RESIDUAL COGNITIVE NETWORK INTERFERENCE DUE TO PRIMARY USER MISS-DETECTION

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ABSTRACT

In this paper, we study the coexistence between a primary user (PU) communication and a cognitive radio (CR) network in a general framework that includes wireless propagation subject to path loss, log-normal shadowing, and Rayleigh fading. The CR network can be composed of just one cognitive user (CU) or by several CUs spatially distributed according to a Poisson point process. Each CU is equipped with a spectrum sensing block that can sense the PU transmission with miss-detection probability that depends on propagation impairments and noise. Therefore, our goal is to evaluate the residual interference that the CR network cause to PU because of miss-detections. We start by determining the outage probability of the PU link interfered by a single CU. Then, we investigate the statistical distribution of the residual interference from multiple CUs, which are active due to PU miss-detection, and follow a non-homogeneous Poisson point process. Numerical results shows the link between PU outage and CU spectrum sensing performance. Therefore, the framework proposed is of practical importance and constitutes an aid for the network designer.

1. INTRODUCTION

Recently proposed cognitive radio (CR) concept has been the key point of wireless communications because it changes the traditional spectrum allocation to improve spectrum utilization. In general, a cognitive user (CU) is allowed to communicate on a frequency band if the interference caused to primary users (PUs) can be tolerated [1,2]. Interference cumulated by CUs is the most important cause of PU performance degradation in wireless networks [3–6]. In particular, in [3] the statistical distribution of the aggregate interference has been analyzed, in realistic propagation environments including path loss, shadowing and fading.

In this paper we consider a general framework where CUs sense the spectrum before their transmission and then start transmit only if PU is not sensed. In particular, we specialize the framework to the most common situation where the PU communication is sensed through an energy detector (ED), which is one of the most used, and simpler, detection technique [7]. In particular, we introduce a direct link between the sensing parameters and their impact on the interference level caused to PU. The choice of the detection parameters has a twofold impact: miss detection causes interference to PUs, while false alarms causes miss transmission opportunities from the CR perspective [8]. In this paper, we focus our attention on the first aspect.

Due to wireless propagation effects such as path loss, shadowing and fading, CUs may miss to detect the PU, thus interfering with the PUs' communication. We call such form of interference, *residual interference*. To quantify the performance of the victim link, we analyze the outage probability. The main contributions of this paper are as follows:

- We provide the statistical distribution of the unexpected network interference. Our analysis reveals the innate connection between the distribution of the network interference and various important system parameters, such as path loss exponent, transmitted power, and spatial density of CUs.
- We calculate the outage probability of PU link under various channel conditions and spatial distributions of the CUs.
- We determine the relationship between the false alarm and detection probabilities at the CR and the outage probability of the PU.

This paper is organized as follows. Section 2 describes the system model. Section 3 formulates the problem and defines the outage probability of the victim link. Section 4 analyzes the outage probability of single CU case. Section 5 determines the characteristic function of residual interference due to spatially distributed CUs according to a Poisson point process. In section 6 we provide some numeral results to emphasize the relationship between the false alarm probability and the outage probability of the PUs. In Section 7 we draw some conclusions.

2. SYSTEM MODEL

We consider a scenario with two types of users, primary and cognitive, respectively. Since we are interested in analyzing the performance of PU link in the presence of interference caused by CUs, we consider a PU that acts as a receiver (PU_R) located in the origin of the coordinate system and a PU that acts as a transmitter (PU_T) at a distance r_0 from PU_R. Since the PU link is bidirectional, we assume that the $PU_R$was acting as a transmitter, previously, so that the CUs can potentially detect the $PU_R$by a spectrum sensing technique. In the following we describe the spatial distribution of CUs and the channel model.

2.1 Spatial distribution of the cognitive users

We consider two scenarios: single CU case and multiple CUs case. In the first scenario we consider one CU at a distance r from the PU_R, while in the second scenario the CUs are spatially distributed according to a homogeneous Poisson point

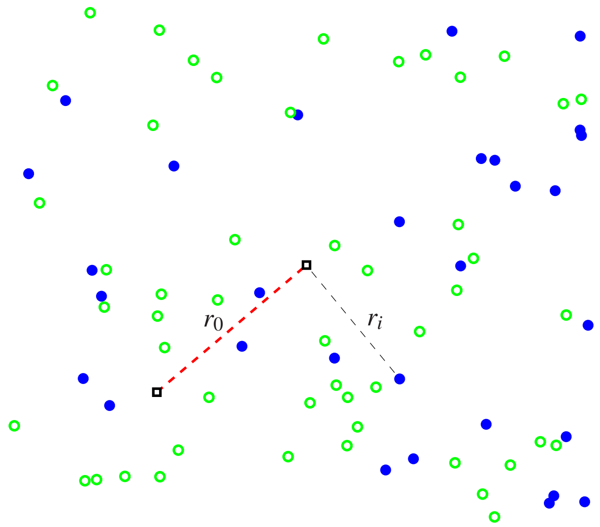

Figure 1: Coexistence scenario with a victim PU_R(square in the center) and spatially distributed CUs: blue circles represents active (interfering) CUs, while green circles represents inactive CUs (i.e., those CUs that successfully detected the PU).

process in the two-dimensional infinite plane with constant density λ that express the average number of CUs per unit area (see Figure 1).

2.2 Channel model

Typically, the effects introduced by propagation in the wireless channel include path-loss, shadowing and fading. Regarding the PU link, we denote with P_0 the average power measured 1 m away from the PU_T, therefore the received power at the $PU_R$is $P_0\theta_0/r_0^{2b}$ and the interference from the i^{th} cognitive users to the $PU_R$is[1]

$$I_i = \frac{P_i}{r_i^{2b}}\theta_i \qquad i = 1, 2, \ldots, \infty \tag{1}$$

where P_i is the average power measured 1 m away from the i^{th} CU; r_i is the distance from the i^{th} CU to the PU_R; θ_i accounts for fading and/or shadowing experienced by the i^{th} interfering link; b is the amplitude loss exponent. Note that, $b = 1$ corresponds to free space propagation, while in practical propagation scenarios b can vary from slightly more than 1 for hallways within buildings to more than 3 for dense urban environments and office buildings.

For the sake of simplicity, our analysis assumes constant transmitter power for all CUs, which is reasonable in a scheme where no power control strategies are implemented in the cognitive network, then $P_i = P$.

We consider the following three situations of the channel propagation characteristics:

- *Path loss (PL).* In this situation signals are attenuated only with distance, so $\theta_i = 1$.
- *PL and shadowing.* In this case, in addition to path loss, log-normal shadowing is included. Therefore, $\theta_i = e^{2\sigma_i G_i}$, where $G_i \sim \mathcal{N}(0,1)$, and σ_i is the shadowing parameter.[2]
- *PL, shadowing and fading.* In this case $\theta_i = \xi_i e^{2\sigma_i G_i}$, includes shadowing and fading. In particular, ξ_i is a r.v. with an exponential p.d.f., $f_{\xi_i}(\xi) = \exp(-\xi)$, $\xi \geq 0$, with $\mathbb{E}\{\xi_i\} = 1$, representing Rayleigh fading.

[1]The use of the average power measured at a reference distance (1 m in this case) is useful because it includes antenna gains, antenna efficiency, and the path loss at the reference distance.

3. PROBLEM FORMULATION

When a primary communication occurs, the handshake procedure of the victim link would trigger the $PU_R$to transmit a beacon. Then, the generic CU decide whether a PU exist based on a spectrum sensing strategy. When the CU fails to detect the existence of PU_Rwe consider the situation where it starts its own transmission causing interference to the PU (victim) link. Therefore, the probability that the i^{th} CU transmit during a PU transmission can be written as the probability of miss-detection, which in turns is a function of the signal-to-noise ratio (SNR) of the PU – i^{th} CU link, i.e.,

$$p_i^{\text{act}} = P_{\text{MD}}(\mathsf{SNR}_i). \tag{2}$$

For example, if PU detection is performed with an energy detection (ED) in each CU node, the miss-detection probability, and thus p_i^{act} can be written as [7][3]

$$p_i^{\text{act}}(\mathsf{SNR}_i) = 1 - Q\left(\frac{Q^{-1}(P_{\text{FA}}) - \sqrt{M}\,\mathsf{SNR}_i}{1+\mathsf{SNR}_i}\right) \tag{3}$$

where $Q(\cdot)$ is the Gaussian Q-function, P_{FA} is the false alarm probability, $M = W \cdot T$ is the time-bandwidth product, with W the ED bandpass zonal filter bandwidth, and T the observation (sensing) time. The SNR at the i^{th} CU is $\mathsf{SNR}_i = P_0\theta_i r_i^{-2b}/(N_0 W)$, where N_0 denotes the one-sided noise power spectral density at the ED.[4]

The approach presented in the following sections is quite general and can be extended to any type of detection technique provided that a relation between P_{MD} and SNR is known. Therefore, in the rest of the paper we assume that $p^{\text{act}}(\cdot)$ is a function of θ_i/r_i^{2b}.

The network interference is due to the accumulation of undesired (from the PU perspective) CUs transmission from those cognitive nodes that did not detect the PU transmission because of path loss, shadowing, fading and noise. The main contribution of this paper is to analyze the aggregate interference caused by miss-detection.

To evaluate the performance of the victim link we define the signal-to-interference ratio (SIR) of the PU receiver as $\mathsf{SIR} = S/I$, where S denotes the received power from the PU transmitter, and I denotes the residual interference from CUs. Then, we define the outage probability of the victim link to indicate whether the SIR is lower than a given minimum value, $\mathsf{SIR}_{\min}$ to guarantee desired performance $P_{\text{out}} = \mathbb{P}\{\mathsf{SIR} \leqslant \mathsf{SIR}_{\min}\}$.

[2]The notation $\mathcal{N}(\mu,\nu^2)$ stands for a Gaussian distribution with expectation μ and variance ν^2. The parameter σ_i can be related to the standard deviation of the channel loss in dB, $\sigma_{i,\text{dB}} = 20\sigma_i/\ln 10$ [4].

[3]For the sake of simplicity, we consider the scenario when the PU signal can be approximated as a Gaussian process, but all derivations are quite general and valid by using the proper P_{MD}.

[4]Note that P_{FA} is chosen to guarantee requirements on the detection probability and the observation time T. However, P_{FA}. affects the CU performance since higher values preclude CU transmissions even when the PU is not active.

4. PRIMARY COMMUNICATION OUTAGE DUE TO MISS-DETECTION BY A SINGLE CU

We consider a scenario with one CU at a distance r from the $\mathrm{PU_R}$.[5]

4.1 Path loss

In this case, the desired received power is $S = P_0/r_0^{2b}$, while the interference power is $I = P\varepsilon/r^{2b}$, where $\varepsilon \in \{0,1\}$ is a binary r.v. equal to 1 when CU is active and 0 otherwise, i.e, $\mathbb{P}\{\varepsilon = 1\} = p^{\mathrm{act}}$ and $\mathbb{P}\{\varepsilon = 0\} = 1 - p^{\mathrm{act}}$, respectively. The outage probability of the PU is therefore

$$P_{\mathrm{out}} = \begin{cases} 0, & \text{if} \quad r \geq r_{\mathrm{th}} \\ p^{\mathrm{act}}, & \text{if} \quad r < r_{\mathrm{th}} \end{cases} \tag{4}$$

where

$$r_{\mathrm{th}} = r_0 \left(\frac{P}{P_0}\mathsf{SIR}_{\min}\right)^{1/2b} \tag{5}$$

and p^{act} depends on the detection strategy and in general on r.

4.2 PL and shadowing

In this case, the desired received power is $S = P_0 e^{2\sigma_0 G_0}/r_0^{2b}$, while the interference power is $I = \varepsilon P e^{2\sigma G}/r^{2b}$. Therefore, after some manipulations the outage probability of the PU link can be written as

$$\begin{aligned} P_{\mathrm{out}} &= \mathbb{P}\left\{e^{2\sigma_0 G_0} \leq \rho \varepsilon e^{2\sigma G}\right\} \\ &= \mathbb{E}_z\left\{\mathbb{E}_\varepsilon\left\{\mathbb{P}\left\{e^{2\sigma_0 G_0} \leq \rho\varepsilon e^{2\sigma z} | \varepsilon, z\right\}\right\}\right\} \\ &= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\left(1 - Q\left(\frac{\ln\rho + 2\sigma z}{2\sigma_0}\right)\right) p^{\mathrm{act}}\left(\frac{e^{2\sigma z}}{r^{2b}}\right) e^{-\frac{z^2}{2}} dz \end{aligned} \tag{6}$$

where

$$\rho = \frac{P}{P_0}\left(\frac{r_0}{r}\right)^{2b}\mathsf{SIR}_{\min}. \tag{7}$$

4.3 PL, shadowing and Rayleigh fading

In this case, the desired received power is $S = P_0 \xi_0 e^{2\sigma_0 G_0}/r_0^{2b}$, while the interference power is $I = \varepsilon P \xi e^{2\sigma G}/r^{2b}$. Following an approach similar to (6) we get

$$\begin{aligned} P_{\mathrm{out}} = \frac{1}{\sqrt{2\pi}}\int_0^{\infty}\int_0^{\infty}\int_{-\infty}^{\infty}\left(1 - Q\left(\frac{\ln\rho + \ln(u/u_0) + 2\sigma z}{2\sigma_0}\right)\right) \times \\ p^{\mathrm{act}}\left(\frac{u e^{2\sigma z}}{r^{2b}}\right) e^{-\left(u_0 + u + \frac{z^2}{2}\right)} du_0\, du\, dz. \end{aligned} \tag{8}$$

where ρ is defined in (7).

Note that in (6) and (8) the Gaussian Q-function can be conveniently approximated by $Q(x) \cong \frac{1}{12}\exp\left(-\frac{1}{2}x^2\right) + \frac{1}{4}\exp\left(-\frac{2}{3}x^2\right)$ [9].

[5] To simplify the notation, in this section we use the subscript 0 to quantities that involves PU link and we omit subscripts for the CU.

5. PRIMARY COMMUNICATION OUTAGE DUE TO MISS-DETECTION BY A COGNITIVE NETWORK

When CUs are spatially distributed according to an homogeneous Poisson point process with density λ, the SIR is

$$\mathsf{SIR} = \frac{S}{P \cdot \mathscr{I}} = \frac{P_0 \theta_0 r_0^{-2b}}{P \sum_{i=1}^{\infty} \varepsilon_i \theta_i r_i^{-2b}} \tag{9}$$

where the term $P \cdot \mathscr{I}$ now is the aggregate interference from active CUs, i.e, the subset of all CUs that did not detect the presence of the PU. The binary r.v. ε_i determine if the i^{th} CU is active or not. Since the r.v.'s ε_i are dependent on p^{act}, which in turns depends on the term θ_i/r_i^{2b}, the active CUs are no longer distributed according to an homogeneous Poisson point process.[6] Such situation, can be represented as a Marked Poisson point process, i.e., an inhomogeneous Poisson process where at each point there is a mark associated represented as a r.v. that depends only on the point location (i.e., r_i). For Marked Poisson point process it is possible to calculate the characteristic function (ch.f.) of a sum in the form like $\mathscr{I}$, $\Psi_{\mathscr{I}}(w) = \mathbb{E}\left\{e^{jw\mathscr{I}}\right\}$, by means of the Campbell's Theorem [10, pp. 57–59]. Defining the mark m_i referred to the i^{th} CU as $m_i = P\theta_i\varepsilon_i/r_i^{2b}$, the ch.f. of $\mathscr{I}$ becomes

$$\Psi_{\mathscr{I}}(w) = \exp\left(-2\pi\lambda\int_0^{\infty}\int\left(1 - e^{jwm}\right) f_m(m|r)\, dm\, r\, dr\right). \tag{10}$$

Now, substituting the p.d.f. of the generic mark m into (10), after some mathematical derivations, we get

$$\Psi_{\mathscr{I}}(w) = \exp\left(-2\pi\lambda\int_0^{\infty}\int_0^{\infty}\left(1 - e^{jw\frac{\theta}{r^{2b}}}\right) f_\theta(\theta)\, p^{\mathrm{act}}\left(\frac{\theta}{r^{2b}}\right) d\theta\, r\, dr\right). \tag{11}$$

Proof of the convergence of the integral in (11) is provided in the Appendix.

From (11) it is possible to derive the cumulative distribution function (c.d.f.) of the residual (aggregate) interference at the $\mathrm{PU_R}$ by the Gil-Pelaez inversion formula

$$F_{\mathscr{I}}(\zeta) = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty}\frac{\mathfrak{I}_{\mathrm{m}}\{\Psi_{\mathscr{I}}(w)e^{-jw\zeta}\}}{w} dw \tag{12}$$

where $\mathfrak{I}_{\mathrm{m}}\{\cdot\}$ denotes the imaginary part of a complex number. Then, the outage probability is finally evaluated as

$$P_{\mathrm{out}} = 1 - \int_0^{\infty} F_{\mathscr{I}}\left(\frac{P_0}{P r_0^{2b}}\frac{\theta_0}{\mathsf{SIR}_{\min}}\right) f_{\theta_0}(\theta_0)\, d\theta_0. \tag{13}$$

Expressions (11)-(13) can be specialized in the three propagation environments considered by choosing the proper distribution for θ_0 and θ.

[6] This is intuitively clear, since CUs that are close to the $\mathrm{PU_R}$ detect the PU transmission with high probability, and thus they are inactive, while CUs that are far from the $\mathrm{PU_R}$ have a lower detection probability, so they are often active.

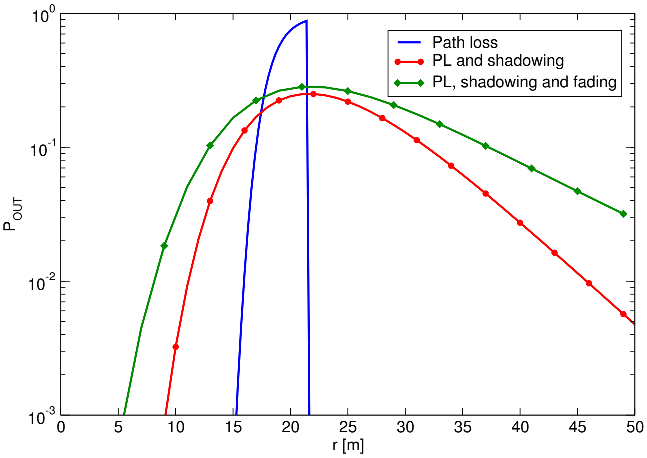

Figure 2: PU outage probability with a single CU as a function of the distance r. The ED threshold is set to have a probability of false alarm $P_{FA} = 0.01$.

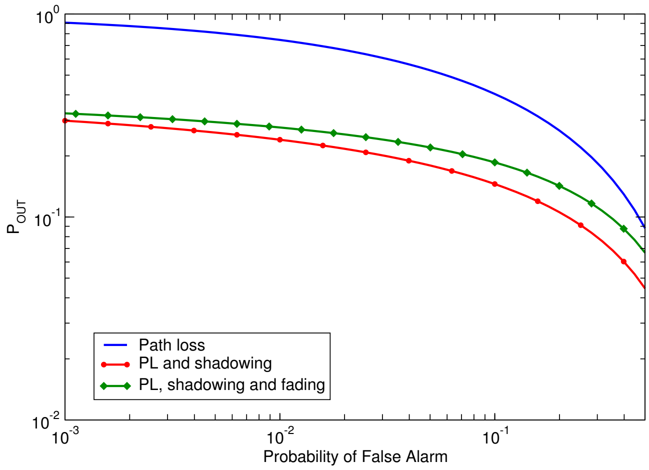

Figure 3: PU outage probability with a single CU as a function of the probability of false alarm. The distance r is 20 m.

6. NUMERICAL RESULTS

In this section we evaluate the outage probability of PU link in different scenarios, based on the analytical framework derived.

We consider a wireless propagation environment with amplitude loss exponent $b = 3$ and, when considered, shadowing with parameters $\sigma_{0,\text{dB}} = \sigma_{\text{dB}} = 6$ and Rayleigh fading. The PU link has a length $r_0 = 10$ m, its outage probability refers to $\text{SIR}_{\min} = 10$ dB and the ratio between the PU and CU power (referred at 1 m) is $P/P_0 = 10$. The detection of PU is based on ED with $M = 100$ and $P_0/(N_0W) = 10^7$.

Figure 2 plots the performance in terms of PU outage probability as a function of the PU-CU distance for a $P_{FA} = 0.01$ and in the three different scenarios. As can be seen, with the parameters considered, there is a peak in PU outage around $r = 20$ m caused by the trade off between the detection probability and the interfering power attenuated by the distance r. The same peak is observed in all propagation scenarios with smoother behavior when shadowing and fading are present. As expected, decreasing r results in a decrease of PU miss-detection and thus a decrease of residual interference. On the contrary increasing r increase P_{MD} which results in an apparent raising of interference counterbalanced by heavier propagation loss, which results in a substantial reduction of P_{out}.

In Figure 3, the same situation is analyzed by fixing the distance $r = 20$ m and varying P_{FA} set in the ED. As can be seen, despite different performance due to the propagation environment, there is a substantial reduction of the outage probability when P_{FA} increases. In fact, an increase in the false alarm cause an increase of detection probability, and thus a decrease of the residual interference. Unfortunately, an increase in P_{FA} reduce the CU efficiency. This trade off is particularly important for the system designer to set the proper parameters depending on the scenario and the desired performance.

Now, we analyze the impact of a network of spatially distributed CUs. With respect to the previous scenario, the following parameters are changed: $\text{SIR}_{\min} = 0$ dB, $P/P_0 = 1$, and $\sigma_{0,\text{dB}} = 0$.

Figure 4 shows the PU outage probability as a function of the P_{FA} set on each CU, the sensing duration represented by M, and the propagation environment. As can be seen, the outage probability decreases when P_{FA} increases. In this situation, the PU communication is preserved at the expense of CU spectrum usage, i.e., miss transmission opportunities. Similarly, PU outage probability can be reduced by increasing the sensing duration M. In fact, the higher M the better are ED performance, and thus the residual interference towards the PU is reduced. Note that however, increasing M the time spent by the CUs to sense the channel increase and correspondingly the spectrum efficiency of CU network decrease.

The same scenario is analyzed in Figure 5 where the PU outage probability is derived as a function of CUs spatial density λ, and the propagation environment. As expected, we note here an increase of the outage probability corresponding to an increase of the CUs density. In particular, in the scenario with shadowing, and for $M = 100$, the outage probability is about 10^{-3} when $\lambda = 0.05\,\text{m}^2$ (which corresponds to an average of 1 CUs per 20 m^2 area) to about 99% when $\lambda = 0.08\,\text{m}^2$ (which corresponds to an average of 1 CUs per 12.5 m^2 area). Such increase can be mitigated by increasing, e.g., the sensing time M at the expense of the CUs network efficiency.

7. CONCLUSIONS

In this paper we analyzed a scenario with a PU link affected by CUs. The CUs are equipped with a spectrum sensing technique that has to detect the presence of a PU communication. In a realistic scenario, because of the presence of signal attenuations due to path loss, shadowing and fading, the detection performance are severely degraded and thus a potential interference caused by PU miss-detection at the CUs occur. The outage probability of the PU victim link in the presence of a single CU as well as spatially distributed CUs and in different propagation scenarios is derived. The analysis could be useful for the system designer to determine the impact of spectrum sensing strategies and their performance to guarantee a desired protection level to PUs.

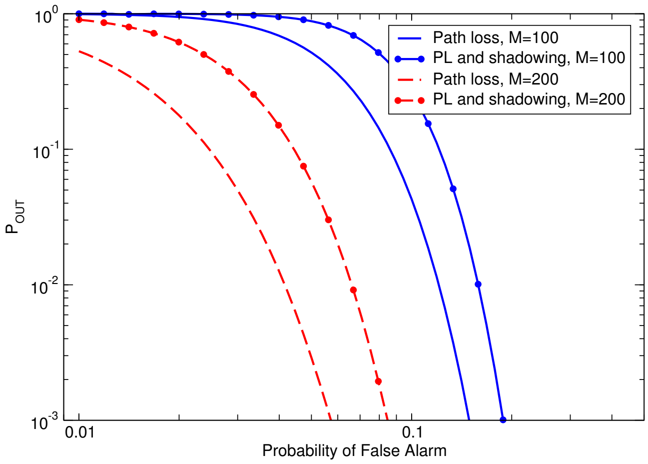

Figure 4: PU outage probability with spatially distributed CUs ($\lambda = 0.1\,\mathrm{m}^{-2}$), as a function of P_{FA} and sensing time M.

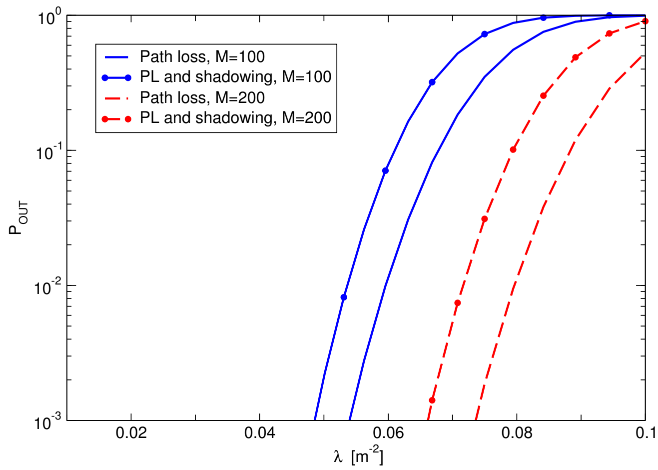

Figure 5: PU outage probability as a function of CUs spatial density λ and the sensing time M with $P_{\mathrm{FA}} = 0.01$.

Appendix

The ch.f. (11) exists and is absolutely convergent with probability 1, if the following integral converges [10]

$$\int_0^\infty \int_0^\infty \min\left(\frac{\theta}{r^{2b}}, 1\right) f_\Theta(\theta) p^{\mathrm{act}}(\theta, r) d\theta r dr < +\infty. \quad (14)$$

This can be easily proved:

$$\begin{aligned} &\int_0^\infty \int_0^\infty \min\left(\frac{\theta}{r^{2b}}, 1\right) f_\Theta(\theta) p^{\mathrm{act}}(\theta, r) d\theta r dr \\ &\overset{(a)}{\leq} \int_0^\infty \int_0^\infty \min\left(\frac{\theta}{r^{2b}}, 1\right) f_\Theta(\theta) d\theta r dr \\ &\overset{(b)}{=} \int_0^\infty \int_{\theta^{1/2b}}^\infty r^{1-2b} dr \theta f_\Theta(\theta) d\theta + \int_0^\infty \int_0^{\theta^{1/2b}} r dr f_\Theta(\theta) d\theta \\ &\overset{(c)}{=} \frac{b}{2b-2} \mathbb{E}\{\theta^{1/b}\} < +\infty \qquad (15) \end{aligned}$$

where inequality (a) is always valid since the integrand function is always positive and $0 \leq p^{\mathrm{act}}(\theta, r) \leq 1$, while the first integral in (b) converges iff $b > 1$ and the latter (c) requires the existence of $\mathbb{E}\{\theta^{1/b}\}$. Note that for practical scenarios, the conditions $b > 1$ and $\mathbb{E}\{\theta^{1/b}\} < +\infty$ are always satisfied.

Acknowledgment

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