Transmit Power Control for Secondary Use in Environments with Correlated Shadowing

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***Abstract*—In this paper we propose a general model to estimate the maximum allowed transmit power of a secondary node based on the measured signal from the primary transmitter that is willing to share its downlink spectrum. The transmit power should satisfy primary constraints related to the minimum required Signal to Interference and Noise Ratio (SINR) of its users. The model can be used by secondary nodes whether or not they have full knowledge about the correlation between the different path losses. Simulation results shows the high impact of the level of correlation on the performance of both primary and secondary users.**

***Index Terms*—Dynamic spectrum access; correlated shadowing; transmit power control.**

I. Introduction

Dynamic Spectrum Access (DSA) is proposed as a solution against non-efficient classical spectrum management techniques [1], [2]. Most of the research work in this framework focuses on the case where primary networks are broadcasting networks (i.e., TV networks) [3]. The DSA algorithms of secondary networks in this case are either developed to exploit, to the maximum, all spectrum opportunities with a fixed power [4], [5] or to find the maximum allowed power for secondary nodes [6], [7], without disturbing primary receivers. In addition, most of these works do not consider correlated shadowing between the different links. The existing works considering shadowing correlations are mainly developed for cooperative sensing considering only the correlation between the signals generated by the primary transmitter and received by different secondary nodes [8]–[10].

In this paper we consider three different types of correlated links that represent virtually most DSA approaches as shown in Fig. 1. The first link is between the primary transmitter and primary receiver where the useful signal is carried. The second link is the link carrying the interference experienced by the primary receiver due to secondary activity. The third link carries the signal transmitted by the primary transmitter and measured by the secondary node to decide about spectrum opportunities. Since each pair of these links has a common node, shadowing factors cannot be always considered as uncorrelated random variables. However there is practically no work on how these correlations can be estimated dynamically and without extensive measurement. Therefore, approximative models are used to determine the correlations [11], [12]. As far as we are aware of, there are no studies about the impact of the errors in estimating these correlations on the performance of DSA networks, although these errors can have high impact on secondary throughput and primary satisfaction. In this context, the main contributions of this paper are:

- Development of a general model to estimate the maximum allowed transmit power by a secondary node that satisfies primary constraints based on the received power from primary transmitter.
- Finding a solution for the studied problem numerically.
- Evaluation of the impact of correlated shadowing using the developed model and simulations.

The paper is organized as follows. In Section II, we formulate the problem and present the considered assumptions. In Section III, we develop the general model to estimate the allowed transmit power. In Section IV, we evaluate the performance of the model in environment with correlated shadowing before concluding the paper in Section V.

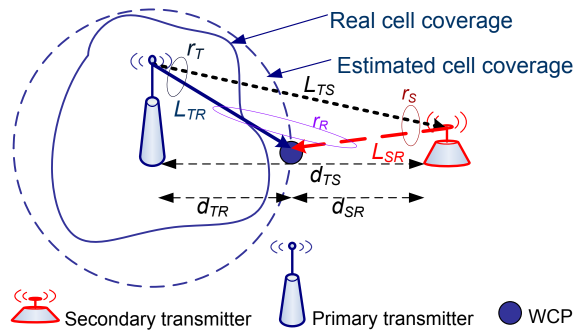

Fig. 1. The considered model for evaluating the impact of correlation (L, d and r represent the path loss, distance and shadowing factor correlation, respectively. Subscripts T, R and S represent the primary transmitter, the primary receiver and the secondary transmitter, respectively. WCP stands for Worst Case Position of primary receivers).

II. Problem Formulation

We consider a primary system consisting of one macrocell transmitting in the downlink. We assume that a secondary node at a given distance will decide on its transmit power based on the estimation of the path loss towards the primary transmitter that can be accurately estimated. This is the case, for instance, of a femtocell (secondary node) that can decode the beacons of a macrocell (primary transmitter).

The considered model is depicted in Fig. 1. The total path loss L_{XY} between a transmitter X and receiver Y can be divided into a distance-dependent path loss $\ell_{XY} = F_{XY}(d_{XY})$ and shadowing factor χ_{XY} (we do not consider fast fading since it occurs in shorter time-scale than shadowing and can typically be eliminated by averaging [13]), where d_{XY} is the distance separating the transceivers and F_{XY} is the path loss function:

$$L_{XY} = F_{XY}(d_{XY}) + \chi_{XY}. \tag{1}$$

We also assume that F_{XY} and the distribution of the shadowing factors are perfectly known by the secondary node. This is, of course, not very realistic since it is very difficult to know this information perfectly. However, the distributions of errors in the estimation of these data can be easily included in the model but are out of the scope of this paper.

We define the correlation between two random variables X and Y as the Pearson's correlation

$$\text{corr}(X,Y) = \frac{E\left[(X - E(X))(Y - E(Y))\right]}{\sigma_X \sigma_Y}, \tag{2}$$

where E is the expectation operator, σ_X and σ_Y are the standard deviations of X and Y, respectively.

We also assume that all path losses are correlated and the correlation coefficients are different. In particular we define correlations

$$\begin{aligned} r_T =& \text{corr}(\chi_{TR}, \chi_{TS}), \\ r_S =& \text{corr}(\chi_{SR}, \chi_{TS}), \text{and} \\ r_R =& \text{corr}(\chi_{TR}, \chi_{SR}), \end{aligned} \tag{3}$$

where χ_{TR} is the shadowing factor between primary transceivers, χ_{TS} is the shadowing factor between the primary transmitter and secondary node, and χ_{SR} is the shadowing factor between the secondary node and the primary receiver.

A. Primary Constraints

We assume that the primary network allows secondary activity if this activity will reduce the Signal to Interference and Noise Ratio (SINR) of any primary receiver to a lower value than threshold γ_r only with a probability lower than ε [3], [7]. Hence, for any number of successive secondary nodes using primary channels, the probability of dissatisfaction of any primary user, Pr_{diss}, should be lower than or equal to ε. For any primary user, this condition is expressed by

$$\text{Pr}_{\text{diss}} = \mathbb{P}\{\gamma < \gamma_r\} \leq \varepsilon. \tag{4}$$

Furthermore, we assume that any required approximation should be biased to a more conservative approach with respect to primary protection. Since the positions of the primary receivers (i.e., terminals) are not known to the secondary nodes, the worst case situation is considered. This means that the secondary node should guarantee that an active primary terminal that might be at the position where the interference generated by secondary activity is at maximum will be satisfied (i.e., $\text{Pr}_{\text{diss}} \leq \varepsilon$). Therefore, the secondary node will consider the Worst Case primary terminal Position (WCP) for its transmit power decision [14]. The WCP is the closest possible primary terminal position in the primary coverage area that have the lowest distance-dependent path loss toward the secondary node. However, the coverage areas of wireless network cells do not, in general, have a known and regular shape. Therefore, the secondary will consider the circle that contains the coverage area as shown in Fig. 1, which is again a conservative assumption to protect the primary. This circle will be considered in the following as the estimated coverage area.

The value of Pr_{diss} is different depending on the relative position of the secondary node toward the WCP and thus the coverage area of the primary cell. The secondary can be either inside the coverage area or outside this area. In the first case, Pr_{diss} is assumed by the secondary node to be one, since the primary receiver can be at any point near to the node. In the second case, this probability will depend on the estimated path loss between the primary receiver at the WCP and the secondary node. In this case the WCP is the intersection of the coverage circle with the line joining the secondary node and the primary transmitter as shown in Fig. 1. Therefore, the condition on the relative position can be applied to the distance between the WCP and the secondary node, d_{SR}: if $d_{SR} > 0$ the node is outside the coverage area, otherwise it is inside. Thus we can rewrite (4) using the law of total probability and considering the limit of primary constraint (i.e., $\text{Pr}_{\text{diss}} = \varepsilon$) as

$$\mathbb{P}\{\gamma < \gamma_r | d_{SR} > 0\}\mathbb{P}\{d_{SR} > 0\} + \mathbb{P}\{d_{SR} \leq 0\} = \varepsilon. \tag{5}$$

All the probabilities in (5) are conditional on the measured value of L_{TS}, but we omit the notation for simplicity.

The power of the secondary node can be any value between 0 Watts and the maximum allowed power of the node, which we consider here to be infinite to make the model as general as possible. The objective of the secondary node is to maximize its throughput and thus its allowed transmit power, based on the measured value of L_{TS} while guaranteeing that the SINR of the primary receiver at the WCP is higher than γ_r with a probability $1 - \varepsilon$. This SINR can be written in dB as

$$\begin{aligned} \gamma = & P_T - \ell_{TR} + \chi_{TR} \\ & -10\log_{10}\left(10^{\frac{P_S - \ell_{SR} + \chi_{SR}}{10}} + 10^{\frac{P_N}{10}}\right), \end{aligned} \tag{6}$$

where P_T, P_S and P_N are the transmit power of the primary transmitter, the transmit power of the secondary node and the noise power, respectively. In the following, we assume that P_T and P_N are known and we aim at finding the maximum allowed secondary transmit power, P_S, that satisfies (5).

B. Correlation Model

We assume that all shadowing factors are correlated, with the correlation matrix

$$M = \begin{pmatrix} 1 & r_R & r_T \\ r_R & 1 & r_S \\ r_T & r_S & 1 \end{pmatrix}. \tag{7}$$

As usual, the correlation matrix is required to be positive semi-definite to guarantee the feasibility of the model [11], leading to the condition

$$\det(M) \geq 0, \tag{8}$$

where $\det(M)$ is the determinant of the matrix M. Therefore, only the correlation values that satisfy (8) can be used and thus defining the space of possible correlations.

In general, the shadowing correlation is considered to be positive. However, recent studies have shown that in some cases the correlation can be negative as well [15]. Thus we consider the general case in our study where correlation coefficients can vary in the interval $[-1, 1]$ while satisfying (8).

III. Estimation of Allowed Transmit Power

In order to find the maximum allowed transmit power P_S, the secondary node should satisfy constraint (5) that depends on the unknown variables d_{SR}, χ_{SR} and χ_{TR}.

Since $d_{SR} = d_{TS} - d_{TR}$, the condition $d_{SR} > 0$ can be also rewritten as $d_{TS} > d_{TR}$. However, χ_{TS} follows a normal distribution [16] and $d_{TS} = F_{TS}^{-1}(L_{TS} - \chi_{TS})$. Hence, knowing the value of L_{TS}, we can write probability $\mathbb{P}\{d_{SR} > 0\}$ as

$$\begin{aligned}\mathbb{P}\{d_{SR} > 0\} &= \mathbb{P}\{F_{TS}^{-1}(L_{TS} - \chi_{TS}) > d_{TR}\} \\ &= \frac{1}{2}\left[1 + \text{erf}\left(\frac{L_{TS} - F_{TS}(d_{TR})}{\sqrt{2}\sigma_{TS}}\right)\right], \quad (9)\end{aligned}$$

where L_{TS} is the measured path loss between the primary transmitter and secondary node, and d_{TR} is the distance between the primary transmitter and the WCP (i.e., coverage radius), which is considered to be known.

The distance-dependent path loss ℓ_{SR} in (6) is computed from the estimated distance d_{SR} between the secondary node and the primary receiver:

$$\ell_{SR} = F_{SR}(d_{SR}). \quad (10)$$

In turn, this distance is estimated considering WCP using relation

$$\begin{aligned}d_{SR} &= d_{TS} - d_{TR} \\ &= F_{TS}^{-1}(L_{TS} - \chi_{TS}) - d_{TR}. \quad (11)\end{aligned}$$

The variables χ_{TS}, χ_{SR} and χ_{TR} are the correlated shadowing factors. We assume that they follow normal distributions [16] with zero mean and standard deviations of σ_{TS}, σ_{SR} and σ_{TR}, respectively. We also assume that these distributions are known by the secondary node.

By combining (5), (6), (9), (10) and (11) we obtain

$$\begin{aligned}\varepsilon = 1 - \frac{1}{2}&\left[1 + \text{erf}\left(\frac{L_{TS} - F_{TS}(d_{TR})}{\sqrt{2}\sigma_{TS}}\right)\right] \\ &\times\left[1 - \mathbb{P}\{\chi \le 10^{P_S/10}\}\right], \quad (12)\end{aligned}$$

where χ is a random variable defined by

$$\begin{aligned}\chi =& 10^{\frac{F_{SR}\left[F_{TS}^{-1}(L_{TS}-\chi_{TS})-d_{TR}\right]-\chi_{SR}}{10}} \\ &\times\left(10^{\frac{P_T - F_{TR}(d_{TR}) + \chi_{TR} - \gamma_r}{10}} - 10^{P_N/10}\right). \quad (13)\end{aligned}$$

In order to solve (12), the cumulative distribution function (cdf) of χ should be computed. This is done herein using Monte-Carlo method due to the complexity of finding a closed form of the cdf.

From (12), we can deduce that the condition $\mathbb{P}\{d_{SR} > 0\} \ge 1 - \varepsilon$ should be satisfied to obtain positive values of P_S. In case this condition is not satisfied, the probability that the secondary node is inside the coverage area will be higher than ε and therefore the secondary will be forbidden to transmit. Thus, the secondary node should first satisfy this condition before starting to compute P_S. Using (9) this condition can be also written in terms of L_{TS} as

$$L_{TS} > F_{TS}(d_{TR}) + \sqrt{2}\sigma_{TS}\,\text{erf}^{-1}(1 - 2\varepsilon). \quad (14)$$

Moreover, the term $I = 10^{\frac{P_T - F_{TR}(d_{TR}) + \chi_{TR} - \gamma_r}{10}} - 10^{P_N/10}$ can be negative or zero. This means that the required SINR by the primary users cannot be reached with desired probability (i.e., $1 - \varepsilon$) even without the presence of secondary activity due to high shadowing. In this case two possibilities exist. The primary network can either reduce the service level to a lower γ_r, or forbid any secondary activity and maintain the actual low SINR of its receivers. Herein we consider the second possibility and we assume that the primary would forbid any secondary activity in this case.

Using the constraint on I, we can reduce the computation time based on the following inequality:

$$\mathbb{P}\{\chi \le 10^{P_S/10}\} > \mathbb{P}\{I \le 0\}. \quad (15)$$

This can be deduced directly from (13) since χ is positively proportional to I and condition $\mathbb{P}\{\chi \le 10^{P_S/10}\}$ can be written as $\mathbb{P}\{I \le A\}$, where A is a positive value. We have $\mathbb{P}\{I \le 0\} < \mathbb{P}\{I \le A\}$ and thus we get the inequality (15). Therefore, by using (9), (12) and (15) the secondary node can only transmit if

$$\begin{aligned}\varepsilon >& 1 - \frac{1}{2}\left[1 + \text{erf}\left(\frac{L_{TS} - F_{TS}(d_{TR})}{\sqrt{2}\sigma_{TS}}\right)\right] \\ &\times[1 - \mathbb{P}\{I \le 0\}], \quad (16)\end{aligned}$$

and thus

$$\begin{aligned}L_{TS} >& F_{TS}(d_{TR}) \\ &+ \sqrt{2}\sigma_{TS}\,\text{erf}^{-1}\left[2\frac{1-\varepsilon}{1 - \mathbb{P}\{I \le 0\}} - 1\right]. \quad (17)\end{aligned}$$

By taking into account that χ_{TR} has a normal distribution, (17) becomes

$$\begin{aligned}L_{TS} >& \sqrt{2}\sigma_{TS}\,\text{erf}^{-1}\left[\frac{4(1-\varepsilon)}{1 - \text{erf}\left(\frac{\gamma_r - P_T + F_{TR}(d_{TR}) + P_N}{\sqrt{2}\sigma_{TR}}\right)} - 1\right] \\ &+ F_{TS}(d_{TR}). \quad (18)\end{aligned}$$

When $\mathbb{P}\{I \le 0\} > \varepsilon$, it is clear that (18) does not have a solution and the secondary node cannot transmit wherever it is. Therefore the secondary node can only transmit if

$$\gamma_r - P_T + F_{TR}(d_{TR}) + P_N < \sqrt{2}\sigma_{TR}\,\text{erf}^{-1}(2\varepsilon - 1). \quad (19)$$

Since $1 - \mathbb{P}\{I \le 0\} <= 1$, the value of the required L_{TS} given by (18) is always higher or equal to the one given by

Algorithm 1 Determining transmit opportunities

if condition (19) is satisfied **then**
  Start sensing
  if condition (18) is satisfied **then**
    Find P_S that satisfies (12)
  else
    Do not transmit
  end if
else
  Do not transmit
end if

(14). Therefore only the former condition is used. A high level pseudo code of the algorithm is given in Algorithm 1.

The proposed methodology here results in an optimal solution. The drawback of the method is its computational time, especially to find the cdf of χ. A secondary node that is trying to opportunistically access the spectrum may have neither the computational power nor the time to find the allowed transmit power. Thus we propose two possible solutions.

In the first solution, the secondary node will estimate power P_S to satisfy its communication requirement. This power level will be used in (12) to estimate Pr_{diss} for a given frequency in case both conditions (19) and (18) are satisfied. If all conditions are satisfied the node can transmit with P_S. Otherwise, it will search for another frequency.

In the second solution, a fixed node — which can reside in the primary, secondary or third party network — will provide a Radio Environment Map (REM) [17] that includes a table of the different cdfs of χ that correspond to a set of path losses. Using these cdfs and the measured L_{TS} the secondary node can find its power using (12).

IV. Performance Evaluation

We consider two cases regarding the knowledge of the correlation between the shadowing factors of the different links: full knowledge and no knowledge. In the first case, we will find the power P_S that can be used by the secondary node. In the second case, we will assume that there is no correlation and we will compute the probability of dissatisfaction.

We consider a primary network with a bandwidth of 180 kHz, a noise figure of 9 dB and a transmit power of 29 dBm. Moreover, we assume that the primary requires that $\varepsilon = 0.05$. The used propagation model constants are summarized in Table I and we assume that all shadowing factors have the same standard deviation $\sigma = 7$.

TABLE I
Constants of the propagation model [18].

	α (dB)	β (dB)	K (dB)
TS	37.6	21	113.2
TR	37.6	21	122.1
SR	40	30	141.7

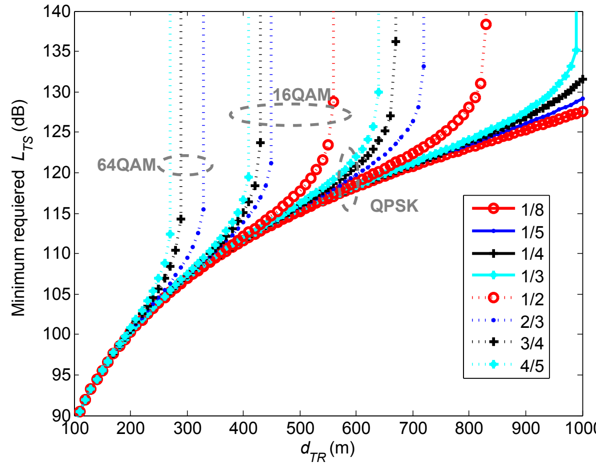

Fig. 2. Minimum required L_{TS} as a function of d_{TR} for different services (The labels represent the different coding rates).

We shall first evaluate the minimum required path loss L_{TS} that satisfies condition (18), allowing the secondary to transmit. In Fig. 2, we show the variation of this minimum threshold as a function of d_{TR} for different types of services that are defined by the used modulation and coding rate. These services require different values of γ_r as shown in Table II. The figure shows the required protection area boundaries around primary coverage area — defined by the measured path loss — for different primary services (i.e., combination of modulation and coding rate represented by γ_r) and coverage areas (i.e., d_{TR}). It shows that with a coverage area defined with a radius $d_{TR} = 250$ m, all types of modulation can be used by the primary while the secondary can be active when L_{TS} is higher than 107 dB. However, when d_{TR} is higher than 550 m the secondary can only share the spectrum with primary services using QPSK modulation and when L_{TS} is higher than 116 dB for coding rate of $1/8$ and 118 dB for coding rate of $4/5$.

We then evaluate the maximum allowed power P_S for all feasible correlation combinations satisfying (8) and considering that the secondary node knows the correlation matrix. In

TABLE II
Required γ_r for different services in an LTE system [19].

Modulation	coding rate (dB)	γ_r (dB)
QPSK	1/8	-2.6
	1/5	-0.4
	1/4	0.8
	1/3	1.5
	1/2	4.5
	2/3	6.8
	3/4	8.0
	4/5	8.7
16QAM	1/2	10.9
	2/3	14.3
	3/4	15.2
	4/5	15.8
64QAM	2/3	19.3
	3/4	21.5
	4/5	22.6

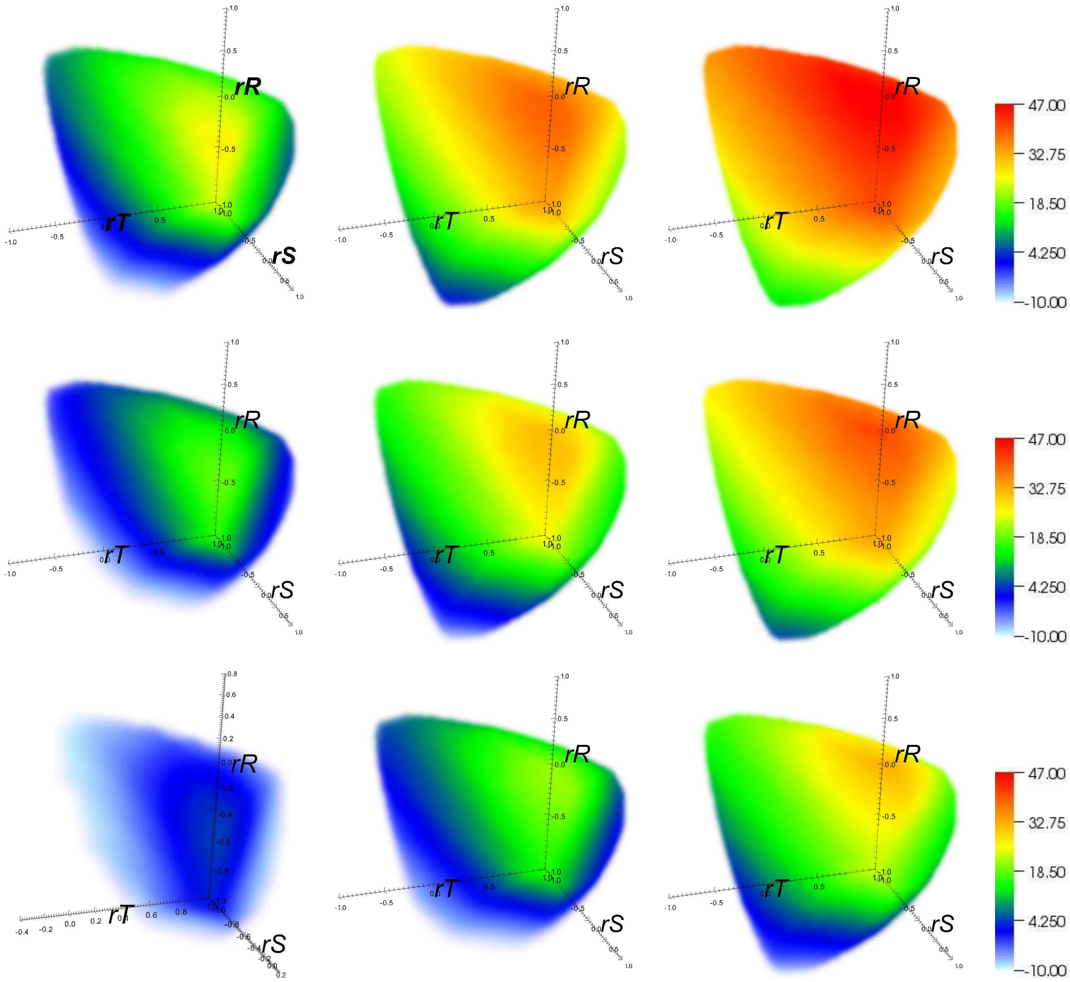

Fig. 3. The values of P_S in dBW as a function of the correlation coefficients for $d_{TR} = 500$ m. The different columns represent different values of L_{TS} (i.e., 121 dB, 127 dB and 133 dB from left to right) and the different rows represent different γ_r (i.e., -2.6 dB, 4.5 dB and 10.9 dB from top to bottom). The values of γ_r correspond to pairs (modulation, coding rate) that are respectively (QPSK,1/8), (QPSK,1/2) and (16QAM, 1/2) [19].

Fig. 3, we show the values of P_S as functions of correlation coefficients for different values of L_{TS} and γ_r. We assume that the secondary node will only transmit if $P_S \geq$ -10 dBW. This power is typical, for example, to a WiFi access point. We assume that d_{TR} is 500 m and therefore, only 16QAM modulation with coding rate of 1/2, and QPSK modulation with all coding rates can be used by the primary network from (19). Moreover, a minimum measured path loss L_{TS} of 118 dB is required based on condition (18).

The high impact of the correlation coefficient on the value of P_S can be seen in Fig. 3, where the range of the power can reach 40 dB for given γ_r and L_{TS}. Moreover, P_S is an increasing function of r_T and r_R but a decreasing function of r_S. The decreasing behavior is interesting and it is due to the fact that when r_S increases for a fixed value of L_{TS}, the distribution of L_{SR} will have a longer tail and a higher standard deviation as can be deduced from (1) and (11). This will lead to higher probability of interference for a fixed P_S and therefore for a lower P_S for a fixed threshold ε. Another interesting result is that the minimum value of P_S corresponds always to the tuple $(r_T = -1, r_R = -1, r_S = 1)$. However, the maxima appear at different tuples for different values of L_{TS} but these tuples do not depend on γ_r. These tuples are $(0.85, -0.45, -0.85)$, $(0.75, 0, -0.65)$ and $(0.7, 0.15, -0.45)$ for L_{TS} equal to 121 dB, 127 dB and 133 dB, respectively. This result is very important for the design of DSA algorithms:

- If we want to be conservative towards protecting the primary, we have to consider the tuple corresponding to the minimum P_S, i.e., $(-1, -1, 1)$.
- If we want to find the best environment to maximize P_S, we have to run the algorithm to find the best tuple based on the received value of L_{TS}.

We shall consider now the case where the secondary node does not know the correlation matrix and assume no-correlation when computing P_S. In Fig. 4, we show the box plots of Pr_{diss} as a function of L_{TS} when P_S is computed assuming that there is no correlation between the shadowing, while this correlation exists. This figure shows that the median of Pr_{diss} is always lower than ε (i.e., 0.05) in this case, and it is a decreasing function of L_{TS}. However, the range of Pr_{diss}

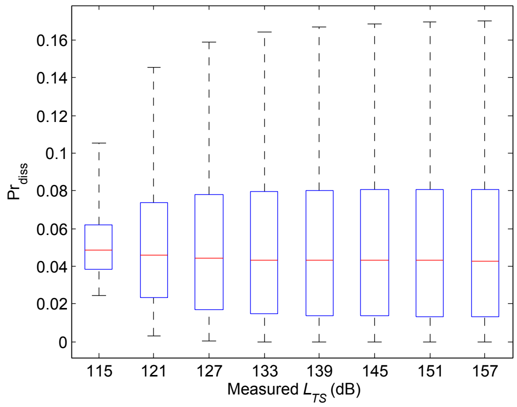

Fig. 4. The box plots of $\mathrm{Pr}_{\mathrm{diss}}$ for $\gamma_r =$ -2.6 dB. Each box plot represents the distribution of $\mathrm{Pr}_{\mathrm{diss}}$ for a given L_{TS} when P_S is computed assuming that there is no shadowing correlation, whereas the latter varies in the interval $[-1, 1]$ (the central mark is the median, the edges of the box are the 25th and 75th percentiles, an the whiskers extend to the maximum and minimum).

increases with L_{TS} and the value of the probability can reach 0.17 for some values of the correlation matrix. This result can be exploited if, for example, the shadowing correlations are uniformly distributed over the covering area of the primary network, which is not very frequent. It is interesting to see that in this case the operator can be still satisfied in average if the secondary assumes no shadowing correlation. Otherwise, the primary can find the value of the tuple (r_T, r_R, r_S) that can be used by the secondary and results in a maximum $\mathrm{Pr}_{\mathrm{diss}}$ over all real correlation coefficient lower than ε. The value of this tuple can be found using numerical methods but it is out of the scope of this paper. In the worst case, the secondary can use the tuple (-1,-1,1) but this will significantly reduce its maximum allowed transmit power by values that ranges between 7 % and 99 % from the optimal one when the correlation is known.

V. Conclusion

In this paper we have developed a general model to estimate secondary maximum allowed transmit power based on the received signal from primary transmitter in an environment with correlated shadowing. The allowed power should satisfies primary constraints on a required level of Signal to Interference and Noise Ratio (SINR) with certain probability. The model involves the characterization of three correlated links.

The results have shown that even if we know the exact correlation between the different links, the allowed power will highly depend on the detailed structure of the correlation matrix. Furthermore, if this information is not available the degradation of either primary or secondary users' quality of service is highly significant.

Another important result is the derivation of a simple equation that enables, first, the primary to know if the channel can be shared based on the SINR requirement and the coverage area, and second, the secondary to decide if it is allowed to transmit based on the measured signal.

The results show that there is a possibility to derive a correlation matrix that maximizes secondary throughput while satisfying primary constraints without knowing the real matrix. The derivation of such a matrix is left for the future work.

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