha_{11})}}{r_s^{(-\alpha_{21}+\alpha_{12})}}$. We assume that $\alpha_{12} = \alpha_{11}$ and would like to budget for the case that $\alpha_{12} > \alpha_{21}$. Hence, the secondary power has to be further scaled down by $10(\alpha_{12} - \alpha_{21}) \log_{10}(r_s)$. Since r_s is at least as large as r_p, this mismatch could be 60dB if $\alpha_{12} - \alpha_{21}$ is 3.

Figure 3 shows the maximum secondary power as a function of secondary sensor sensitivity for the four cases discussed above. It is interesting to note that considering all mismatches and a SNR wall of -3dB, the secondary power should be limited to -36dBm; thats 56dB below the primary power in the band of interest. This gap between the primary and secondary power is similar to the gap between a TV transmitter and a IEEE 802.11 CPE (100kW versus 1W ~ 50dB).

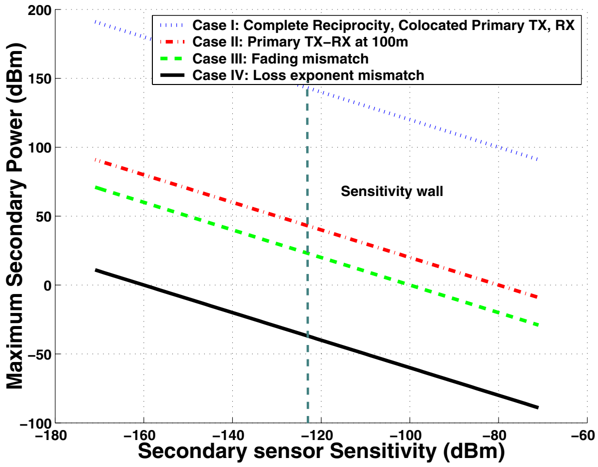

Fig. 3. Maximum secondary power as a function of secondary sensor sensitivity. Considering all mismatches and a sensitivity of -124dBm, the secondary power should be limited to -36dBm; thats 56dB below the primary power in the band of interest.

Before we continue with our discussion, let us examine two aspects of the above analysis. The first is the choice of exponents and the second questions the impact of diversity on the above analysis.

a) The case for Path Loss Exponents:: Can the loss exponent between the primary transmitter and the secondary sensor be as high as 5? The fixed fading margin that we have assumed takes into account multipath and the shadowing in the immediate vicinity of the receiver/transmitter. To factor in the effect of distance dependent shadowing, we need to use higher path loss exponents. Secondly, there are example scenarios where the path loss exponent for sensing is large while the path loss exponent for interference could be small. Consider the case where the wireless microphone is on the ground while the microphone receiver is mounted on a truck 100 meters away. The secondary transmitter is roof mounted and hence has a clear line of sight to the primary receiver.

b) The impact of multiuser diversity:: The 20dB fading mismatch that we budget has two components: The first part is the fading between the primary transmitter and the secondary sensor. This fading can be reduced by multiuser diversity at the sensors. The second part is the fading from the secondary transmitter to the primary receiver. For this, each secondary transmitter must budget on its own – there *is no multiuser diversity gain for this part.* Similarly, during cooperative sensing, a secondary user may have a line of sight to the primary transmitter. In this case, we do not need to budget for the worst case path loss exponent from the primary transmitter to the secondary. But there is no way to avoid assuming worst case path loss from the secondary to the primary.

The preceding analysis emphasizes the following fact: if an IEEE 802.22 CPE does not sense a wireless microphone and decides to transmit, it may interfere with a wireless microphone receiver. So what can a secondary device like a IEEE 802.22 CPE do to deal with a primary user which is matched in scale?

c) A sensor network perspective:: One of the solutions to this problem is to decouple sensing and admission control. Sensing answers the question '*Where is the primary?*' while admission control seeks to answer the question '*Can I transmit?*'. In the analysis so far, the radio that performs sensing also decides whether it can transmit. This approach was valid for large scale primary users [10] where a secondary user could make a transmission decision on its own (with a little cooperation with nearby secondaries to increase robustness). This is not the case for small scale primary users. For small scale primaries, we need a sensor network to localize the position of the primary user[4] and an admission control network to decide on which radios can transmit. This decoupling is the key to handling small scale primary users.

To calculate a target sensor density, we set a diversity target of 8 users (we would like 8 users to be within the

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[4] This sensor network may not be separate from the radio network; however sensor density requirements greater than the density of active users would require inactive nodes to sense.

sensing region with the hope that at least one of them will have a good channel to the primary user). This would mean we only need to budget 20dB for the fading margin since cooperation among 8 users causes sensitivity to get within 20dB of the path loss [7]. Table II shows the sensing density requirements for various path loss exponents. Ideally, we would like the density of active users (users that have data to transmit) to meet the requirements of Table II so that we do not require inactive users to sense. Unfortunately, the IEEE 802.22 Working Group targets areas where the population density is around 1.25 people/km^2 [15]. Hence, in the best case this implies a deployment density of 1.25 secondary nodes/km^2. In this case, the deployment density (leave alone the active user density), is not adequate if the primary to secondary loss exponent is 4 or greater.

d) The path loss exponent revisited:: We have seen that an increase in the primary-to-secondary path loss exponent causes the sensor density to increase. What if we budget for the worst case ($\alpha_{12} = 5$) and the actual loss exponent turned out be be 2; would that impact the system adversely? If the actual loss is 2 then many of the radios/sensors around the primary user will detect the primary. The impact of this would depend on the actual admission control algorithm. If all the radios that sense the primary need to be quiet, then a small loss exponent would render a large area unusable. On the other hand, many sensors sensing the primary will help localize the primary's location better. With this information, even radios that sense the primary may be able to transmit. The opposite is true for the secondary-to-primary path loss exponent. In this case a large exponent is preferred (see Table III) but we need to budget for a small exponent.

To deal with secondary density requirements while preserving the robust operation of wireless microphones, the IEEE 802.22 Working Group must either lower the CPE power, target suburban/urban environments where the deployment density is large enough to provide the required sensor density, or it must characterize the rural environment to ensure that the path loss exponent is better than 4.

IV. ADMISSION CONTROL

In the last section we established the fact that an admission control network is required to decide on which users can actually transmit; a single user cannot make this decision on its own.

A. Secondary Pollution Area

To develop a simple admission control algorithm, we first introduce the concept of a *secondary pollution area*. Pollution area is a region around a secondary user where a primary receiver will face undesired interference. This pollution area is easy to calculate for a single secondary radio, but the presence of multiple secondary users make this pollution radius larger due to cumulative interference.

To start, we first calculate the acceptable interference level at the primary receiver. Assuming a primary-primary loss exponent (α_{11}) of 5 and and a fading margin of 20dB, the acceptable interference turns out to be -110dBm.

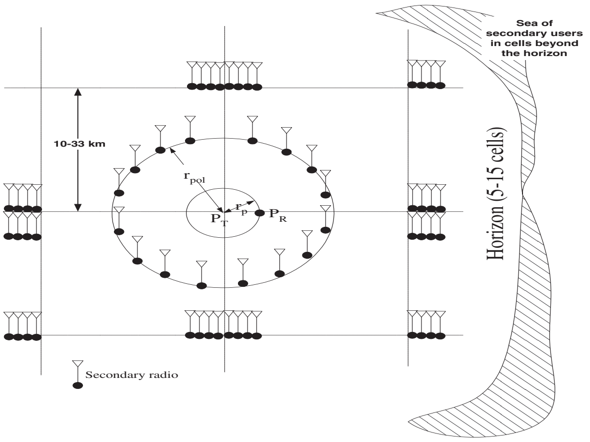

Fig. 4. The worst case pollution radius (and assuming that $r_{pol} \gg r_p$ is for an radio that is at the corner of a cell (for convenience we assume square cells). Around each microphone, each adjoining cell can have up to 4 radios at the pollution radius boundary. Radios outside the horizon are treated as a seas of secondary users with a power density corresponding to 4 simultaneous transmitting users. For cells within the horizon, we assume worst case radio placements which will impact the microphone adversely.

To obtain the worst case pollution radius are we need a model for the placements of the secondary radios. In [5] the power of a secondary radio was smeared over its footprint – this was a viable option since the primary was far away from the secondary and from its perspective, the secondaries seemed like a sea of transmitting users. The main mode of failure was that all the primary receivers at the edge of the protected radius received undesired interference. For small scale primaries this is not the case – the typical mode of failure is that some small group of secondary radios is close enough to interfere with the primary. In the absence of a trusted model for radio placements, we need to budget for worse case placements. Hence we must calculate the maximum number of secondary users simultaneously transmitting on the uplink in the band of a microphone (∼200kHz). We arbitrarily assume that 4 secondary users in a single cell can be active simultaneously on the channel occupied by a wireless microphone.

Next we factor in the interference from the other cells. For these cells, in keeping with our modeling philosophy, we assume worst case radio placements for the transmitting radios i.e. we assume that the radios are placed at the corner which is nearest to the microphone (See Figure 4). We make this exact computation for all cells which are within the horizon (the horizon (H) is defined in terms of number of cells and is a variable in our model).

Loss Exponent (α_{12})	Area of sensing region (km^2)	Secondary density requirements secondary nodes/km^2 secondary nodes/km^2
2	7.89 × 10^6	10.16 × 10^{-7}
3	580.52	0.0136
4	4.98	1.68
5	0.29	27.92

TABLE II

Area of sensing region for various primary-to-secondary path loss exponents. Since we require 8 secondary sensing nodes in each sensing region, this gives the equivalent sensing density requirements. The target IEEE 802.22 deployment density is 1.25 secondary nodes/km^2 [15]. This means that the deployment density is not adequate if the primary to secondary loss exponent is 4 or greater.

Path Loss Exponent (α_{21})	Pollution radius of a single secondary user (km)
2	1778
3	14
4	1.33

TABLE III

Pollution area is a region around a secondary user where a primary receiver will face undesired interference. Due to the symmetry in our model, the pollution area is a circle and hence the pollution radius is the right parameter to study. This table shows the pollution radius around a single secondary user for various secondary-to-primary path loss exponents

To calculate the influence from the users beyond the horizon, we use Equation (12) in [5]. This equation states that the effect of a sea of secondary users with power density D is the same as a single user of the same power but a loss exponent which is reduced by 2 (for this case the power density will correspond to a density of 4 radios per cell, $D = \frac{4P_2}{R^2}$ where R is the length of each side of the cell and P_2 is the power of a single secondary node).

Hence, the pollution radius is the smallest value of r that satisfies:

$$N_w\, P_2 r^{-\alpha_{21}} + D\, K(\alpha_{21})\, (R\, H)^{-\alpha_{21}+2} + \\ 4\, P_2\, R^{-\alpha_{21}} \sum_{i=1}^{H} \sum_{j=1}^{H} (i^2 + j^2)^{-\alpha_{21}/2} + 8\, P_2 \sum_{j=1}^{H} (R \times j)^{-\alpha_{21}} \\ \leq 10^{\frac{I_{max}}{10}}$$

where D is the maximum transmission density of the secondary nodes (as calculated above) (Watts/m^2), $K(\alpha_{21}) = \frac{2}{\alpha_{21}-2} \int_{-\pi/2}^{\pi/2} cos(\theta)^{-\alpha_{21}+2}\, d\theta$, I_{max} is the interference limit (-110dBm), N_w is the number of users around the pollution circle, and H is the number of cells within the horizon.

Our analysis shows that the sea of secondary users beyond the horizon has very little effect if the transmission densities are assumed to be small (4 transmitting radios per cell). For this case, Table IV shows the value of the pollution radius for various worse case configurations (4/8/12/16 radios just around the pollution circle).

To quantify the effect of a microphone on the performance of a 802.22 cell, we introduce the notion of *effective microphone footprint*. This is the area around the microphone where a secondary user cannot transmit. The microphone has an actual footprint that is dependent on the situation on the ground. Since we do have complete knowledge of this, we have to be conservative and need to budget by using worst case exponents, location uncertainty and worst case placement assumptions. The *effective microphone footprint* captures this loss from conservatism.

Since it is impossible to know if the sensed microphone is near the edge of the cell of near the center we need to budget for the worst case (microphone is in a corner and hence there can be up to 16 users just outside the pollution circle). In this case the pollution radius is 2.67km and the effective microphone footprint is 7.27km^2 ($\alpha_{21} = 4$).

It is prudent to compare these results to the results from a model which considers all secondary users as a sea of secondaries with a certain power density. The density model of [5] yields a pollution radius of 315 meters for the same set of parameter values; this is much more optimistic than the prediction from worst case placement assumptions.

B. Location uncertainty of the primary

In section IV-A, we assumed that the location of the primary and secondary users is known exactly. In this section we relax the assumption that the location of the primary is known. This is important since the the primary is being sensed and hence the location of the primary will only be known approximately.

Number of radios around the pollution circle	Radius of pollution circle (km)
4	1.89
8	2.24
12	2.48
16	2.67

TABLE IV

POLLUTION RADIUS FOR VARIOUS NUMBER OF RADIOS AROUND THE POLLUTION CIRCLE. SINCE THE TRANSMISSION DENSITIES IN THE SEA OF RADIOS BEYOND THE HORIZON ARE VERY LOW, THE POSITION OF THE HORIZON DOES NOT IMPACT THE POLLUTION RADIUS.

We first characterize the *location uncertainty* of the primary user as a function of the sensor density. A location uncertainty of x meters implies that the primary could be closer/further by x meters from its true location. It is important to note that this is an example of a case where uncertainty can be reduced by actual measurements on the ground and hence we do not need to stick with worst case assumptions.

In Table II, the maximum sensing radius was calculated by requiring a diversity of 8 sensing radios around the primary. A diversity of 8 assumes that at least one radio will catch the primary and the uncertainty would be equal to the sensing radius[5]. When the sensing density increases beyond this, multiple radios exist in the sensing circle - in this case the sensing radius is governed by the distance to the radio that sees the best channel. This distance shrinks (in an expected sense) as the density of sensing nodes increases.

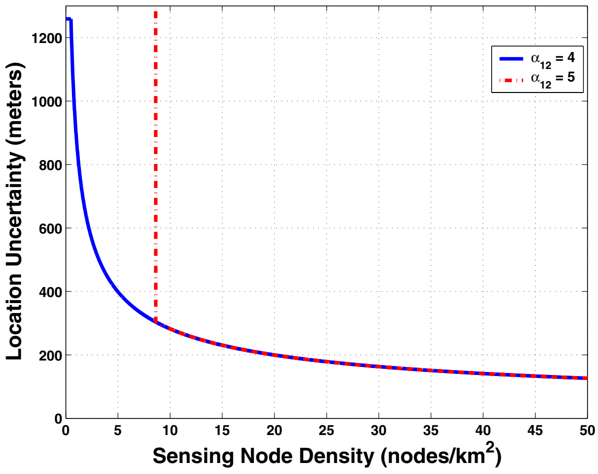

Fig. 5. Location uncertainty about the primary as the secondary density is scaled. This uncertainty must be added to the pollution radius to ensure that the primary radio is protected.

Figure 6 shows the *effective microphone footprint* for various secondary densities (Figures (a) and (b) differ in the worst case assumptions about the number of simultaneous radios operational in a cell. For (a) we assume 4 simultaneous radios per cell while for (b) we assume a single radio per cell). Increasing the densities of secondary sensors improves the location uncertainty which in turn decreases the effective microphone footprint. At the basic required density for $\alpha_{12} = 4$ (1.68 sensing nodes/km^2 - see Table II), the effective microphone footprint goes up by a factor of 2 in the worst case (4 simultaneous radios per cell).

C. Location uncertainty of the secondary

There are three different ways to resolve location uncertainty of secondary users. The first is to have people/technicians register these devices. The method suffers from costs related to technicians or to trust issues related to people registering their own devices. It also rules out CPE mobility or even nomadic operation. The second method is to install location aware devices on these radios – this method also imposes costs. The third (and the method analyzed in this paper) is to have the sensor nodes that sense the primary also sense the secondary users in order to estimate their locations.

Since the IEEE 802.22 devices have large power as compared to wireless microphones (1W versus 100mW), they can be sensed by the same infrastructure that is sensing the primary user. By our previous assumption, the location uncertainty related of these secondary devices would be the same as the location uncertainty of the primary for a given secondary sensor density.

Figure 6 again shows the effect of the combined location uncertainty of secondary and primary users. At the basic required density for $\alpha_{12} = 4$ (1.68 sensing nodes/km^2), the effective microphone footprint goes up by a factor of 4 in the worst case (4 simultaneous radios per cell).

V. DISCUSSION

So what choices do we have for enabling coexistence between primaries and secondaries of similar scale? We can place the burden of coexistence on either the secondary user alone or we can have obtain primary assistance as well.

If the burden lies entirely on the secondaries, they can either increase their sensor densities (as explained in earlier sections) or they can employ sophisticated sensing techniques

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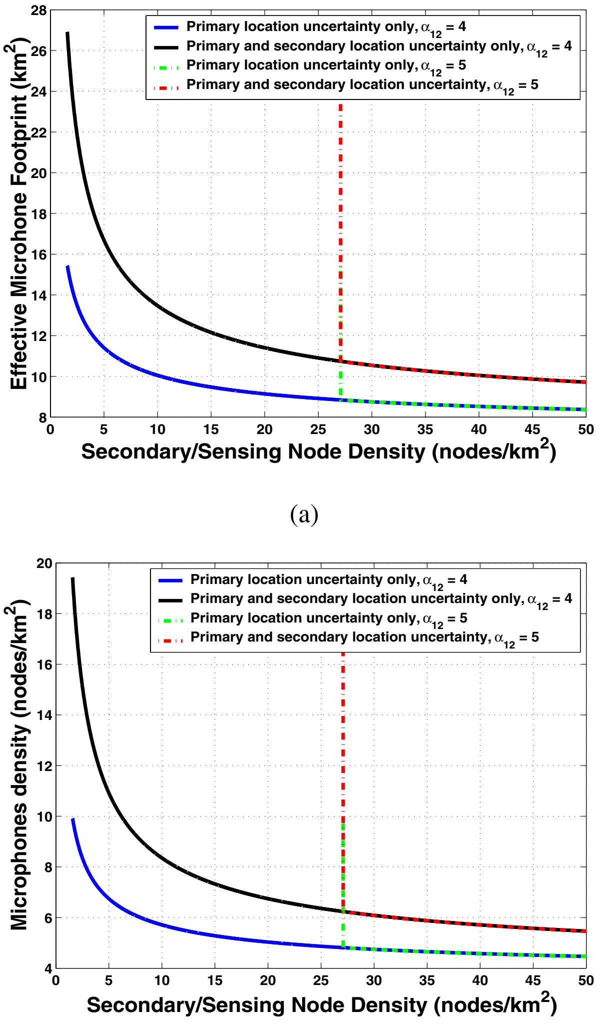
[5] This is a worst case assumption - location uncertainty would be better than the sensing radius in most cases.



(a)

(b)

Fig. 6. (a) Effective Microphone Footprint with location uncertainty of the primary and secondary users - assuming **4** simultaneous radios/cell (b) Effective Microphone Footprint with location uncertainty of the primary and secondary users - assuming **1** simultaneous radio/cell

(like coherent detection)[6]. The SNR wall for energy detection can be reduced by 20dB by using coherent detection [9]. This increases the sensing radius which in turn reduces sensor density requirements. Figure 7 shows the improvement in sensor density requirements as the sensitivity is scaled. For a primary-to-secondary sensing exponent of 5 ($\alpha_{12} = 5$, we need a sensitivity improvement of 23dB to get within the current deployment density requirements (1.25 nodes/km^2).

The primary user can enable opportunistic sharing by one of the following ways: Firstly, primaries could introduce beacons which could facilitate coherent detection (as discussed above). Secondary, the primary receivers can issue denials whenever the interference is larger than the desired/undesired ratio[7]. Since denials have low probability of occurrence the entire secondary network could cease transmission once a denial is issued. After this, secondary nodes could gradually reenter the system calibrating their impact on the primary.

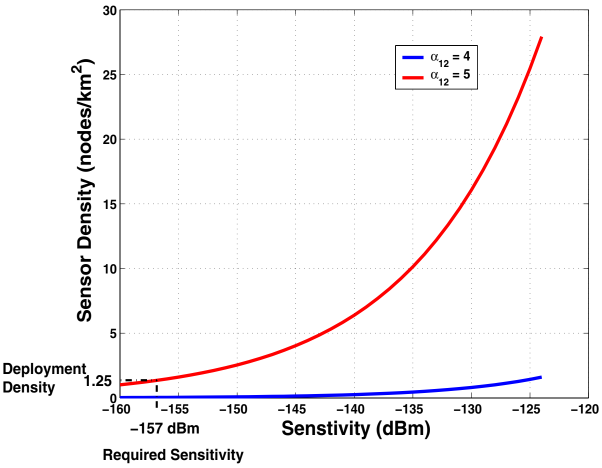


Fig. 7. Sensor density requirements are reduced as the radio sensitivity is improved.

VI. CONCLUSIONS

Real world cognitive systems will need to coexist with multiple classes of primary users each with its own scale of operation. Unfortunately, coexistence with primary users of different scale leads to different infrastructure requirements on the secondary system. While sensing a primary user of a scale much larger than the secondary user (primary power 5 orders of magnitude greater than secondary power), the secondary user can make the decision about its transmission based on the sensing results in its own neighborhood. This key system assumption breaks down in the presence of small scale primary users. For such primaries, we need to decouple the sensing and admission control decisions. A secondary user that does not sense a primary *cannot* transmit until a separate admission control entity/network allows it to do so. In the case of IEEE 802.22, the sensor network requirements needed to ensure that all microphones can be reliably sensed with simple detectors are much larger than the target deployment density. These density requirements could be relaxed by either limiting the number of simultaneous users per cell or by improving the sensitivity of each radio by employing coherent detection.

A simple admission control algorithm is proposed which only allows a secondary user to transmit if it beyond the worst case pollution radius from the primary. Even if we assume that the location of the primary and secondary radios is

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[6] This does require primary users to have beacons/pilots that can be easily detected.

[7] A denial is a identifiable signature that can be issued by the receiver whenever interference reaches an unacceptable level.

known exactly, the effective microphone footprint is $7.13km^2$. If the location of the primary and secondary users is known approximately (based on having the sensor network sensing the primary and secondary radios), then the effective microphone footprint scales up by a factor of (around) 4.

REFERENCES

[1] R. W. Broderson, A. Wolisz, D. Cabric, S. M. Mishra, and D. Willkomm. White paper: CORVUS: A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum. Technical report, 2004.

[2] Spectrum policy task force report. Technical Report 02-135, Federal Communications Commision, Nov 2002.

[3] Dupont Circle Spectrum Utilization During Peak Hours. Technical report, The New America Foundation and The Shared Spectrum Company, 2003.

[4] C. Cordeiro, K. Challapali, D. Birru, and Sai Shankar. IEEE 802.22: the first worldwide wireless standard based on cognitive radios. In *Proc. of the first IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, 2005.

[5] N. Hoven and A. Sahai. Power Scaling for Cognitive Radio. In *Proc. of the WirelessCom 05 Symposium on Signal Processing*, 2005.

[6] R. Tandra and A. Sahai. Fundamental limits on detection in low SNR under noise uncertainty. In *Proc. of the WirelessCom 05 Symposium on Signal Processing*, 2005.

[7] S.M. Mishra, A. Sahai, and R.W. Brodersen. Cooperative Sensing Among Cognitive Radios. In *Proc. of the IEEE International Conference on Communications (ICC)*, 2006.

[8] A. Ghasemi and E. S. Sousa. Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments. IEEE DySPAN05), 2005.

[9] R. Tandra and A. Sahai. Fundamental limits on feature detection. In *Submitted to IEEE DySPAN07*, 2007.

[10] A. Sahai, R. Tandra, S.M. Mishra, and N.K.Hoven. Fundamental Design Tradeoffs in Cognitive Radio Systems. In *Proc. of the First International Workshop on Technology and Policy for Accessing Spectrum, (TAPAS)*, 2006.

[11] D. Cabric, A. Tkachenko, and R.W. Brodersen. Experimental study of Spectrum Sensing based on Energy Detection and Network Cooperation. In *ACM TAPAS*, 2006.

[12] M. McHenry. The Probe Spectrum Access Method. In *Proc. of the first IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, 2005.

[13] J. F. Chamberland and V. V. Veeravalli. How Dense Should a Sensor Network Be for Detection With Correlated Observations? *IEEE Transactions on Information Theory*, 51(11):5099–5106, November 2006.

[14] D. Tse and P. Viswanath. *Fundamentals of Wireless Communications*. Cambridge University Press, 2005.

[15] C. R. Stevenson, C. Cordeiro, E. Sofer, and G. Chouinard. RAN requirements. Technical Report 22-05-0007-47-0000, IEEE 802.22 Working Group, January 2006.