The Primary Exclusive Region in Cognitive Networks

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(Invited Paper)

***Abstract*—In this paper, we consider a cognitive network in which a single primary transmitter communicates with primary receivers within an area of radius R_0, called the *primary exclusive region* (PER). Inside this region, no cognitive users may transmit. Outside the PER, provided that the cognitive transmitters are at a minimal distance ϵ_p from a primary receiver, they may transmit concurrently with the primary user. We determine bounds on the primary exclusive radius R_0 and the guard band ϵ_p to guarantee an outage performance for the primary user. Specifically, for a desired rate C_0 and an outage probability β, the probability that the primary user's rate falls below C_0 is less than β. This performance guarantee holds even with an arbitrarily large number of cognitive users uniformly distributed with constant density outside the primary exclusive region.**

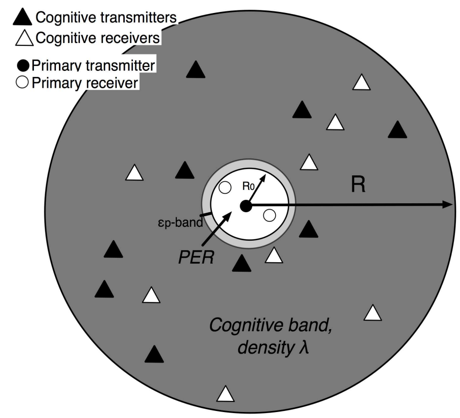

Fig. 1. A cognitive network consists of a single primary transmitter at the center of a *primary exclusive region* (PER) with radius R_0, which contains its intended receiver. Surrounding the PER is a protected band of width $\epsilon_p > 0$. Outside the PER and the protected bands, n cognitive transmitters are distributed randomly and uniformly with density λ.

I. Introduction

Cognitive networks are becoming a reality. Such networks consist of primary nodes, which have priority access to the spectrum, and cognitive (secondary) nodes, which access the spectrum according to some defined *secondary spectrum licensing* rules [1]. For example, consider a TV station which broadcasts in a currently licensed and exclusive band. Despite the high prices paid for these exclusive bands in spectral auctions [2], measurements show that *white space*, or temporarily unused time or frequency slots, are alarmingly common [3]. Notably, TV bands are wasted in geographic locations barely covered by the TV signal. This has prompted various regulatory and legislative bodies to put forth procedures [4] which would open up TV channels 2-51 (54 MHZ - 698 MHz) for use by secondary devices. These devices, often cognitive radios [5], [6], would be able to dynamically access the spectrum provided any degradation they cause to the primary license holders' transmissions is within an acceptable level. While the definition of what is acceptable is a still topic of much debate [7], its model is of great interest. This type of re-licensing of exclusive bands is often termed *secondary spectrum licensing* [1] or *dynamic spectrum access* [8]–[10]. For practical feasibility studies of such TV-band networks, see [11] and references therein.

In this paper, we focus on a theoretical formulation of the secondary-spectrum problem. We consider a network with a single primary transmitter, with possibly multiple primary receivers, and multiple cognitive [1] users. The primary transmitter may be thought of as the TV broadcaster, and the primary receivers as TV subscribers, which have priority access to the given band. The cognitive users use "smart" wireless devices to opportunistically access the spectrum of the primary users, while guaranteeing the primary users a certain performance. Our formulation also applies to other scenarios, such as the downlink in a cellular network.

[1]We use the terms cognitive and secondary interchangeably

We model the network as shown in Figure 1. A single primary transmitter (Tx) wishes to communicate with one or more primary receivers (Rx) within a circle of radius R_0, which we call the *primary exclusive region*. This region is void of cognitive users. Furthermore, any cognitive transmitter must be at least an ϵ_p radius away from a primary receiver. Assuming the location of the primary receiver is unknown to the cognitive users, we place a guard band of width ϵ_p around the PER, in which no cognitive transmitters may be operate. We then place a constraint that, in the presence of the interference from the cognitive users, the primary user must be guaranteed an outage capacity, a minimum rate for a certain portion of time. Based on this constraint, we derive bounds on the PER radius R_0 and the guard band ϵ_p, which are also functions of other network parameters, including the primary and cognitive transmit power, the cognitive user density, and the overall network radius R. Our results hold for the 'worst case' scenario for the primary users, in which an infinite network, randomly distributed with constant density λ of cognitive users lies outside the PER and ϵ_p-band. This limit is achieved by letting the network radius $R \to \infty$ as the number of cognitive users increases, equivalent to an extended network. Our analyses assume very simple receivers in which all undesired signals are treated as noise. This assumption is somewhat pessimistic, and our results thus form a conservative lower bound. In practice, some form of multi-user detection allowing for interference suppression or mitigation may be used to enhance the rates achieved.

A. Previous work on cognitive networks

In this paper, we are interested in the design of the primary exclusive region radius and the guard band ϵ_p to meet the desired primary outage constraint. We formulate this problem using tools from information theory, which allows us to analyze the underlying and fundamental limits of communication. Existing works on cognitive networks vary in a wide range, from regulatory issues [6], [12] to game-theoretic analysis [13], from white space sensing [14], [15], to MAC-layer and PHY-layer protocols [16], [17], from theoretical interference analyses [18], [19] to actual testbeds and experiments of cognitive networks [20]–[22].

Due to space constraint, we only mention two of the most closely related papers on cognitive networks. The network model considered here is that of [23], where the sum-rate scaling law is analyzed. Specifically, in [23], we show that the single-hop cognitive network with bounded transmission distances may achieve a total throughput which scales linearly in the number of cognitive nodes. In [23], we also introduced the problem considered here and obtained some preliminary results. In this paper, we extend the model and provide additional bounds, with graphical interpretations of the design parameters.

Another related work is [18], of which we were unaware of until a late stage of the current paper's research. In [18], the authors study the question of how cognitive radios must scale their power to meet a desired maximal interference constraint at a primary receiver, first for a single cognitive transmitter, then for a large network of cognitive transmitters. By studying the aggregated secondary interference power, the authors of [18] provide bounds on the allowable cognitive transmit power. Our focus here is on the radius of the primary exclusive region, subject to a primary outage constraint rather than a maximal interference constraint. Furthermore, we obtained exact expressions for some cases, in addition to the bounds on the interference at the primary receiver.

B. Paper outline

In Section II, we introduce our network model and formulate the problem. In Section III, we first derive lower bounds, upper bounds, and an exact expression for the expected interference seen at the primary receiver. Using these expressions, we then examine the outage constraint on the primary user and derive the relations among the radius of the *primary exclusive region*, R_0, the guard band ϵ_p, and all the other network parameters. In Section V, we make our conclusions and final remarks.

II. Problem Formulation

We consider a cognitive network with two types of users: primary and cognitive users. The goal is to provide a relation between the design parameters of the network. In this section, we first outline the geometric network model, then describe the assumptions made about the wireless communication, and finally formulate the problem.

A. Network model

We consider an extended network with transmitters and receivers located on a planar circle of radius R, as shown in Figure 1. We assume that the single primary transmitter is located at the center of this network, a model corresponds to a broadcast scenario. Also centered at primary transmitter is a primary exclusive region (PER) of radius R_0. All primary receivers are located in this region. Each primary receiver is surrounded by a guard band of radius ϵ_p in which no cognitive transmitters may lie. In the most general scenario, the exact locations of the primary receivers are unknown to the cognitive transmitters (as in a TV broadcast scenario for example). Thus for the cognitive transmitters to meet this constraint, they must lie outside the circle of radius $R_0 + \epsilon_p$. We assume that the cognitive transmitters know this radius. All cognitive transmitters are randomly and uniformly distributed with density λ in the cognitive band between radii $R_0 + \epsilon_p$ and R, the outer radius of the network.

B. Channel and signal models

We consider a path-loss only model for the wireless channel between a cognitive transmitter and a primary receiver. Given a distance d between the transmitter and the receiver, the channel h is

$$h = \frac{A}{d^{\alpha/2}} \tag{1}$$

where A is a frequency-dependent constant and α is the power path loss. In subsequent analysis, we normalize A to be 1 for simplicity. We consider $\alpha > 2$ which is typical in practical scenarios. We assume that the channels between different transmitters and receivers are independent. Furthermore, they all undergo independent zero-mean additive white Gaussian noise of power σ^2.

In an additive white Gaussian noise channel, transmitting using a Gaussian codebook is known to be optimal for capacity achieving [24]. Thus, we assume all transmissions are Gaussian. Furthermore, we assume that the receivers, primary and cognitive, have no knowledge of other users' signals and treat their interference as noise. Again, this is a pessimistic assumption, but will provide a conservative lower bound on what may be achieved if multi-user detection is employed. We assume that the primary user's signal is constrained by a constant power P_0, and each cognitive user by P. Furthermore, the signals of different users are statistically independent.

C. The primary exclusive region

We now mathematically model the condition that guarantees a certain performance for the primary user in the presence of the cognitive users. Specifically, our problem consists of determining the radius R_0 of the primary exclusive region, in which no cognitive transmitters may transmit, as well as the guard band size ϵ_p such that, for the primary receivers in the PER, the following outage constraint holds

$$\Pr\left[\text{primary user's rate} \leq C_0\right] \leq \beta \tag{2}$$

where C_0 and β are pre-chosen constants. This constraint guarantees the primary user a rate of at least C_0 for all but β fraction of the time.

Denote h_0 as the channel between the primary transmitter and the primary user of interest, and g_i as the channel from cognitive transmitter i to this primary receiver. The interference power from the cognitive users to the considered primary user is

$$I_0 = \sum_{i=1}^{n} P|g_i|^2 \tag{3}$$

This interference power is random because of the random placement of the cognitive users. With Gaussian signaling, the rate of this primary user may be expressed as

$$C_p = \log\left(1 + \frac{P_0|h_0|^2}{I_0 + \sigma^2}\right) .$$

This rate is random because of random interference I_0. The outage constraint can now be written as

$$\Pr\left[\log\left(1 + \frac{P_0|h_0|^2}{I_0 + \sigma^2}\right) \leq C_0\right] \leq \beta. \tag{4}$$

Since our channels depend only on the path loss, the outages that occur here are not because of fading as in traditional schemes, but because of the random placement of cognitive users.

III. Bounds on the Interference at the Primary Receiver

We now study the relation between the primary exclusive region radius R_0 and the primary receiver guard band width ϵ_p. We consider the worst case scenario in which a primary receiver is at the edge of the PER, on the circle of radius R_0, as shown in Figure 2. The outage constraint must also hold in this (worst) case, and we find a relation between R_0 and ϵ_p that ensures this. Furthermore, we determine bounds, and in some cases exact values, of the expected interference at the primary receiver from the network of cognitive users.

Consider interference at the primary receiver on the boundary of the PER from a cognitive transmitter at radius r and angle θ. The distance $d(r,\theta)$ (the distance depends on r and θ) between this interfering transmitter and the primary receiver satisfies

$$d(r,\theta)^2 = r^2 + R_0^2 - 2R_0 r\cos\theta .$$

For uniformly distributed cognitive users, θ is uniform in $[0, 2\pi]$, and r has the density

$$f_r(r) = \frac{2r}{R^2 - (R_0+\epsilon_p)^2}.$$

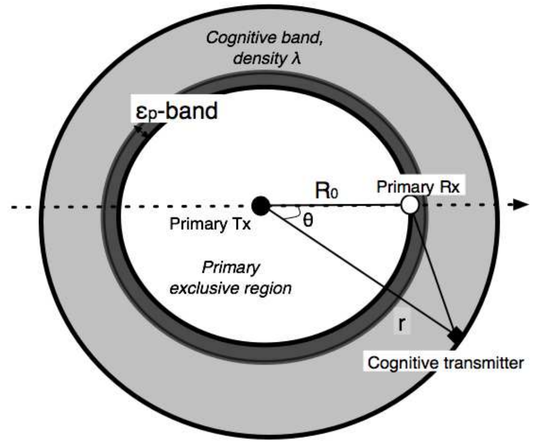

Fig. 2. Worst-case interference to a primary receiver: the receiver is on the boundary of the primary exclusive region of radius R_0. We seek to find R_0 to satisfy the outage constraint on the primary user.

The expected interference *power* experienced by the primary receiver from all $n = \lambda\pi(R^2 - (R_0+\epsilon_p)^2)$ cognitive users is then given as

$$E[I_0] = \int_{R_0+\epsilon_p}^{R}\int_0^{2\pi} \frac{\lambda r P\ dr\ d\theta}{(r^2 + R_0^2 - 2R_0 r\cos\theta)^{\alpha/2}}. \tag{5}$$

For $\alpha = 2k$ with integer k, we can calculate $E[I_0]$ analytically. As an example, for $\alpha = 4$, we obtain the values of $E[I_0]$ as

$$E[I_0]_{\alpha=4} = \lambda\pi P\left[-\frac{R^2}{(R^2-R_0^2)^2} + \frac{(R_0+\epsilon_p)^2}{\epsilon_p^2(2R_0+\epsilon_p)^2}\right]. \tag{6}$$

The derivation may be found in [25]. Letting $R \to \infty$, this average interference becomes

$$E[I_0]_{\alpha=4}^{\infty} = \lambda\pi P\left[\frac{(R_0+\epsilon_p)^2}{\epsilon_p^2(2R_0+\epsilon_p)^2}\right]. \tag{7}$$

Next, we derive bounds on this expected interference power $E[I_0]$ at the primary receiver for general α. We use these bounds to analyze the interference versus the radius R_0 and the path loss α. We then relate the outage probability to the average interference through the Markov inequality and establish an explicit dependence of R_0 on ϵ_p and other design parameters.

A. Upper and lower bounds on the average interference

In this subsection we obtain two lower bounds and an upper bound on $E[I_0]$. Because of space constraints, we defer all proofs and derivations of these bounds to [25].

1) A first lower bound on $E[I_0]$: A first lower bound on $E[I_0]$ can be established by re-centering the network at the *primary receiver*. We then make a new exclusive region of radius $2R_0$, and a new outer radius of $R - R_0$, both centered at the primary receiver, as shown in Figure 3. The set of cognitive users included in the new ring will be a subset of the original, making the interference a lower bound, given by

$$E[I_0]_{\text{LB1}} = \frac{2\pi\lambda P}{\alpha-2}\left(\frac{1}{(2R_0+\epsilon_p)^{\alpha-2}} - \frac{1}{(R-R_0)^{\alpha-2}}\right). \tag{8}$$

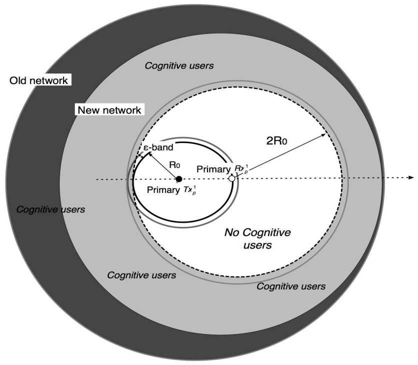

Fig. 3. A lower bound on the expected interference at the primary receiver is obtained by forming a cognitive-free circle of radius $2R_0$ around the primary receiver and reducing the network radius, now centered at the primary receiver, to $R - R_0$. All cognitive transmitters now lie within these two new boundaries.

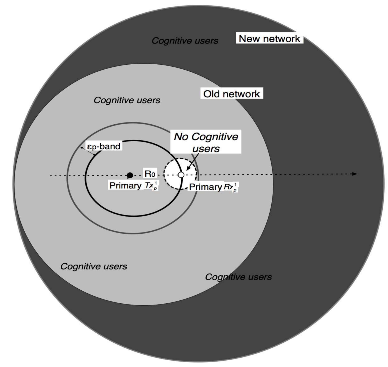

Fig. 5. An upper bound on the expected interference at the primary receiver is obtained by forming a cognitive-free circle of radius ϵ_p around the primary receiver and enlarging the network radius, centered at the primary receiver, to $R + R_0$. All cognitive transmitters now lie within these new boundaries.

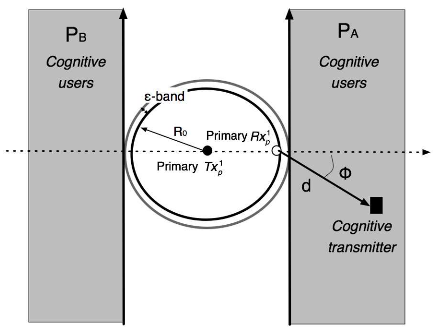

Fig. 4. Another lower bound on the expected interference at the primary receiver is obtained by approximating the interference region by two half-planes P_A and P_B. The region between these planes is free from cognitive transmitters.

As $R \to \infty$, this bound approaches the limit:

$$E[I_0]^{\infty}_{LB1} = \frac{2\pi P\lambda}{\alpha - 2}\frac{1}{(2R_0 + \epsilon_p)^{\alpha-2}}. \quad (9)$$

2) A second lower bound on $E[I_0]$: Another lower bound on the interference can be derived by approximating the interference region by two half-planes, similar to [18]. As illustrated in Figure 4, consider only interference from the cognitive users in the two half-planes P_A and P_B which touch the circle of radius $R_0+\epsilon_p$. Consider a line in P_A that makes an angle ϕ at the primary receiver, the distance d from any point on this line to the primary receiver satisfies $\frac{\epsilon_p}{\cos(\phi)} \le d < \infty$. Since the cognitive users are distributed uniformly, as $R \to \infty$, the distribution of d becomes similar to the distribution of r given in (III), and ϕ will be uniform in $[-\frac{\pi}{2}, \frac{\pi}{2}]$. Similar analyses hold for P_B. Hence the average total interference from the cognitive users in P_A and P_B to the primary receiver is

$$E[I_0]_{\text{LB2}} = \frac{P\lambda}{\alpha-2}\left(\frac{A(\alpha)}{\epsilon_p^{\alpha-2}} + \frac{A(\alpha)}{(2R_0+\epsilon_p)^{\alpha-2}} - \frac{\pi}{R^{\alpha-2}}\right), \quad (10)$$

where

$$A(\alpha) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos^{\alpha-2}(\phi)\, d\phi. \quad (11)$$

For an integer α, we can compute $A(\alpha)$ in closed form. For other α, numerical evaluation of $A(\alpha)$ is possible. When $R \to \infty$, this lower bound approaches

$$E[I_0]^{\infty}_{LB2} = \frac{P\lambda A(\alpha)}{\alpha-2}\left(\frac{1}{\epsilon_p^{\alpha-2}} + \frac{1}{(2R_0+\epsilon_p)^{\alpha-2}}\right). \quad (12)$$

Since this bound takes into account the interfering transmitters close to the primary receiver, for a small ϵ_p or large R_0, this lower bound is tighter than the previous one in (9).

3) An upper bound on $E[I_0]$: For the upper bound, similar to the first lower bound, we re-center the network at the primary receiver. We now reduce the exclusive region radius, centered at the primary receiver, to ϵ_p and extend the outer network radius, also centered at the primary receiver, to $R_0 + R$, as in Figure 5. The set of cognitive transmitters contained within these two new circles is a superset of the original, creating an upper bound on the interference as

$$E[I_0]_{\text{UB}} \quad = \quad = \frac{2\pi P\lambda}{\alpha-2}\left(\frac{1}{\epsilon_p^{\alpha-2}} - \frac{1}{(R+R_0)^{\alpha-2}}\right). \quad (13)$$

As $R \to \infty$, this upper bound becomes

$$E[I_0]^{\infty}_{U} \quad = \quad \frac{2\pi P\lambda}{\alpha-2}\frac{1}{\epsilon_p^{\alpha-2}}. \quad (14)$$

4) Numerical examples: In Figure 6, we compare the upper bound in (14), the lower bounds in (9) and (12), and the exact expression of the expected interference of (7) for various values of R_0 and $\lambda = 1, P = 1$, $\alpha = 4$ and $\epsilon_p = 2$ and assuming an infinite network ($R \to \infty$). We see that lower bound 2 is asymptotically tight, and that the expected interference approaches a finite limit as $R_0 \to \infty$.

IV. The Primary Exclusive Region Radius

A. Bounds on the primary exclusive radius

The established bounds on the expected interference can be used to bound the radius R_0 of the primary exclusive region. In particular, for a given outage capacity C_0, the primary outage constraint (4) can be written as

$$\begin{aligned} P_e &= \Pr\left[\log_2\left(1 + \frac{P_0/R_0^{\alpha}}{I_0+\sigma^2}\right) \le C_0\right] \\ &= \Pr\left[I_0 \ge \frac{P_0/R_0^{\alpha}}{(2^{C_0}-1)} - \sigma^2\right]. \end{aligned}$$

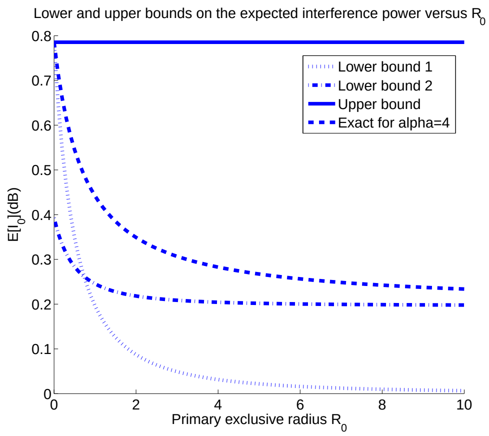

Fig. 6. Upper (14), lower bound 1 (9), lower bound 2 (12) for $\alpha = 4$, $\lambda = 1$, $P = 1$, $\epsilon_p = 2$. In this case we have the exact expression for $\alpha = 4$, which we compare to the other bounds to give an indication of their tightness.

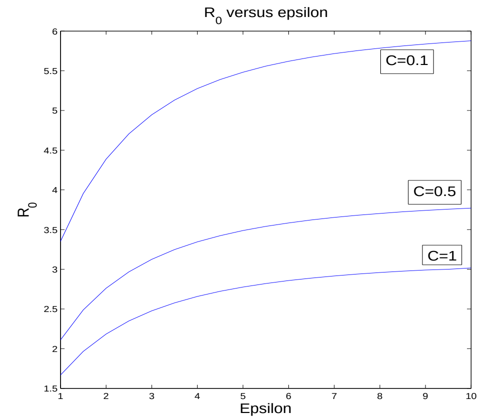

Fig. 7. The relation between the exclusive region radius R_0 and the guard band ϵ_p according to (17) for $\lambda = 1, P = 1, P_0 = 100, \sigma^2 = 1, \beta = 0.1$ and $\alpha = 4$.

We note that even if there are no cognitive users, the radius R_0 will be finite for a finite power P_0. This is because once the primary receiver is too far away, the receiver signal to noise ratio is below what is needed to ensure a rate of C_0. Thus, an upper bound on R_0 to achieve a given rate C_0 in the presence of Gaussian noise of power σ^2 alone is given by

$$R_0 \leq \left(\frac{P_0}{\sigma^2 (2^{C_0} - 1)} \right)^{1/\alpha} \triangleq R_0^u. \tag{15}$$

Assuming that R_0 satisfies (15), we can apply Markov's inequality to bound the outage probability in the presence of an infinite network of cognitive users as

$$P_e \quad \leq \quad \frac{E[I_0]}{\frac{P_0/R_0^\alpha}{(2^{C_0}-1)} - \sigma^2}.$$

Assuming an infinite network ($R \to \infty$), using the upper bound on $E[I_0]$ in (14), we can further bound P_e as

$$P_e \quad \leq \quad \frac{2\pi P \lambda}{\alpha - 2} \frac{1}{\epsilon_p^{\alpha-2}} \left(\frac{P_0/R_0^\alpha}{(2^{C_0} - 1)} - \sigma^2 \right)^{-1}.$$

Bounding this probability by the outage constraint β, we get

$$R_0^\alpha \leq \frac{P_0}{(2^{C_0} - 1)} \left(\frac{2\pi P \lambda}{\beta(\alpha - 2)} \frac{1}{\epsilon_p^{\alpha-2}} + \sigma^2 \right)^{-1}. \tag{16}$$

This bound is always smaller than the bound in (15). Thus, as expected, the maximum distance that we can guarantee an outage probability for a primary receiver will be reduced in the presence of cognitive users.

When α is an even integer, we can use the exact value of $E[I_0]$ in the Markov inequality to obtain a tighter bound on R_0. Using the example for $\alpha = 4$ in (7), we obtain an implicit equation for all exclusive region radii R_0 such that (4) holds as

$$\frac{(R_0 + \epsilon_p)^2}{\epsilon_p^2 (2R_0 + \epsilon_p)^2} \leq \frac{\beta}{\lambda \pi P} \left(\frac{P_0/R_0^4}{2^{C_0} - 1} - \sigma^2 \right). \tag{17}$$

Equations (16), for general $\alpha > 2$, and (17), for $\alpha = 4$, provide a relation among the system parameters: P_0 (the primary transmit power), P (the cognitive users' power), C_0 (the outage capacity), β (the outage probability), λ (the cognitive user density), σ^2 (the noise power), R_0 (the exclusive region radius) and ϵ_p (the guard band around each primary receiver). These equations may be of particular interest when designing the primary system to guarantee the primary outage constraint $\Pr[\text{primary user's rate} \leq C_0] \leq \beta$. By fixing several of the parameters, we can obtain relations among the others. The largest R_0 is obtained by setting the inequality in (17) to be an equality.

B. Numerical examples with $\alpha = 4$

As an example, we plot in Figure 7 the relation between the exclusive region radius R_0 and the guard-band width ϵ_p for various values of the outage capacity C_0, while fixing all other parameters according (17) for $\alpha = 4$. The plot shows that R_0 increases with ϵ_p, and the two are of approximately the same order. This is intuitively appealing since at the primary receiver there is a trade-off between the interference seen from the secondary users, which is of a minimum distance ϵ_p away, and the desired signal strength from the primary BS, which is of the distance R_0 away. The larger the ϵ_p, the less interference, and thus the further away the primary receiver may lie from the base station. We also notice that as C_0 increases, R_0 decreases for the same ϵ_p. This is again intuitively appealing: as we require a higher capacity, the relative interference (to the desired signal) must be reduced, which is achieved by reducing R_0 for a fixed ϵ_p. Finally, as $\epsilon_p \to \infty$, R_0 approaches the limit of the interference-free bound in (15) for $\alpha = 4$.

Alternatively, we can fix the guard band ϵ_p and the secondary user power P and seek the relation between the primary power P_0 and the exclusive radius R_0 that can support the outage capacity C_0. In Figure 8, we plot this relation according to (17) for $\alpha = 4$. The fourth-order increase in power (in relation to the radius R_0) here is in line with the path loss $\alpha = 4$. Interestingly, a small increase in the gap band ϵ_p can lead to a large reduction in the required primary transmit power P_0 to reach a receiver at a given radius R_0 while satisfying the given outage constraint.

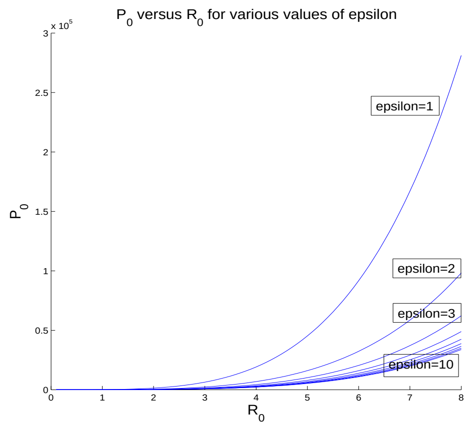

Fig. 8. The relation between the BS power P_0 and the exclusive region radius R_0 according to (17) for $\lambda = 1, P = 1, \sigma^2 = 1, \beta = 0.1, C_0 = 3$ and $\alpha = 4$.

V. Conclusion

As cognitive networks are rapidly becoming a reality, it is of crucial importance to properly design the the network parameters to guarantee primary users a certain level of performance. In this paper, we model this guarantee as an outage condition: for any primary receiver in the PER of radius R_0 and guard band ϵ_p, the probability that its rate falls below C_0 is less than β fraction of time. By determining the expected interference at the worst-case primary receiver, we obtained bounds relating the design parameters R_0 and ϵ_p to the desired parameters C_0 and β. These bounds can help in the design of cognitive networks with PERs.

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