Positioning-based Framework for Secondary Spectrum Usage

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Abstract

In this paper, we introduce a framework encompassing the creation and the exploitation of secondary spectrum usage opportunities. The paper develops a complete positioning-based framework to assess the feasibility of supporting secondary communications on frequencies which are released by primary spectrum management methodologies. In particular, the paper analyzes four possible combinations, depending on known/unknown positions of primary/secondary transceivers. Afterwards, the paper focuses on a specific applicability case, where the dynamic spectrum management mechanism of a WCDMA-based network operator aims at releasing certain frequencies in a large area when possible and thus facilitating secondary exploitation of the released spectrum. Moreover, some practical examples are introduced to show the different procedures when secondary networks with infrastructure are sharing the same frequency with a mobile network. In this context, results have been obtained to assess the practical usability of the released spectrum under different conditions as well as the efficiency of different dynamic spectrum management methodologies.

***Keywords*- Secondary spectrum use; Cognitive radio; Dynamic spectrum management.**

1. Introduction

The key purpose of spectrum management techniques is to maximize the value that society gains from the radio spectrum by allowing as many users as possible while ensuring that the interference between different users remains at acceptable levels [1]. Cognitive radios, as devices with the capabilities to be aware of actual transmissions across a wide bandwidth and to adapt their own transmissions to the characteristics of the spectrum, offer great potential of developing advanced spectrum management approaches. Additionally, the pervasive presence of positioning mechanisms in mobile equipments could be very advantageous for novel forms of spectrum management.

Adaptive, agile, cognitive radios and networks have unlimited potential to spawn many innovative applications and services that can benefit society as a whole. However, many new technical, business and regulatory challenges need to be addressed to realize such potential.

Moreover, there is also a need for understanding the fundamental performance limits of these new technologies and techniques [2].

We refer to secondary spectrum usage whenever a communication takes place over a licensed frequency band by parties other than the licensee. The secondary user may get permission (and rules) to operate from the regulator or from the license-holder. The primary-secondary spectrum sharing can take the form of cooperation or coexistence. Cooperation means there are explicit communications and coordination between primary and secondary systems, whereas coexistence means there are none [3, 4]. When the spectrum sharing is based on coexistence, secondary devices are essentially invisible to the primary. Thus, all of the complexity of sharing is borne by the secondary and no changes to the primary system are needed. On the contrary, when sharing is based on cooperation, the primary and secondary interact in order to optimize the use of the spectrum. This exchange provides an opportunity for the license-holder to demand payment.

The paper focuses on primary/secondary coexistence in the form of spectrum overlay (e.g. opportunistic exploitation of white spaces in spatial-temporal domain). In this framework, this paper firstly develops a basic framework to assess the feasibility of supporting a secondary communication under different conditions. In this respect, some interesting papers can be found in the literature [4]-[7]. In [5], the authors study the possibility of coexistence of a secondary network with a primary of different scales using sensing mechanisms, where the transmission power of the secondary is fixed. In [6], the authors use the Radio Environment Map (REM) as a database in order to compute the distance between the primary transmitter and the secondary receiver and propose a simple algorithm for coexistence. In [7], the interference between primary and secondary is modeled in case the positions of primary receiver and secondary transmitter are known. With this same assumption, the authors of [4] propose an algorithm allowing secondary use of the spectrum enabled by a primary control unit. Then, as a difference from previous works, the primary/secondary characterization introduced in this paper provides a comprehensive perspective by analyzing, not only the case where the positions of the secondary transmitter and primary receiver are known (as in [6], [7] and [4]), but all other possible combinations (i.e. known/unknown positions of primary/secondary transceivers).

Afterwards, this paper focuses on a specific applicability case in which the primary user is a cellular operator who exploits dynamic spectrum management mechanisms to meet the traffic demand using the minimum needed bandwidth in each cell. One of the objectives of the dynamic spectrum management algorithm is to release certain frequencies in an as large as possible area facilitating secondary exploitation of the released spectrum. It is worth mentioning that dynamic spectrum management algorithms have been widely studied in the literature with the objective of sharing the spectrum between different networks with infrastructure having the same priorities [8]-[12]. Only recently, some works have focused on releasing frequencies in large geographical zones when it is possible so that they can be used by secondary networks such as in [13] and [14]. Finally, the practical usability of the released spectrum in the space dimension is assessed depending on the available information about primary/secondary networks. Therefore, this paper presents, to the authors' best knowledge, the first attempt to quantify at what extent the released frequencies coming from a dynamic spectrum assignment mechanism in a network can be exploited for a secondary usage, and identifies the main aspects that could increase the spatial feasibility for secondary communications.

The rest of the paper is organized as follows. Section 2 formulates the feasibility constraint to enable a secondary communication in the presence of a primary network. Section 3 develops a comprehensive framework to define the secondary spectrum usage opportunities for positioning-based scenarios. Section 4 illustrates how dynamic spectrum management solutions applied to primary network can facilitate secondary spectrum usage exploitation and presents an example

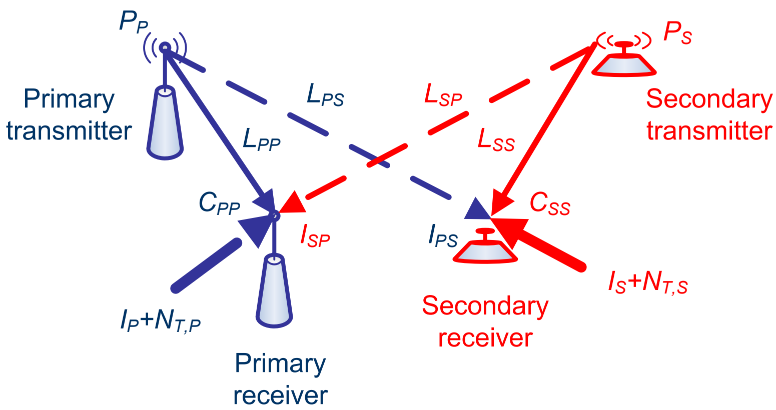

Figure 1: Generic scenario of primary and secondary networks using the same frequency (primary elements are represented by thin blue antennas while secondary ones are represented by thick red antennas).

for the coexistence of infrastructure-based primary and secondary networks. Section 5 presents the performance assessment of secondary spectrum use for the different positioning-based scenarios identified in Section 3. Results are obtained for an illustrative use case presented in Section 4. While the theoretical framework presented in Section 3 only considers path loss, some results presented in Section 5 also take into account shadowing effects. Finally, Section 6 summarizes the conclusions reached and future work.

2. Feasibility Conditions to Exploit Spatial Secondary Spectrum Usage Opportunities

A secondary communication will be feasible provided that (1) a target quality for the secondary communication is attained while (2) the secondary communication does not degrade the target quality for primary communication.

In order to analyze the above two constraints, the interference between all transceivers should be first characterized. For this purpose, figure 1 shows a generic scenario where a primary and a secondary network use the same frequency. In the following, we refer to a secondary by the subscript S and to the primary by the subscript P. Moreover, a subscript SP means that the transmitter is the secondary and the receiver is the primary, whereas PS means primary transmitter and secondary receiver.

2.1. Primary Communication

The signal to noise plus interference ratio of a primary receiver is given by:

$$\gamma_P = \frac{\frac{P_P}{L_{PP}}}{N_{\mathrm{T},P} + I_P + I_{SP}} \tag{1}$$

where L_{PP} is the path loss between primary transmitter and receiver, P_P is the transmitted power by the primary transmitter, $N_{T,P}$ is the noise power in the primary receiver, I_P is the interference received by the primary receiver from the primary network and I_{SP} is the interference received by the primary receiver from the secondary transmitter(s). If only one secondary transmits at a time, interference I_{SP} can be obtained from the transmitted power P_S by the secondary and path loss L_{SP} between the secondary transmitter and the primary receiver:

$$I_{SP} = \frac{P_S}{L_{SP}} \tag{2}$$

2.2. Secondary Communication

The signal to noise plus interference ratio of a secondary receiver is given by:

$$\gamma_S = \frac{C_{SS}}{N_{T,S} + I_S + I_{PS}} \tag{3}$$

where $N_{T,S}$ is the noise power in the secondary receiver, I_{PS} is the interference received by the secondary receiver from the primary transmitter(s) and I_S is the interference received by the secondary receiver from the secondary network. The received signal by the secondary receiver from the secondary transmitter is given by:

$$C_{SS} = \frac{P_S}{L_{SS}} \tag{4}$$

where L_{SS} is the path loss between secondary transmitter and receiver while P_S is the useful transmitted power by the secondary transmitter.

2.3. Constraints

In order to preserve the primary communication, whose target quality is reflected by a minimum signal to noise plus interference ratio, γ_{th}, the secondary transmitted power must be limited. By combining (1) and (2), this constraint can be reflected by:

$$P_S \leqslant \underbrace{\left(\frac{P_P}{L_{PP}\gamma_{\text{th}}} - I_P - N_{T,P} \right)}_{\iota_P} L_{SP} \tag{5}$$

where ι_P represents the acceptable interference level that depends only on parameters related to primary communication whereas L_{SP} depends on the properties of both primary and secondary networks. Furthermore, since the interference must be limited for all primary users, the maximum allowed power by a secondary transmitter should be expressed by:

$$P_{S,\max} = \min_{\Re} \left(\iota_P L_{SP} \right) \tag{6}$$

where $\Re$ is the set of all primary receivers.

In order to satisfy the constraint related to the target quality on the secondary communications, reflected by a signal to noise plus interference ratio higher than a given threshold $\gamma_{S,\text{th}}$, the minimum transmitted power by a secondary should be derived from (3) and (4):

$$P_{S,\min} = \underbrace{\gamma_{S,\text{th}} \left(N_{T,s} + I_S + I_{PS} \right)}_{C_{S,th}} L_{SS} \tag{7}$$

where $C_{S,\text{th}}$ represents the minimum level of received signal necessary to guarantee the target of the secondary communication.

As a result, and for a maximum transmitted power available at the secondary transmitter $P_{T,\max}$, the secondary communication is feasible in the presence of a primary network if and only if:

$$P_{S,\min} \leqslant P_{S,\max} \tag{8}$$

$$P_{S,\min} \leqslant P_{T,\max} \tag{9}$$

These two equations represent the general condition for spectrum sharing between primary and secondary networks. In the special case where the secondary element could be either inactive or has the right to transmit with only the maximum power, the latter conditions become:

$$P_{S,\max} \leqslant P_{T,\max} \tag{10}$$

3. Characterization of Spatial Secondary Spectrum Usage Opportunities

In the framework of coexistence between primary and secondary networks, the basic question to be formulated is: can the secondary user transmit and at which maximum power level in this case?

The above question may be answered through different mechanisms and strategies, with corresponding different implementations. Besides, the different mechanisms and strategies would provide different levels of accuracy in the provided answer. In this respect, two main approaches can be distinguished:

- Sensing-based approach: In this case, the assessment is performed through physical measurements obtained from the radio environment. A range of possibilities arises depending on whether the source of the measured signal is known or not, on whether it is the primary transmitter or receiver, etc. Similarly, different situations arise depending on whether the measurement entity is the secondary transmitter, secondary receiver, an independent sensor network, etc.

- Positioning-based approach: In this case, the assessment is performed based on considerations about the location of different elements in the radio scenario. Again, a range of possibilities arises, depending on which are the elements (primary/secondary transmitter/receiver) with known positions.

3.1. Assumptions and Scenarios

This section focuses on the characterization of the positioning-based approach while the sensing-based approach is left for future work. In this respect, the feasibility conditions expressed in (8) and (9) provide the framework to answer the basic question formulated above. The analysis of the feasibility conditions is complex, since many parameters are involved. In the following, some considerations about different parameters are introduced:

- The acceptable interference level ι_P depends only on primary network configuration and parameters. In general, this parameter can be variable over time and space and can be receiver-specific. Nevertheless, practical engineering considerations may suggest defining

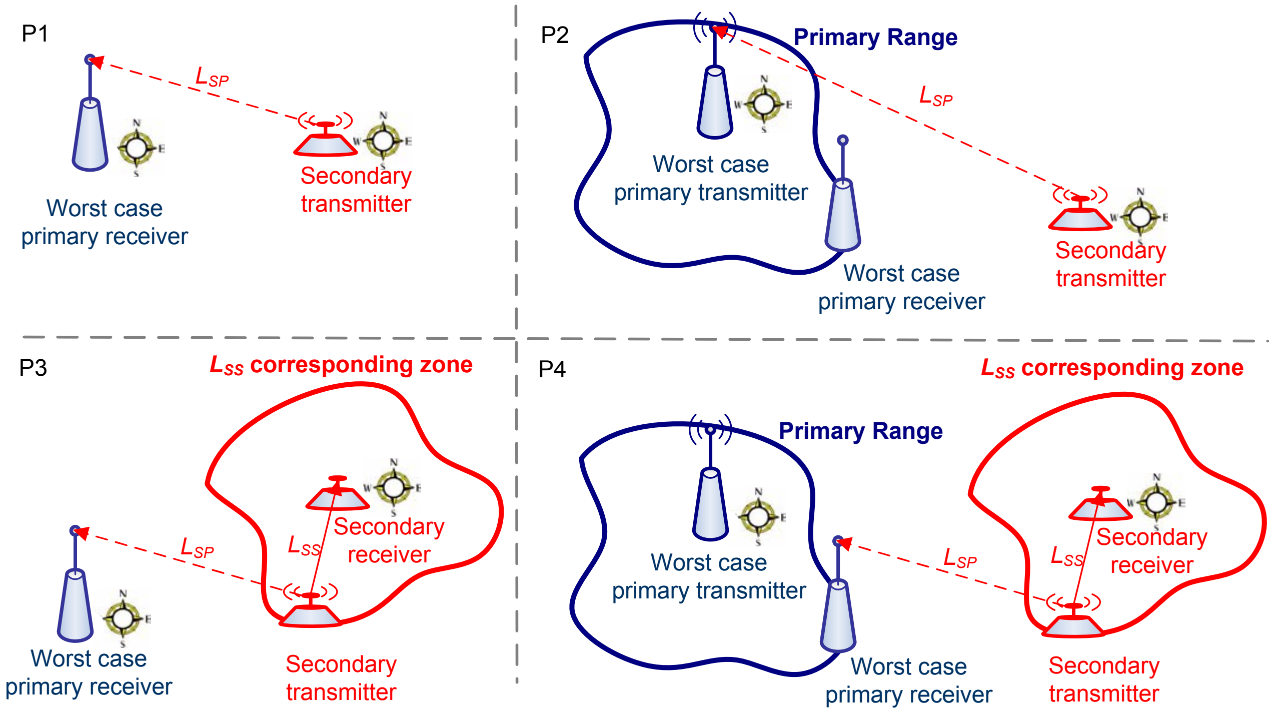

Figure 2: Illustrative examples of scenarios P1, P2, P3 and P4. The compass near to a transceiver means that the position of this transceiver is known.

ι_P as a fixed value for a given primary network. In this case, it could be specified e.g. such as in [15]: "Interference at the receiver should not exceed X dBW for more than $Y\%$ of time [at no more than $Z\%$ of locations]". In this paper, we assume that the value of ι_P is fixed and known.

- The value of $C_{S,\text{th}}$ will also vary over time and space and will be receiver-specific. This parameter could be available at the secondary receiver through standard measurements over the communication link. In this contribution, we assume that this value is known.

- The maximum transmitted power available at the secondary transmitter $P_{T,\max}$ is assumed to be known.

Based on these considerations, four different scenarios, illustrated in figure 2, are identified for the positioning-based approach and analyzed in the following:

- Scenario P1: Secondary transmitter and primary receiver positions are known.

- Scenario P2: Secondary transmitter and primary transmitter positions are known

- Scenario P3: Secondary receiver and primary receiver positions are known.

- Scenario P4: Secondary receiver and primary transmitter positions are known.

In all scenarios, we denote by Δ the distance between the primary and secondary transceivers with known positions. Then, given that Δ is known, the following subsection aims at estimating the corresponding value of L_{SP} for the four scenarios. The estimation of L_{SP} is performed considering the worst case for primary receiver and secondary transmitter. By assuming that

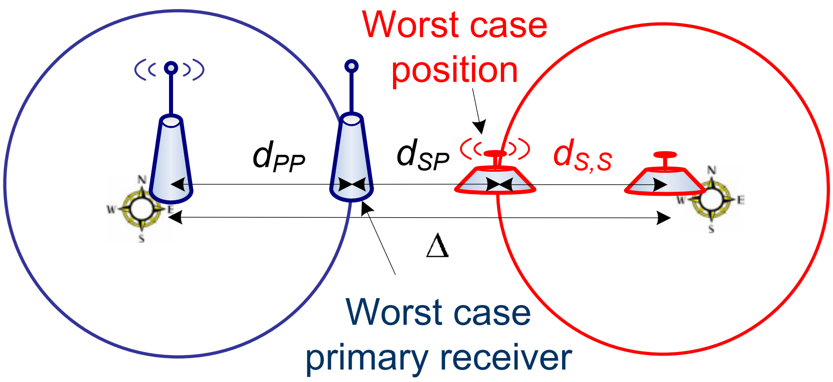

Figure 3: Estimation of distance d_{SP} in scenario P2.

$C_{S,\text{th}}$ and ι_P are known, a secondary communication allowing a given range reflected by path loss L_{SS} is considered feasible when L_{SP} is estimated if it satisfies (6), (7) and (8):

$$L_{SP} \geqslant \frac{C_{S,\text{th}} L_{SS}}{\iota_P} \tag{11}$$

Alternatively, the maximum L_{SS} allowed for the secondary communication for a given L_{SP} can be estimated by reversing inequality (11) and taking into account condition (9).

3.2. Estimation of the Value of L_{SP} in Each Scenario

We represent the propagation path loss between two transceivers X and Y separated by a distance x as a continuous function $F_{XY}(x)$ in the interval $]0, +\infty[$. This function depends on transceivers, propagation environment characteristics, and frequency range. Therefore, it is specific for each transceiver couple and each environment. Notice that $F_{XY}(x)$ could be defined e.g. with the support of a planning tool.

In scenario P1, the distance between the secondary transmitter and the primary receiver is known (Δ) and, therefore, the path loss between them, L_{SP}, is given by:

$$L_{SP} = F_{SP}(\Delta) \tag{12}$$

In scenario P2, the maximum allowed power should be computed assuming that a primary receiver is at the worst case in terms of the experienced interference from the secondary transmitter. Considering that the primary transmitter range defines a circle and the secondary is outside the primary coverage area, the worst-case primary receiver is at the intersection of the primary coverage area, which is a circle of radius d_{PP}, and the line connecting the primary and the secondary transmitters as shown in figure 3. Therefore, the distance between the secondary transmitter and the worst-case primary receiver, d_{SP}, is:

$$d_{SP} = \Delta - d_{PP} \tag{13}$$

Consequently, L_{SP} can be written as:

$$L_{SP} = F_{SP}(\Delta - d_{PP}) \tag{14}$$

In case the secondary transmitter is inside the primary coverage area, then $d_{SP} = 0$ and the secondary transmission is not allowed.

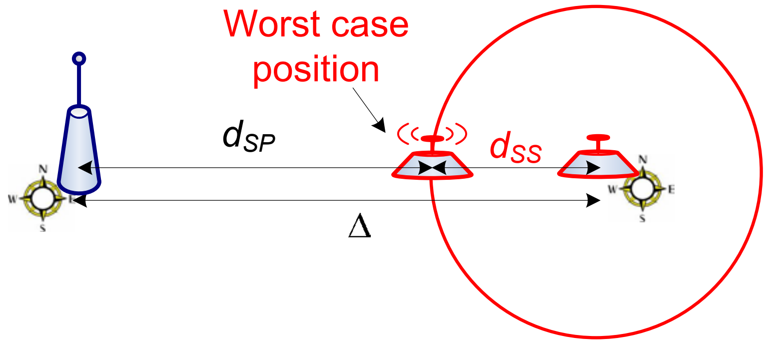

Figure 4: Estimation of distance d_{SP} in scenario P3.

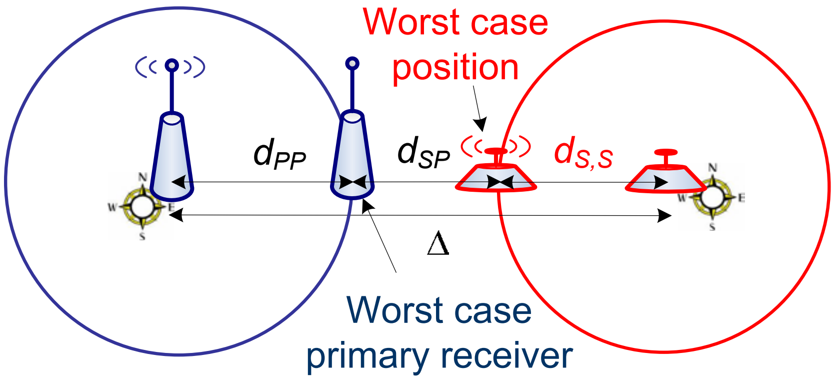

Figure 5: Estimation of distance d_{SP} in scenario P4.

In scenario P3, depicted in figure 4, L_{SP} will be calculated for the worst-case location of the secondary transmitter towards primary receiver since the distance between primary receiver and secondary transmitter is not known. This worst-case location introduces the highest level of interference to the primary network and corresponds to the intersection of the secondary range, which is a circle of radius d_{SS}, and the line connecting the primary and the secondary receivers as shown in figure 4. Therefore, path loss L_{SP} between the secondary transmitter and the primary receiver could be written as:

$$L_{SP} = F_{SP}\left(|\Delta - d_{SS}|\right) \tag{15}$$

Notice that, in (15), the absolute value is considered since the secondary transmitter could be farther than the primary receiver (i.e. $d_{SS} > \Delta$).

In scenario P4, the unknown positions of the secondary transmitter and primary receiver are considered to be at the worst case as shown in figure 5. Therefore, path loss L_{SP} between the secondary transmitter and the primary receiver could be written as:

$$L_{SP} = F_{SP}\left(|\Delta - d_{SS}| - d_{PP}\right) \tag{16}$$

From this analysis, we can deduce that the value of d_{PP} and d_{SS} should be known. Otherwise, no secondary transmission could be allowed in scenarios P2, P3 and P4.

All notations used in this paper are summarized in Table I.

Table I: Index Notations.

Variables	Description
C_{PP}	The useful received signal by the primary
C_{SS}	The useful received signal by the secondary
$C_{S,\text{th}}$	The minimum level of received signal necessary to guarantee the target of the secondary communication
$F_{XY}(x)$	The propagation path loss between two transceivers X and Y separated by a distance x as a continuous function
I_P	The interference received by the primary receiver from the primary network
I_{PS}	The interference received by the secondary receiver from the primary transmitter(s)
I_{SP}	The interference received by the primary receiver from the secondary transmitter(s)
I_S	The interference received by the secondary receiver from the secondary network
L_{PP}	The path loss between primary transmitter and receiver
L_{PS}	The path loss between the primary transmitter and the secondary receiver
L_{SP}	The path loss between the secondary transmitter and the primary receiver
L_{SS}	The path loss between secondary transmitter and receiver
$N_{T,P}$	The noise power in the primary receiver
$N_{T,S}$	The noise power in the secondary receiver
P_P	The useful transmitted power by the primary
P_S	The transmitted power by the secondary
$P_{S,\max}$	The maximum allowed power by a secondary transmitter due to primary constraints
$P_{S,\min}$	The minimum transmitted power by a secondary to meet secondary constraints
$P_{T,\max}$	The maximum transmitted power available at the secondary transmitter
d_{PP}	Primary coverage area radius
$d_{SP}^{(s)}$	The distance between the secondary transmitter and the worst-case primary receiver considering shadow fading
d_{SS}	Secondary range
$d_{SS}^{(s)}$	Secondary range with shadow fading
d_{SP}	The distance between the secondary transmitter and the worst-case primary receiver
Δ	The distance between the primary and secondary transceivers with known positions
$t_{e_{XY}}$ (σ_{XY})	Shadowing margin between transmitter X and receiver Y with standard deviation (σ_{XY})
K_{XY}, β_{XY}, α_{XY}	Path loss constants computed using the NLOS-LOS models
ι_P	The acceptable level of interference by primary receiver
γ_{th}	The minimum signal to noise plus interference ratio of the primary
$\gamma_{S,\text{th}}$	The minimum signal to noise plus interference ratio of the secondary

4. Case Study: Infrastructure-based Primary and Secondary Networks

The realization of scenarios P1 to P4 would be related to the practical implementation of the primary/secondary networks and its corresponding mechanisms to enable secondary communications. In the following, we consider a primary mobile network composed of base stations and mobile terminals and that owns a license for frequency f. This network could be connected to a spectrum broker that communicates the necessary information and conditions to secondary networks in order to access to the licensed frequency. Another option would be a direct connection between the primary and secondary networks. The secondary network is composed of several access points and portable terminals spread out among primary base stations. Moreover, a secondary central unit, connected to both the spectrum broker (or directly to the primary network) and the secondary access points, is responsible for the activation/deactivation of the access points. In the coexistence framework, the positions of the access points are known by the central unit to allow spectrum sharing without introducing harmful interference to the primary. Therefore, the central unit activates different sets of secondary access points depending on the information about the primary base stations that are using frequency f, the value of ι_P and propagation loss information.

As discussed in previous sections, a secondary communication over a licensed frequency band exploiting the spatial dimension is sustained by sufficient radio-electrical distance between secondary transmitter and primary receiver. Therefore, the larger the geographical area where a given band is not used the better the opportunity for secondary communications to become feasible.

Frequency planning on primary network determines the spatial usage of frequencies. Network deployment and planning responds to quality and coverage targets (e.g. broadcast networks) as well as traffic demand (e.g. mobile networks). Focusing on mobile networks, dynamic planning strategies allow better adaptation of the frequency assignment to traffic demand changes in minute/hour time scales. In this respect, a methodology is developed in [13, 16, 17] for WCDMA-based networks, whose objective is three folds:

- Detect significant variations in traffic distribution.
- Determine the needed number of frequencies for each cell that satisfies QoS requirements.
- Release some spectrum blocks when and where possible, in order to facilitate secondary spectrum usage.

In the mentioned works, the problem of spectrum assignment is transformed into an optimization problem with constraints related to the allowed transmitted powers and outage probability. While spectrum efficiency can be considered as a reasonable function to maximize, the authors introduced in [13] the so-called Useful Released Surface (URS) as the function to maximize. For a given frequency assignment, the URS is defined by

$$\mathrm{URS} = \sum_{f=1}^{F} W^{(f)} \sum_{c=1}^{C^{(f)}} S_c^{(f)} \omega_c^{(f)} \tag{17}$$

where $W(f)$ is the bandwidth of frequency f, $C(f)$ is the set of non-contiguous areas where the frequency f could be used by a secondary network, $S_c^{(f)}$ is the surface of the area c in relation with frequency f and $\omega_c^{(f)}$ is the weight given to this area depending on the expected number of secondary users in this area to account for the fact that the release of frequencies will be more effective in areas with a significant number of potential secondary users. In [13], $\omega_c^{(f)}$ is considered to be equal to the ratio between the surface $S_c^{(f)}$ and the total surface. The URS represents the surface where a released frequency can be used by the secondary network and, therefore, dynamic spectrum management strategies considering URS metric would facilitate the creation of secondary spectrum usage opportunities.

The primary network can either use a spectrum methodology that maximizes the spectrum efficiency (method 1) or a methodology that maximizes the URS (method 2). Moreover, the proposed methodology is based on coupling matrix properties that were introduced in [16] to reflect inter-cell interactions and uses simulated annealing meta-heuristic to find a near-optimum solution.

In the following, we introduce an example of the performed procedure for spectrum sharing at frequency f as illustrated in figure 6. In this example, an access point can be either active with its maximum power and therefore with maximum range if primary constraints allow it or inactive otherwise. The different steps of this procedure are:

1. The spectrum management algorithm is executed in the primary network as a response to a triggering event reflecting significant variations in inter-cell interactions.
2. The spectrum management algorithm finds the best frequency-to-cell assignment Λ and computes the acceptable level of interference ι_P.
3. d_{PP}, Λ and ι_P together with the positions of the base stations of set Λ and primary transmission direction (i.e. uplink or downlink) are sent to the spectrum broker who sends them to the secondary central unit.

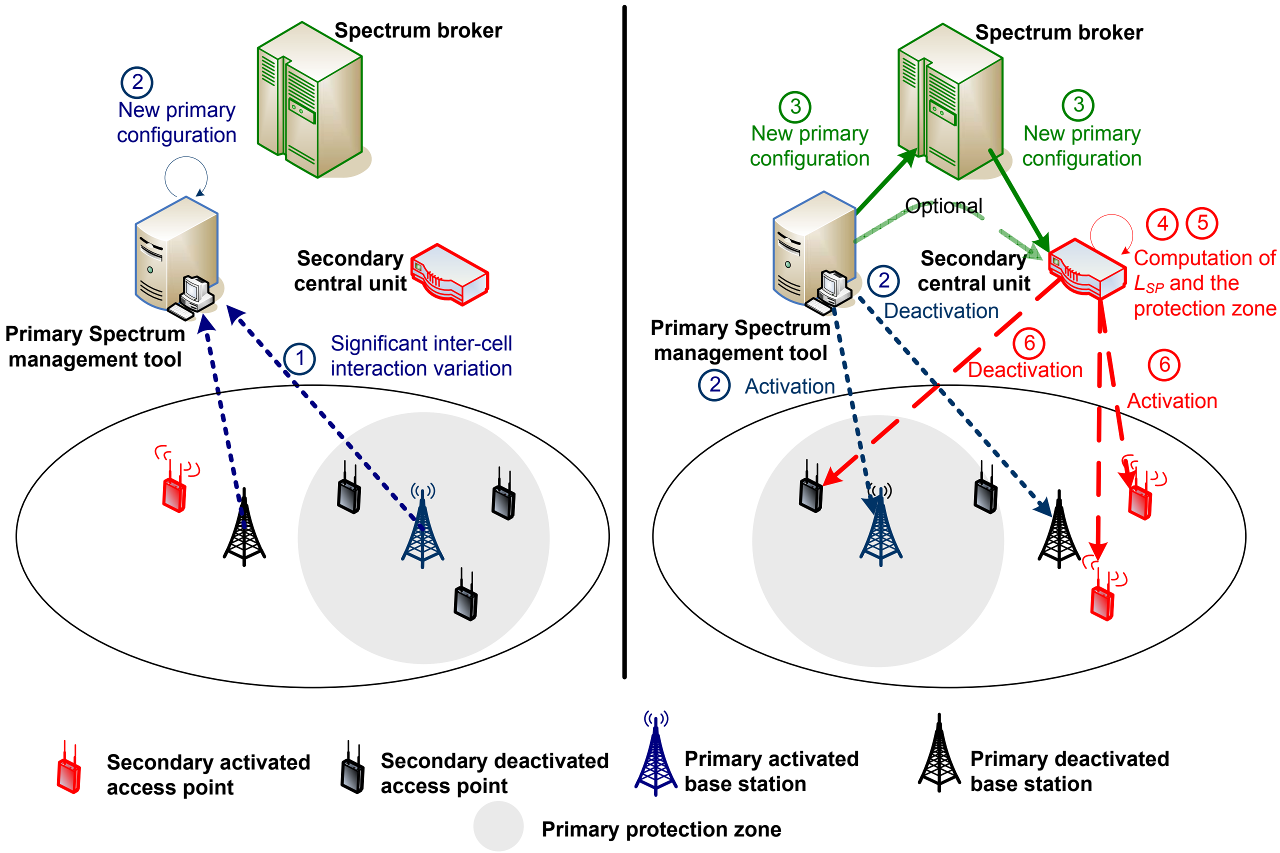

Figure 6: An illustrative example of the activation/deactivation procedure in a secondary network with infrastructure.

4. The central unit computes the minimum value of L_{SP} using (11) and based on the position of the primary active base stations, the values of ι_P and d_{PP}, the values of $C_{S,\text{th}}$ and L_{SS} and the propagation model. In this case, the value of L_{SS} is estimated as the maximum path loss for which the signal can be received with level $C_{S,\text{th}}$ when the transmitter uses $P_{T,\max}$:

$$L_{SS} = \frac{P_{T,\max}}{C_{S,\text{th}}} \tag{18}$$

   Then, the value of d_{SS} is computed as $F_{SS}^{-1}(L_{SS})$.

5. The central unit determines the protection zone depending on transmission direction. That is, it is the minimum distance computed using (12) and (15) if the primary is active in uplink or using (14) and (16) if the primary is active in downlink.

6. The central unit activates the access points outside the protection zone and deactivates the ones inside it.

7. The activated access points start to transmit their pilot channels with the maximum power using frequency f whereas the deactivated ones stop this transmission.

5. Simulation and Results

One of the possible applications of the spatial release of frequencies achieved with the dynamic planning strategy presented in Section 4 would be the exploitation of the released spectrum

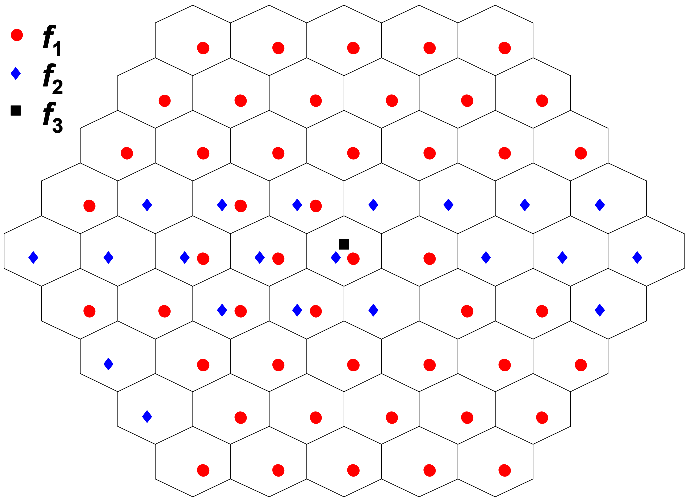

Figure 7: Frequency assignment to cells (the circles, the diamonds and the square mean that respectively frequencies f_1, f_2 and f_3 are used by the cell).

by a secondary system. In this respect, the framework developed in Section 3 can be used to quantify the areas and corresponding maximum transmitted powers where the constraints defined in Section 2 are met, depending on known positions of certain primary/secondary transceivers. The analysis developed in the present section will assess at which extent different degrees on primary/secondary knowledge will lead to different degrees of available surface to support secondary communications. Finally, an initial assessment of the influence of shadow fading will be introduced.

Figure 7 shows the frequency assignment to cells using the spectrum management methodology that maximizes the URS in a macro-cellular scenario of 61 cells with 1 Km radius. The primary mobile operator has three licensed frequencies and about 5000 mobiles around the scenario. All cells have the same load, except the central cell (that has 4 times more load) and the 6 cells at the left of the central cell (that have two times more load). Moreover, the spectrum management methodology aims at keeping the outage probability lower than 5% in all cells. This scenario and the corresponding assumptions are fully described in [13].

In the following, we consider that the primary network uses the spectrum assignment of Figure 7 for both uplink and downlink and that the secondary network is formed by an access point with known position and a mobile terminal. Moreover, we consider the example of section 4 as a deployment scenario.

In all simulations, we consider a propagation model that is a combination of the Xia-Bertoni model for NLOS and free space model for LOS as in [18][19]. For distance above $d_{\max,XY}$ between transceivers X and Y, the NLOS model is used. For distance below $d_{\min,XY}$, the LOS path loss model is used. Between $d_{\min,XY}$ and $d_{\max,XY}$, the NLOS model is selected with a probability that increases linearly with distance [18]. This model is chosen since it is able to take into account all types of propagation losses such as the propagation loss between base stations and propagation loss between mobiles in addition to usual propagation loss between a base station and a mobile. Given a frequency f in GHz and distance d between transmitter X and receiver Y, path loss L_{XY} is given by:

$$L_{XY} = 10^{\frac{(K_{XY}+\beta_{XY}\log_{10}(f)+\alpha_{XY}\log_{10}(d_{XY}))}{10}} \quad (19)$$

where K_{XY}, β_{XY} and α_{XY} are constants computed using the NLOS-LOS models. The characteristics of the transceivers needed for the computation of the path losses inspired by [18, 19] and the obtained propagation constants are collected in Table II and Table III, respectively.

Table II: Parameters for path loss computation.

Buildings mean height	12 m
Separation between building rows	80 m
BS height	27 m
Access point height 3 m	
Mobile height	1.5 m
Horizontal distance between the access point and the diffracting edge	80 m
Horizontal distance between the mobile and the diffracting edges	15 m
Frequency	2 GHz

5.1. Impact of Δ and ι_P

Let us consider that an 802.11 secondary mobile is requesting a communication using frequency f_3 in the scenario of figure 7 such that $C_{S,\text{th}} = -85$ dBm and $P_{T,\max} = 20$ dBm, which corresponds to a secondary coverage area of 17×10^{-3} Km^2 or a range of 75 m taking into account the parameters of Table II without shadowing effect. This communication is enabled if the distance between the base station and the access point is higher than a given value as was introduced in the previous sections. In figure 8, we show the value of allowed secondary range (d_{SS}) as a function of distance Δ between the base station and the access point, and acceptable interference level ι_P for the four scenarios. In these figures, we can distinguish three zones:

- The full coverage zone (in white) corresponds to the couple (Δ, ι_P) for which the value of d_{SS} is at its maximum (i.e. 75 m). In this zone, secondary transmitted power and its range are limited by $P_{T,\max}$ and the secondary can act as if no primary users exist.
- The forbidden zone (in black) is the zone to the couple (Δ, ι_P) where the value of d_{SS} is 0 m. In this zone, no secondary transmission is allowed.
- The power limited zone (with colors) corresponds to the couple (Δ, ι_P) where the value of d_{SS} is lower than 75 m but not null. In this zone, secondary transmitted power and its range are limited by primary constraints and not by $P_{T,\max}$.

Notice that a forbidden zone with a radius of 1 km, which is the radius of the primary coverage zone d_{PP}, appears only in scenarios P2 and P4 since no secondary users are allowed to transmit inside the primary coverage zone as was explained in section 3. In all scenarios, the secondary is able to have successful communication with full coverage considering high primary constraint (e.g.$\iota_P = -110$ dBm) when the separation distance Δ is only 1.9 Km. This means that for the considered parameters, at least 152 Km2 of the total 158 Km^2 (i.e. 96%) in the scenario of Figure 7 can be used by the considered secondary network for frequency f_3. Moreover, a minimum distance $\Delta = 1.1$ Km is necessary in scenarios P2 and P4 whereas a distance of only $\Delta = 0.1$ Km is necessary in some cases of scenarios P1 and P3. However, the needed distance Δ in scenarios P1 and P3 increases more drastically than in scenarios P2 and P4 when ι_P decreases, especially in scenario P1 where the secondary cannot have a full coverage

Table III: Constants of the propagation model.

	α (dB)	β (dB)	K (dB)	$d_{\min}$ (m)	$d_{\max}$ (m)
BS - AP	37.6	21	113.2	60	100
BS - MT	37.6	21	122.1	20	100
AP - MT	40	30	141.7	2.5	50
MT - MT	40	30	141.7	2.5	50
LOS	20	20	92.45	-	-

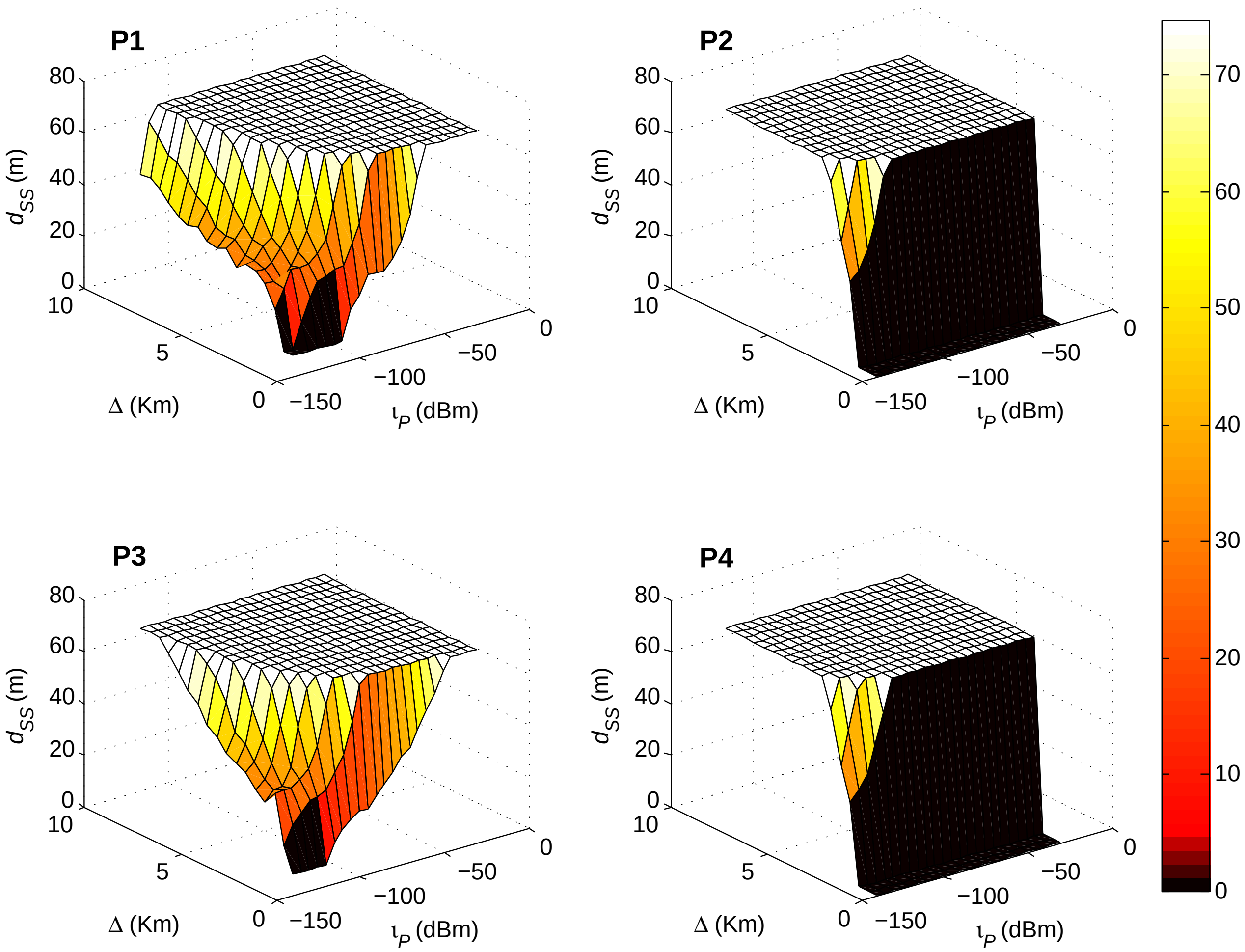

Figure 8: The allowed secondary range (d_{SS}) as a function of ι_P and Δ for $P_{T,\max} = 20$ dBm and $C_{S,\text{th}} = -85$ dBm. (The colorbar represents the mapping between the color and the value of the computed range in m).

even at a distance of 7.8 Km (the limits of the system in Figure 7) when ι_P is approximately -140 dBm or lower.

The differences in the results of the four scenarios are mainly due to two reasons: (1) the different propagation losses between the secondary transmitter and primary receiver reflected by the different values of K_{XY}, α_{XY} and β_{XY} in Table III and (2) the types of primary and secondary transceivers with known positions. In the latter, if the known position is related to a primary transmitter (i.e. scenarios P2 and P4) or a secondary receiver (i.e. scenarios P3 and P4), worst-case considerations about the position of the unknown transceivers are made, leading to a reduction in secondary range. This explains why the results of P1 are close to the results of P3 even though the propagation losses between the primary receiver and the secondary transmitter are higher in P3. For instance, at the lowest value of Δ (i.e. 0.1 Km), scenario P1 can allow full coverage for relatively low values of P (i.e. -60 dBm approximately) whereas a full coverage in scenario P3 allows a full coverage for higher value of ι_P (i.e. -45 dBm approximately) for the same distance. Therefore, the higher radio-electrical isolation in scenario P3 compared to scenario P1 facilitates the feasibility of the secondary communication.

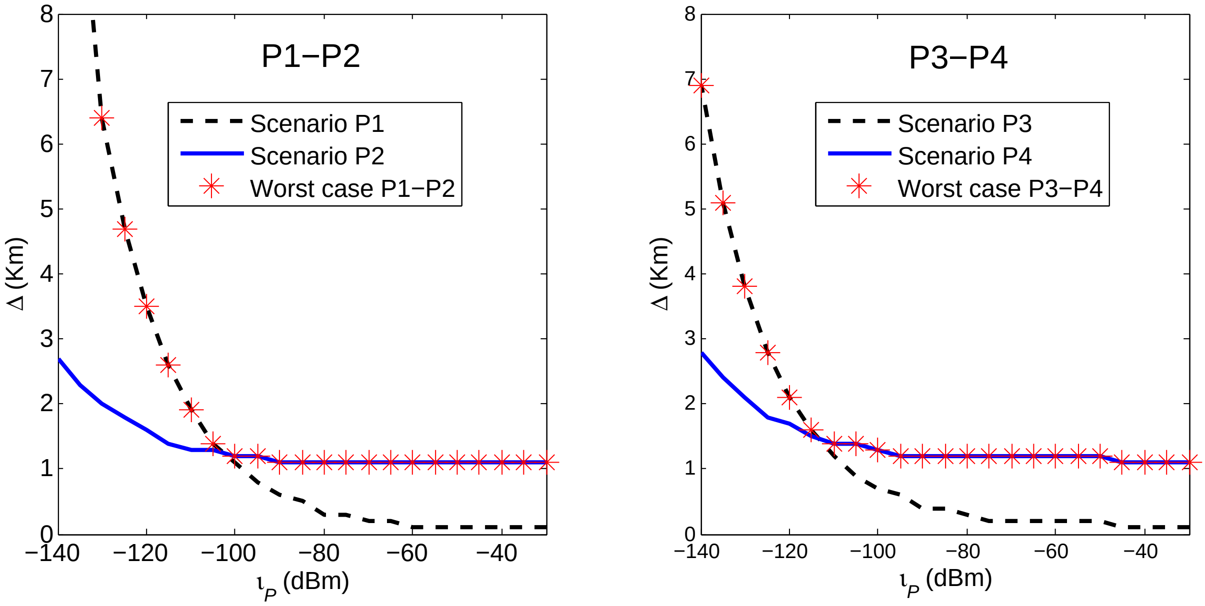

Figure 9: Needed distance Δ that allows a full secondary coverage as a function of the acceptable interference level ι_P when the type of the primary with known position is known/unknown by the secondary.

5.2. Impact of Additional Information: Type of Primary Transceiver with Known Position

Let us consider again f_3 in figure 7 as a candidate frequency for a unidirectional secondary communication in a scenario where the positions of a primary base station and a secondary access point are known. If the access point is intending to transmit using this frequency, this corresponds to either scenario P2 or P1 depending on whether f_3 is used in downlink or uplink direction by the primary network. It is worth noting that if the secondary central unit does not know whether f_3 is used by the base station to transmit (downlink) or to receive (uplink), the feasibility conditions should consider the worst case between P1 and P2. A similar analysis could be done for scenarios P3 and P4. In the following, we refer to these scenarios by worst-case P1-P2 and worst-case P3-P4.

In figure 9, we show the minimum distance Δ required to enable full secondary coverage when the information about the primary transceiver with known position is not available (i.e. worst-cases P1-P2 and P3-P4). In the same figures, we show also the required distance when this information is available (i.e. P1, P2, P3 and P4) in order to compare it with the worst case. These results show that the lack of information about the type of primary transceiver with known position will lead to significant increase in the separation distance in some cases. Specifically, higher distances are needed in case the position of the primary receiver is known (P1) when ι_P is higher than -105 dBm. For instance, the needed distance should be always higher than 1 Km in the worst-case P1-P2 whereas it could be only 0.1 Km if the central unit knows that it is scenario P1. Moreover, higher distances are needed in case the position of the primary transmitter is known (P2) when ι_P is lower than -105 dBm. For instance, if the primary is active in uplink and can handle low values of ι_P (i.e. $\iota_P = -140$ dBm), the secondary communication is not feasible even for $\Delta = 8$Km in the worst-case P1-P2, whereas a full coverage could be granted at a distance of only 2.7 Km if the central unit knows that it is scenario P2. It could be noted that for this scenario, the results have shown that further knowledge about the primary may lead to substantial increase in the useful area for secondary communications.

5.3. Impact of shadowing

Shadowing effect has not been considered in the previous results. At this point, let us consider a shadowing margin [20] of $t_{e_{XY}}(\sigma_{XY})$ dB for the path loss between transmitter X and receiver Y, where e_{XY} corresponds to the probability that the shadow fading is higher than $t_{e_{XY}}$ dB and σ_{XY} is the shadowing standard deviation that depends on transceivers and environment characteristics. For a given probability e_{XY}, the margin $t_{e_{XY}}(\sigma_{XY})$ for a log-normal shadowing is given by:

$$t_{e_{XY}}(\sigma_{XY}) = \sqrt{2}\sigma_{XY}\mathrm{erf}^{-1}(1-2e_{XY}) \tag{20}$$

where erf is the error function.

This shadowing margin should be taken into account each time the function F_{XY} is used. In particular, F_{XY} is used to compute d_{SS} knowing L_{SS} and to compute dSP knowing L_{SP}. In the following, we refer by $d_{SS}^{(s)}$ to the distance between the secondary access point and the secondary terminal at the edge of access point range computed using the value of L_{SS} when the shadow fading is considered. Moreover, we refer by $d_{SP}^{(s)}$ the distance between the secondary transmitter and the primary receiver computed using the estimated value of L_{SP} and considering the worst case of shadow fading (i.e. lowest value) to reflect the worst case of interference between secondary transmitter and primary receiver.

In this context, a margin of $t_{e_{SS}}(\sigma_{SS})$ dB should be extracted from $F_{SS}\left(d_{SS}^{(s)}\right)$ to find the maximum range of the secondary access point considering shadowing effect, whereas a margin of $t_{e_{SP}}(\sigma_{SP})$ dB should be extracted from $F_{SP}\left(d_{SP}^{(s)}\right)$. Therefore, the path losses L_{SS} and L_{SP} could be written as functions of distances $d_{SS}^{(s)}$ and $d_{SP}^{(s)}$ when the shadowing is considered as:

$$\begin{aligned} L_{SS} &= F_{SS}\left(d_{SS}^{(s)}\right) - t_{e_{SS}}(\sigma_{SS}) \\ L_{SP} &= F_{SP}\left(d_{SP}^{(s)}\right) - t_{e_{SP}}(\sigma_{SP}) \end{aligned} \tag{21}$$

By comparing (21) to the case where shadowing is not considered (i.e.$t_{e_{SS}}(\sigma_{SS})$ and $t_{e_{SP}}(\sigma_{SP})$ are null) and some simple mathematical manipulations to (12), (14), (15) and (16), we obtain:

$$\begin{array}{ll} \Delta^{(s)} = \xi_{SP}\Delta & \text{scenario P1} \\ \Delta^{(s)} = \xi_{SP}(\Delta - d_{PP}) + d_{PP} & \text{scenario P2} \\ \Delta^{(s)} = \xi_{SP}(\Delta - d_{SS}) + \xi_{SS}d_{SS} & \text{scenario P3} \\ \Delta^{(s)} = \xi_{SP}(\Delta - d_{PP} - d_{SS}) + d_{PP} + \xi_{SS}d_{SS} & \text{scenario P4} \end{array} \tag{22}$$

where $\Delta^{(s)}$ is the needed distance between primary and secondary transceivers with known positions when the shadowing effect is considered and ξ_{XY} is defined by:

$$\xi_{XY} = 10^{\frac{t_{e_{XY}}(\sigma_{XY})}{\alpha_{XY}}} \tag{23}$$

In figure 10, $\Delta^{(s)}$ and $\Delta^{(s)}/\Delta$ are plotted as functions of the acceptable error in the presence of shadowing for specific values of $P_{T,\max}$, $C_{S,\mathrm{th}}$ and ι_P. The values of the standard deviation between transceivers are inspired by [19] and collected in Table IV. The same values of parameters as in the previous section are considered here leading to Δ equal to 0.8 Km, 1.2 km, 0.6 Km and 1.3 Km for scenarios P1, P2, P3 and P4, respectively. Moreover, we assume that the probability e_{SS} is 0.1 corresponding to a shadowing margin of 12.8 dB for the secondary range. The results show that the highest $(\Delta^{(s)}/\Delta)$ is obtained for scenarios P1 and P3. This is due to the fact that the value of α_{SP} is lower in case that the path loss is considered between a base station and a mobile or an access point than the other cases as can be seen in Table III.

Table IV: Shadowing standard deviation.

	BS - AP	BS - MT	AP - MT	MT - MT
σ_{XY}(dB)	6	10	10	12

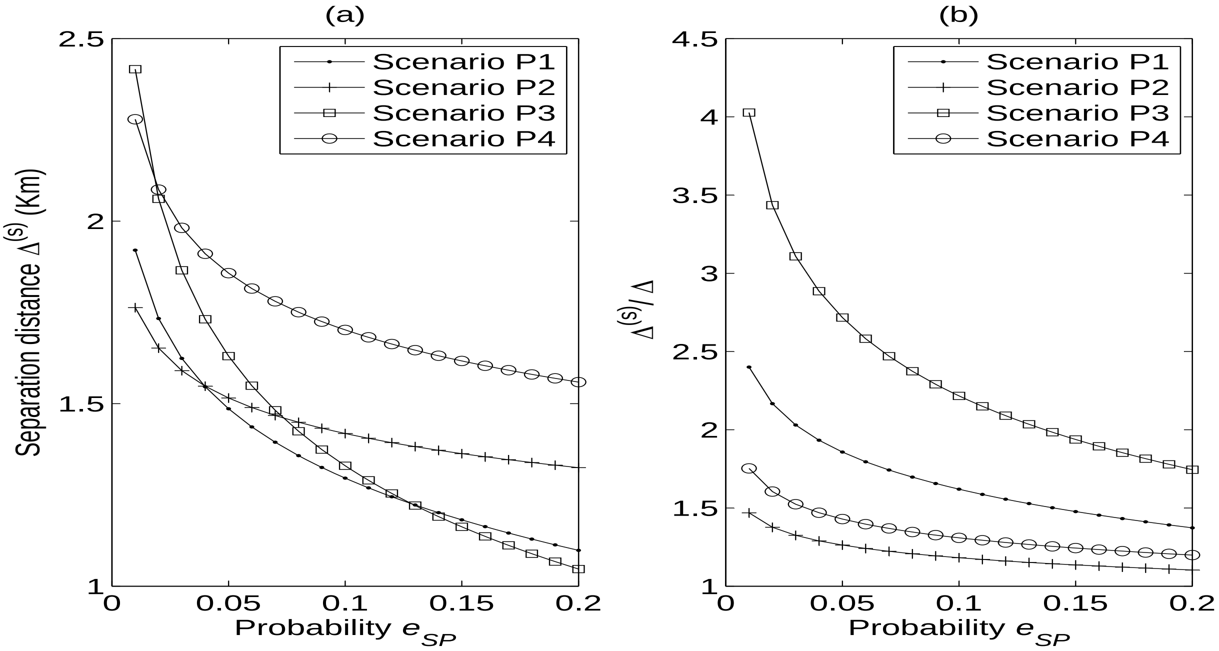

Figure 10: $\Delta^{(s)}$ and $\Delta^{(s)}/\Delta$ for $P_{T,\max} = 20$ dBm, $C_{S,\text{th}} = -85$ dBm, $\iota_P = -95$ dBm, and $t_{e_{SS}}\,(\sigma_{SS}) = 12.8$ dB.

5.4. Impact of Spectrum Management Methodologies

In the following, we study the impact of spectrum management methodologies on the possibility of releasing frequencies that could be used by secondary networks. To this end, we consider that the primary is active in uplink (P1 and P3) and that the secondary network uses time division duplex mode for its transmission. Therefore, each primary frequency can be used for both transmission directions in the secondary and the maximum separation distance (Δ) computed in P1 and P3 should be considered. Moreover, we consider the same conditions of the previous subsection and the same protection distance that corresponds to 0.8 Km when shadowing effect is not considered and 2.4 Km when it is considered (i.e. the maximum between the needed separation distance in P1 and P3). In Table V, we show the results obtained in terms of URS when method 1 or method 2 introduced in section 4 is applied to the primary network that has the licenses of three frequencies. Method 2 is able to highly increase the URS from 35 to 666 km2MHz when compared to method 1 that maximizes the spectrum efficiency. It can be noticed that even when the shadow fading is considered, a large surface can be used by the secondary with method 2. Moreover, we can see that the difference between method 1 and method 2 decreases when the shadow effect is not considered.

6. Conclusions and Future Work

This paper has focused on wireless communication scenarios where a licensed frequency band can be used by parties (secondary users) other than the licensee (primary user). Standing

Table V: Comparison between spectrum management methodology results from the point of view of reusability of the frequency by a secondary.

	URS (Km^2MHz)
Method 1	552
Method 2	991
Method 1+Shadowing	35
Method 2+Shadowing	666.5

on some preliminary concepts, the paper has developed a complete positioning-based framework to assess the feasibility of supporting secondary communications. In particular, the paper has analyzed four possible combinations, depending on known/unknown positions of primary/secondary transceivers. The involved parameters related to the primary and the secondary communications have been clearly identified.

Afterwards, the paper has focused on a specific applicability case, where a primary cellular operator exploits dynamic spectrum management mechanisms leading to the release of certain frequencies in a large area when possible and thus facilitating secondary exploitation of the released spectrum. In this context, results have been obtained to assess the practical usability of the released spectrum under different conditions. A candidate frequency for secondary usage will show different degrees of spatial usability depending on aspects such as the duplexing mode and the frequency assignment in primary and secondary communications as well as the shadowing effect. Results have shown that better exploitation of secondary communication can be achieved when the primary element with known position is known to be active as a receiver or as a transmitter. Furthermore, results have revealed the relevance of the different radio-electrical isolation depending on the types of involved transceivers (e.g. base station to base station, base station to mobile), leading to different feasibility levels on secondary communication. The impact of the shadowing factor has been analyzed and the obtained results have assessed the loss in the area surface where a secondary can be deployed. This loss depends on the specific scenario and the propagation loss factors between the secondary transmitter and primary receiver. Finally, the impact of spectrum management methodologies has been studied. Simulation results have shown that the methodology aiming at maximizing the zone where the frequency can be used by a secondary outperforms the traditional methodology aiming at maximizing spectrum efficiency especially when the protection zone is bigger than the primary cell surface.

In this study, we have considered that only one secondary communication is active at a given time. The impact of multiple secondary communications is the subject of further research. Besides, a comparison of position-based mechanisms with sensing-based mechanisms is identified as an interesting task to complete the presented framework. Furthermore, shadowing effects will be further considered, with the help of simulation tools.

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References

[1] M. Cave et al., *Essentials of modern spectrum management*, Cambridge University Press, 2007.

[2] C. Cordeiro et al., "Guest Editorial - Adaptive, spectrum agile and cognitive wireless networks," *IEEE Journal on Selected Areas in Communications*, Vol. 25, n 3, pp.513-516, April 2007.

[3] A. Tonmukayakul, M. B. H. Weiss, "Secondary Use of Radio Spectrum: A Feasibility Analysis," *Telecommunications Policy Research Conference*, 2004.

[4] S. Panichpapiboon, and J. M. Peha, "Providing secondary access to licensed spectrum through coordination," *Wireless Networks, Springer*, 9 October 2006.

[5] S. M. Mishra, R. Tandra, A. Sahai, "Coexistence with Primary users of different scales," in Proc. *IEEE International Symposium on New Frontiers Dynamic Spectrum Access Networks (DySPAN07)*, 2007.

[6] Y. Zhao, D. Raymond, C. da Silva, J. H. Reed, and S. F. Midkiff, "Performance evaluation of radio environment map-enabled cognitive spectrum-sharing networks," in Proc. *IEEE Military Communications Conference (MILCOM07)*, Orlando, FL, pp. 1-7, 2007.

[7] A. E. Leu, M. McHenry, and B. L. Mark, "Modeling and analysis of interference in Listen-Before-Talk spectrum access schemes," *Int. Journal of Network Management* vol. 16, no 2, pp. 131-147, 2006.

[8] Grandblaise, K. Moessner, P. Leaves and D. Bourse, "Reconfigurability support for dynamic spectrum allocation: from the DSA concept to implementation," in Proc. *the First IEEE Joint Workshop on Mobile Future and Symposium on Trends in Communications*, pp. 9-12, 2003.

[9] L. Kovacs and A. Vidacs, "Spatio-Temporal Spectrum Management Model for Dynamic Spectrum Access Networks," in Proc. *the 1st International Workshop on Technology and Policy for Accessing Spectrum*,2006.

[10] M. M. Buddhikot, et al., "DIMSUMNet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum Access", in Proc. *IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM05)*, 2005.

[11] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, pp. 8- 14, 2004.

[12] M. K. Pereirasamy, J. Luo, M. Dillinger and C. Hartmann "Dynamic Inter-Operator Spectrum Sharing for UMTS FDD with Displaced Cellular Networks," in Proc. *IEEE Wireless Communications & Networking Conference (WCNC05)*, vol. 3, pp.1720- 1725, 2005.

[13] J. Nasreddine, J. Prez-Romero, O. Sallent, R. Agust, "A Primary Spectrum Management Solution Facilitating Secondary Usage Exploitation," in Proc. *ICT-Mobile Summit*, Stockholm, 2008.

[14] D. Thilakawardana, K. Moessner, "Enhancing Spectrum Productivity through Cognitive Radios facilitating Cell-by-Cell Dynamic Spectrum Allocation", *Software Defined Radio Technical Conference*, 2007.

[15] Ofcom, "Spectrum usage rights," *Final Report - Case Studies*, 10th February 2006.

[16] J. Nasreddine, J. Prez-Romero, O. Sallent, R. Agusti, "Simulated Annealing-Based Advanced Spectrum Management Methodology for WCDMA Systems," *IEEE International Conference in Communications (ICC08)*, Beijing, 2008.

[17] J. Nasreddine, J. Prez-Romero, O. Sallent, R. Agusti, "Dynamic Spectrum Management Methodology for WCDMA Systems Based on Inter-Cell Interaction Approach", in Proc. *Wireless Personal Multimedia Communications (WPMC06)*, September 2006.

[18] ETSI TR 101 112 v3.2.0, *Selection procedures for the choice of radio. transmission technologies of the UMTS (UMTS 30.03)*, April 1998.

[19] AG-Siemens, "TDD UE-UE interference simulations," *TSG-RAN Working Group 4 (Radio meeting n26)*, 2003.

[20] N. Hoven, A. Sahai, "Power scaling for cognitive radio," in Proc. *International Conference on Wireless Networks, Communications and Mobile Computing*, 2005 , vol.1, pp. 250-255, 2005.