Impact of Control Channel Design on Cooperative Spectrum Sensing in Opportunistic Spectrum Access Networks

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***Abstract*—In Opportunistic Spectrum Access (OSA) networks, Secondary unlicensed Users (SUs) need a common Control Channel (CC) to identify the spectrum opportunities, i.e., common spectrum holes unused by licensed Primary Users (PUs). Typically, an *interference-free* CC is unrealistically assumed in the literature. In this paper we evaluate the impact of the availability and the characteristics of the CC on the performance of cooperative spectrum sensing. We deal with the dimensioning of an underlay Ultra-wideband (UWB) signalling network for the exchange of sensing data among secondary Cognitive Radio (CR) nodes avoiding harmful interference to PUs. To this aim, we analyse the trade-off between the connectivity degree of a multi-hop underlay UWB signalling network, directly related to the possibility to perform cooperative sensing, and its coexistence with PUs. It is observed that the correct dimensioning of the UWB signalling network allows to achieve high accuracy of PU detection without compromising primary systems.**

***Keywords* - Cognitive Radio; Opportunistic Spectrum Access; Ultra-wideband; Control Channel.**

I. Introduction

A lot of experimental studies prove the inefficient use of the radio spectrum [1], [2]. This result does not comply with the general belief that the available spectrum resources are not sufficient to meet the needs of the next generation wireless networks. Within the Cognitive Radio (CR) context [3], fixed spectrum allocation policy could be replaced by innovative forms of dynamic use, referred to as Dynamic Spectrum Access (DSA) [4]. Among the DSA options it is of great interest the so-called Hierarchical Access model (HAM) [5], according to which an unlicensed secondary CR user (SU) can access the spectrum licensed to a primary user (PU), provided that harmful interference is avoided.

In the literature, mainly two HAM approaches have been proposed [6]: "Spectrum Underlay", also called horizontal sharing since based on spreading signals transmitted by SUs, for example by means of Ultra Wide Band (UWB) techniques; "Spectrum Overlay", also known as Opportunistic Spectrum Access (OSA), according to which secondary nodes access the unusued portion of band in a vertical way.

In order to guarantee protection to PUs [7], the underlay approach imposes SU transmission power below the required maximum interference tolerance. This condition does not allow to provide SUs with high data rate services for medium and long range communications. The impossibility to make the best use of the unused spectrum resources prevents the underlay solution from achieving high values of spectral efficiency.

Conversely, OSA is the most performing solution in terms of achievable throughput, but it requires adaptive techniques accounting for the state of transmission of the PUs in order to allow the secondary nodes to identify the so-called "spectrum opportunity" [6], i.e., common white spaces, at a given location and time, agreed by a pair of SUs for communication. The spectrum opportunity identification requires a dedicated control channel (CC) to implement efficient signalling protocols for realizing OSA among SUs. More in general, a coordination among SUs is needed to improve the performance in terms of detection probability of PUs by means of cooperative spectrum sensing techniques [8]. Such methods assume particular relevance for detecting the spectrum occupancy when wireless channels are affected by shadow fading [9]. For these reasons the CC plays a fundametal role in OSA networks. Nevertheless, typically an *interference-free* CC is unrealistically assumed in the literature. Indeed, the allocation of a separate fixed CC for exchanging information on spectrum opportunities is very likely unavailable on PU networks with fast varying spectrum usage [10], and anyway it can entail waste of spectrum resources only for signalling data.

An interesting promising solution is represented by the usage of an underlay UWB channel for sharing spectrum sensing information, as proposed in [11]. Usually signalling channels require low bit-rates and this feature permits to extend the UWB radio coverage even for low transmission power. This satisfies the double target of ensuring as wide signalling coverage as possible with minimal interference to PUs, allowing to continuously perform coordination for white spaces exploitation. However, in [11], the authors consider just one licensed transmitter in the area without facing the problem of dimensioning the signalling network. Indeed, this issue entails to take into account the trade-off between the amount of sensing data exchanged on the secondary network and the interference caused to the PUs by the underlay signalling.

In this paper, we propose to exploit the benefits of both

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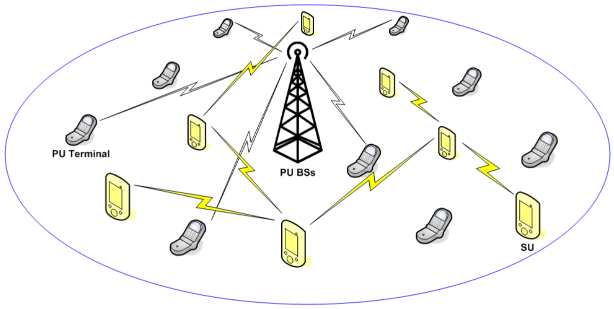

Figure 1. Interference scenario for secondary CR nodes and primary users.

HAM strategies by designing a *two-tier* OSA network, in which overlay spectrum access for data transmissions is driven by an underlay signalling network. We evaluate the impact of the availability and the characteristics of the CC on the performance of the OSA network in terms of cooperative detection probability. To this aim, we analyse the trade-off between the bit-rate of the CC and the connectivity degree of the underlay network for the exchange of sensing data among SUs. We also assess the maximum allowable density of the UWB devices such that the coexistence with primary systems is ensured, i.e., the interference caused by the signalling network does not compromise the performance of PUs.

The paper is organized as follows. In Section II, we describe the interference scenario for evaluating the performance of the underlay network in terms of accuracy of cooperative sensing and coexistence with PUs. The model for the analysis is detailed in Section III. Simulation results are reported in Section IV. Finally, conclusions are drawn in Section V.

II. Interference Scenario

The interference scenario is shown in Figure 1. SUs can opportunistically access the spectrum for sensing information exchange provided that the interference level to PUs does not exceed a predefined threshold. We assume that the technology used by all the PUs in the scenario is the Global System for Mobile Communications (GSM). We considered three co-sited Base Stations (BSs) situated at the center of an area of 0.64 km^2 in a suburban environment. We assume that both PU terminals served by the BSs and SUs are randomly distributed within the area in accordance to an uniform spatial distribution. We suppose that BSs transmit at maximum power, whereas PU terminals implement power control mechanisms. This downbeat case is considered to demonstrate the capability of SUs to perform spectrum sensing sharing on the UWB underlay network even when hard interference conditions occur. For the same reason, we disregard traffic statistics of PUs and SUs by assuming that all the devices continously transmit on their frequency band. Hence, more conservative results are expected by introducing a model accounting for users activity.

For the propagation model among devices in the area, we considered the following expression for path loss calculation:

$$L(d) = \frac{MCL}{G_{tx} \cdot G_{rx}} \cdot \left(\frac{d}{d_0}\right)^{\gamma} \quad (1)$$

where $d > d_0$ is the distance (in m) between transmitter and receiver, $MCL > 0$ is the minimum coupling loss for $d_0 = 1$ m, γ is the path loss exponent and G_{tx} and G_{rx} are the antenna gains related to the transmitter and the receiver, respectively. According to values in [12], we conservatively set $\gamma = 2.5$ for outdoor propagation among UWB devices, while a path loss exponent equal to 3 is assumed for both PU links (between terminal and BS) and attenuation among PUs and SUs.

III. Analysis

In this section we describe the proposed procedure to evaluate the density of SUs in the area such that a connectivity degree is reached guaranteeing the required level of protection to PUs at the same time. This trade-off depends on the bit-rate of the signalling channel. Then we provide an expression for calculation of cooperative detection probability accounting for the availability of the CC for exchanging sensing information among SUs.

A. UWB signalling network connectivity and coexistence

We characterize the availability of the CC in terms of the *Outage Probability* of the secondary underlay signalling network, given by:

$$P_{out} = Prob\{SINR < \rho_0\} \leq \alpha \quad (2)$$

$$s.t.\ 0 \leq P_{SU} \leq P_{max}$$

where ρ_0 is the required QoS level for the sensing information exchanging, α is the target outage probability and $SINR$ is the *Signal-to-Noise plus Interference Ratio* expressed by the following formula:

$$SINR = \frac{E_b}{I_0 + \eta_0} = \left[\left(\frac{E_b}{I_{PU,0}} \cdot \frac{B_{UWB}}{B_{PU}}\right)^{-1} + \left(\frac{E_b}{\eta_0}\right)^{-1}\right]^{-1} =$$

$$= \left(\frac{C}{\eta}\right) \cdot \left[1 + (I_{BS} + I_T) \cdot \frac{R_b}{B_{UWB}}\right]^{-1} \quad (3)$$

where C is the received signal, R_b and B_{UWB} are the bit-rate and the bandwidth of the UWB devices, respectively, and η is the thermal noise power given by:

$$\eta = \eta_0 \cdot B_{UWB} \cdot N_F$$

where $\eta_0 = -174\ dBm/Hz$ is the noise PSD and N_F is the corresponding noise figure. As indicated in (2), the outage probability depends on both the interference from the active PUs and the propagation conditions. Furthermore, it is constrained on the transmission power of SUs, i.e., P_{SU}, which can not exceeds the maximum allowed power P_{max}.

Since the control traffic exploits an underlay channel known by each CR node of the OSA network, the exchange of sensing data among SUs does not cause interference to the overlay communications. According to this assumption, in (3) we can

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neglect the interference due to the other UWB nodes and we only consider the interference caused by PU links, which is defined as:

$$I_{PU} = I_{PU,0} \cdot B_{PU} = I_{BS} + I_T \quad (4)$$

where B_{PU} is the bandwidth of the PU receiver and $I_{PU,0}$ is the interference spectral density on UWBs due to the PUs. $I_{PU,0}$ is composed of two main interference contributions to SUs due to PU BSs and PU terminals. These are given by the following expressions:

$$I_{BS} = \sum_{i=1}^{N_{BS}} \frac{P_{BS_i}}{L(d_i)} \quad (5)$$

$$I_T = \sum_{i=1}^{N_T} \frac{P_{T_i}}{L(d_i)} \quad (6)$$

where N_{BS} and N_T are the number of PU BSs and PU Terminals, respectively, d_i is the distance between the i-th PU (BS or terminal) and the considered SU, while P_{BS_i} and P_{T_i} are the transmission power of the i-th PU BS and PU terminal, respectively. As shown in (3), the interference terms are reduced by the ratio R_b/B_{UWB}, which represents a factor accounting for the signalling requirements and the characteristics of the UWB devices. It means that for a given UWB bandwidth and a fixed transmission power, the higher the bit-rate the worse the outage probability.

The proposed methodology for dimensioning a HAM cognitive network can be synthesized as follows:

1) given the considered scenario (e.g., the propagation characteristics, the number of interferers, the maximum allowed transmission power, etc.), calculate the outage probability of the signalling network under these conditions;
2) verify if the obtained outage probability is above the defined threshold α:
   2.1 if *yes*, we obtain the maximum UWB SUs transmission power satisfying constraints that fulfill the outage requirements;
   2.2 if *no*, the transmission power of the UWB devices is incremented in accordance to the regulatory restrictions.
3) calculate the maximum coverage range of UWB SUs;
4) determine the connectivity of the UWB signalling network with the obtained coverage. This metric is defined as the probability that a SU can reach all the other SUs of the signalling network according to a multi-hop architecture.
5) for a required connectivity degree, verify if the correspondent density of SUs in the area is compliant with the maximum number of UWB devices that guarantee the established level of protection to PUs. This is accounted for by the *Probability of Coexistence*, related to the interference to PUs from the underlay secondary network and calculated as:

$$P_{coex} = Prob\{I_{UWB} < I_{th}\} \quad (7)$$

I_{UWB} is the average interference caused to PUs (BSs or terminals) by the number N_{SU} of transmitting SUs, defined as:

$$I_{UWB} = \sum_{i=1}^{N_{SU}} \frac{P_{SU_i,0}}{L(d_i)} \cdot B_{PU} = \beta \sum_{i=1}^{N_{SU}} \frac{P_{SU_i}}{L(d_i)} \quad (8)$$

where:

$$P_{SU_i,0} = \frac{P_{SU_i}}{B_{UWB}} \ , \ \beta = \frac{B_{PU}}{B_{UWB}}$$

are the PSD of DS-UWB devices and the ratio between the bandwidths of PUs and UWB SUs, respectively. This latter parameter is defined since the flat spectrum approximation, valid for narrowband PU, is assumed [13]. In (7) I_{th} is the allowable interference threshold. It is directly derived from the *Signal-to-Noise Ratio* (SNR) degradation, r, expressed as [13]:

$$r = \frac{\eta + I_{UWB}}{\eta} \quad (9)$$

This parameter measures the impact of the UWB interference on the SNR with respect to the thermal noise power N of the PU receiver chain. Once determined the maximum allowed value for the SNR degradation, namely r_{max}, the allowable interference threshold can be easily calculated as:

$$I_{th} = (r_{max} - 1) \cdot \eta \quad (10)$$

6) verify if the obtained probability of coexistence respects the required level of protection to PUs:
   6.1 if *yes*, the desired density of SUs is admitted. Hence the connectivity degree is accepted.
   6.2 if *no*, the bit-rate of the underlay signalling channel should be decreased up to match both the coexistence and connectivity requirements.

As shown by results presented in the next section, the described methodology allows to find a set of admissible pairs of values for the number of SUs and the bit-rate, all providing a desired connectivity degree subject to constraints on both the maximum transmission power of SUs and the interference to PUs.

B. Cooperative Detection Probability

Cooperative spectrum sensing techniques have been proposed to increase detection probability of PUs especially in shadowed or deeply faded channels However, in order to perform cooperative sensing a CC is required for the exchange of sensing data among SUs. Typically an *interference-free* CC is assumed in the literature, but actually the unavailability of such a channel can reduce the cooperative sensing performance. Hence the characteristics of the signalling channel should be considered in the expression of the cooperative detection probability.

We assume that a number of Cognitive Cluster Head Nodes (CCNs) have been elected in the secondary network in accordance to a distributed algorithm using the UWB signalling channel. CCNs are responsible for collecting sensing data from the SUs within their coverage and processing these data to decide on the availability of the spectrum holes. We also assume that SUs associated with a CCN are in the same PU activity area and that measurements taken by SUs are independent. Then, by considering the AND decision rule, that is a PU is considered idle only if an available band is detected out of all sensing data, the detection probability associated to the CCN decision is given by [14]:

$$P_D(k) = 1 - (1 - p_d)^{k+1} \ , \ k \geq 0 \qquad (11)$$

where k is the number of sensing data collected from the single CCN, which corresponds to the number of SUs within its coverage, while p_d is the detection probability of the single SU. Note that we assume a collaborative CCN which performs spectrum sensing together with the other SUs. The expression in (12) is valid if a channel among the CCN and the k SUs is available. Hence the average detection probability in cooperative spectrum sensing can be defined as:

$$\overline{P}_D(\delta_{SU}) = \sum_{k=0}^{N_c} P_D(k) \cdot Prob\left\{k|\delta_{SU}\right\} \qquad (12)$$

where N_c is the number of SUs within the coverage range of the considered CCN, δ_{SU} is the density of SUs in the area and $Prob\left\{k|\delta_{SU}\right\}$ represents the probability of having at least k SUs within the CN coverage with which to perform cooperative spectrum sensing. It takes into account for the availability and the characteristics of the UWB CC for sensing information exchange among SUs. In other words, the cooperative detection probability is strictly related to the connectivity of the SU signalling network and its coexistence with primary systems, as shown in the next section.

The average missed detection probability of cooperative spectrum sensing can be then calculated as:

$$\overline{P}_{MD}(\delta_{SU}) = 1 - \overline{P}_D(\delta_{SU}) \qquad (13)$$

IV. RESULTS

We carried out several simulations to assess the dimensioning of a SU underlay signalling network accounting for the trade-off between the level of protection to PUs and the connectivity degree of the SUs. We also evaluate the accuracy of the cooperative detection of PUs with respect to both the characteristics of the signalling network and its coexistence with primary systems. Results have been obtained using a Monte Carlo-based approach. The values assumed for the simulation parameters are reported in Table I. We assume a maximum tolerance on the outage probability of the UWB signalling data $\alpha = 5$ %. Omni-directional antennas are considered for both UWB SUs and PU terminals. We also suppose that each PU BS transmits on 14 carrier frequencies. As discussed in previous sections, typically low data rate are needed for signalling channels. Hence we performed simulations by assuming bit-rate ranging from 1 to 10 kbit/s.

In Figure 2 we report both the connectivity degree and the probability of coexistence of the multi-hop underlay signalling network as a function of the density of SUs in the area. It is observed that the signalling bit-rate R_b impacts on the percentage of connectivity among UWB devices. This can be explained by looking at the formula in (3), where the term R_b acts as a scaling factor reducing interference from the PUs to the SU receiver. Hence, the lower the CC bit-rate the higher the connectivity among UWB SUs. In other words, a higher density of UWB devices in the area is needed to obtain a required connectivity degree if the bit-rate increases due to the smaller coverage range. Moreover, the reduction of the SU SINR due to an increased number of active PUs implies a lower percentage of connectivity, as highlighted in Figure 2. As regards the probability that the underlay UWB signalling network causes harmful interference to primary systems, the obtained curves give an indication on the maximum allowed number of SUs in the considered scenario. We consider different values of the maximum interference tolerance r_{max} with respect to PU terminals. The coexistence only depends on the parameter β regardless of the bit-rate of the CC, as indicated in (7) and (8). As expected, for a given density of SUs in the area the higher the allowable interference threshold the lower the probability to harm PU performance.

	SUs	PU BSs	PU Terminals
B [MHz]	3000	0.4	0.4
f_c [MHz]	3100	1805 ÷ 1825	1775 ÷ 1785
P_{max} [dBm]	-6	43	33
γ	2.5	3	3
ρ_0 [dB]	4.5	9	9
G_{rx} [dBi]	1	12	1
G_{tx} [dBi]	1	12	1
N_f [dB]	5	9	9

Table I
VALUES FOR THE SIMULATION PARAMETERS

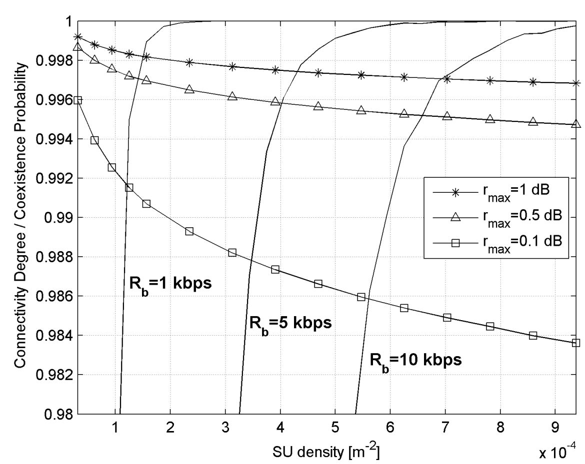

Figure 2. Connectivity degree and Probability of Coexistence vs density of SUs in the area (with 300 PU terminals and 3 co-sited BSs).

As we explained in Section III, the proposed methodology allows to dimension the underlay UWB signalling network such that a predefined protection degree to PUs is guaranteed. As an example, starting from the curves in Figure 2 related to $r_{max} = 0.1$ dB and considering a coexistence requirement of $P_{coex} \geq 98.6$ %, up to about 350 SUs can be tolerated for the considered scenario. As shown by the connectivity curves, this density of UWB devices implies a maximum percenatge of connectivity of about 98.3 % for a signalling bit-rate of 10 kbit/s. If a completely connected UWB network is required, we have to decrease the bit-rate to 5 kbit/s. It is worthwhile to remind that, by assuming collaborative spectrum sensing among SUs, the percentage of connectivity of the underlay network is directly related to the detection probability performance, and consequently to an efficient usage of spectral resources. This is shown in Figure 3 and Figure 4, where we report the cooperative detection probability as a function of the density of UWB SUs in the area. Given a coverage range and a detection probability of the single SU, the higher the density of SUs in the area the more accurate the probability of detecting PUs activity. When the bit-rate of the CC increases, the lower coverage leads to a decrease of the cooperative detection probability. This is due to the lower probability of finding CR nodes within the coverage of the CCN in order to maintain the same availability of the CC. Evidently, for a given bit-rate an incresed detection probability of the single SU results in better cooperative detection performance.

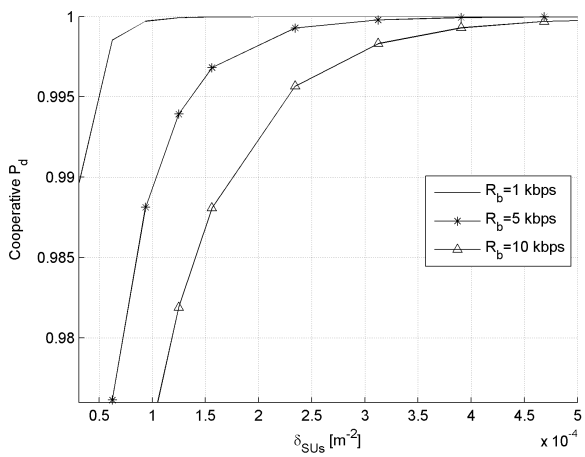

Figure 3. Performance of cooperative sensing in terms of detection probability vs density of SUs of the underlay signalling network (150 PU terminals, 3 co-sited PU BSs, P_d=0.9).

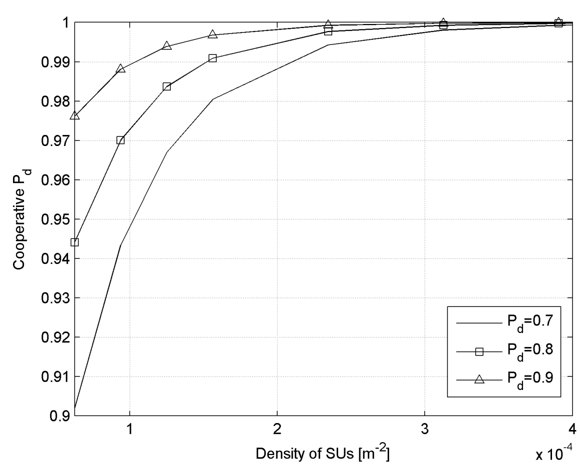

Figure 4. Performance of cooperative sensing in terms of detection probability vs density of SUs of the underlay signalling network (150 PU terminals, 3 co-sited PU BSs, R_b=5 kbps).

In Figure 5 and Figure 6, we report the performance of cooperative sensing in terms of probability of missed detection as defined in (13). By taking into account for the availability and the parameters of the CC, it is observed that the values related to the expression of traditional cooperative sensing, i.e., $P_D(k)$, are obtained when the density of SUs in the considered scenario is sufficient to guarantee the maximum probability of finding at least k SUs within the coverage of the CCN. The trends of the curves related to the different values of k can

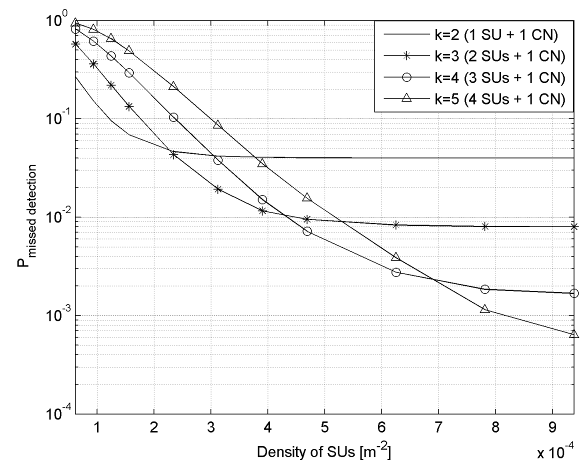

Figure 5. Performance of cooperative sensing in terms of probability of missed detection vs the density of SUs of the underlay signalling network (200 PU terminals, 3 co-sited PU BSs, R_b=5 kbps, P_d=0.8).

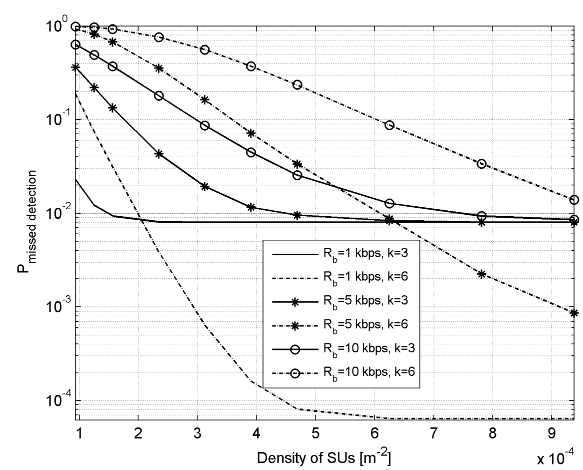

Figure 6. Performance of cooperative sensing in terms of probability of missed detection vs the density of SUs of the underlay signalling network (200 PU terminals, 3 co-sited PU BSs, P_d=0.8).

be explained looking at the Figure 7, where the *probability density function* of k is reported for different number of SUs. Given the outage probability of the signalling network, the maximum transmission power of UWB nodes and the bit-rate of the CC, and then the CCN coverage range, when more sensing data are desired to perform cooperative detection, the probability of having at least k SUs within the CCN coverage, i.e., $Prob\{k|\delta_{SU}\}$, increases with the increase of the SU density. Hence, with the increase of the SU density a CCN can actually exploit more sensing data, so achieving a more accurate detection, up to reach the asymptotic value imposed by the terms $P_D(k)$. In other words the number k of SUs with

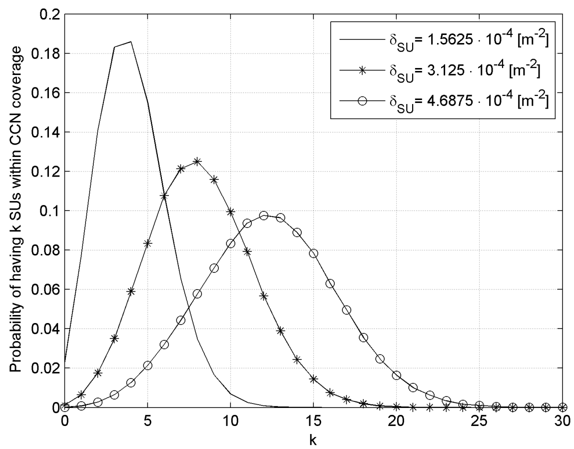

Figure 7. Probability of having k SUs within the coverage of the CCN vs k (150 PU terminals, 3 co-sited PU BSs, R_b=5 kbps).

which to decide of performing cooperative spectrum sensing depends on the density of SUs in the considered scenario. For a lower bit-rate of the CC, the resulting increase in CCN coverage leads to a minor density of SUs needed to obtain the target performance in terms of detection probability, as shown in Figure 6. In Figure 8 the cooperative detection probability is plotted as a function of the probability that the proposed UWB signalling network coexists with the primary systems in the considered scenario. As expected, a more stringent requirement on the maximum interference tolerance r_{max} entails a more rapid degradation of detection performance. Furthermore, the reduction in CC bit-rate allows to obtain better accuracy of PU detection while maintaining the same coexistence probability.

V. Conclusions and Future Works

In this paper, we faced the problem of the design of the control channel in OSA networks. We proposed to exploit the DS-UWB technology to realize an underlay signalling network for spectrum opportunity identification and cooperative spectrum sensing. We defined a cooperative detection probability accounting for the availability and the parameters of the control channel. We proved that the correct dimensioning of the proposed signalling network can provide SUs with a high

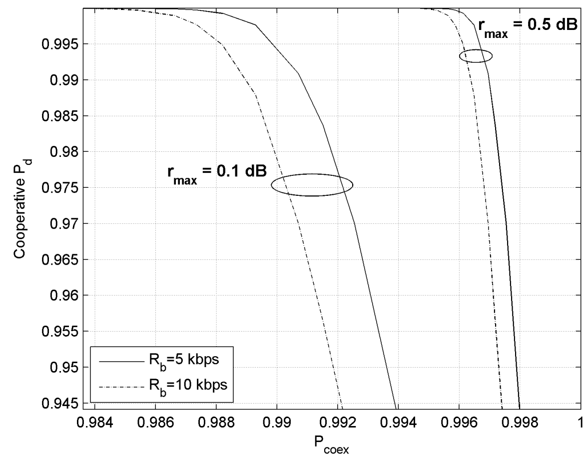

Figure 8. Cooperative detection probability vs coexistence probability of the underlay signalling network (150 PU terminals, 3 co-sited PU BSs, P_d=0.8).

availability of sensing data, thus increasing the accuracy of PU detection while avoiding harmful interference to PUs.

Future research can pertain to the design of suitable signalling protocol over the proposed underlay UWB CC to optimize the throughput in OSA networks.

References

[1] FCC, "Spectrum policy task force report", Tech. Rep. 02-135, Nov. 2002.

[2] V. Valenta, Z. Fedra, R. Marsalek, G. Baudoin, M. Villegas, "Towards cognitive radio networks: Spectrum utilization measurements in suburban environment", IEEE Radio and Wirel. Symp., pp. 352-355, Jan. 2009.

[3] J. Mitola III and G. Q. Maguire Jr., "Cognitive radio: making software radios more personal", IEEE Pers. Commun., pp. 13-18, Aug. 1999.

[4] I. F. Akyildiz, W.Y. Lee, M. C. Vuran, S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey", Computer Networks, vol. 50, pp. 2127-2159, May 2006.

[5] A. Ben Hadj Alaya-Feki, B. Sayrac, A. Le Cornec, E. Moulines, "Semi dynamic parameter tuning for optimized opportunistic spectrum access", IEEE 68th Vehic. Technol. Conf., pp. 1-5, Sept. 2008.

[6] Q. Zhao and B. Sadler, "A survey of Dynamic Spectrum Access", IEEE Sign. Proces. Mag., pp. 79-89, May 2007.

[7] Federal Communications Commission, "Revision of part 15 of the commissions rules regarding ultra-wideband transmission systems, first report and order", Washington, DC, ET Docket 98-153, FCC 02-48, 2002.

[8] J. Unnikrishnan and V. V. Veeravalli, "Cooperative sensing for primary detection in cognitive radio", IEEE Jour. Sel. Topics Signal Process., vol. 2, no. 1, pp. 18-27, Feb. 2008.

[9] A. Ghasemi and E. S. Sousa, "Opportunistic spectrum access in fading channels through collaborative sensing, IEEE Jour. Comm., vol. 2, no. 2, pp. 71-82, Mar. 2007.

[10] P. Pawelczak, S. Pollin, H.-S.W. So, A. Bahai, R.V. Prasad, R. Hekmat, "Performance Analysis of Multichannel Medium Access Control Algorithms for Opportunistic Spectrum Access", IEEE Trans. on Vehic. Technol., vol. 58, no. 6, pp. 3014-3031, Jul. 2009.

[11] M. E. Sahin and H. Arslan, "System design for cognitive radio communications", in Proc. CrownCom, Jun. 2006.

[12] IEEE P802.15 Working Group for Wireless Personal Area Networks, "UWB Channel Characterization in Outdoor Environments", Aug. 2004.

[13] R. Giuliano and F. Mazzenga, "On the coexistence of power-controlled ultrawide-band systems with UMTS, GPS, DCS1800, and fixed wireless systems", IEEE Trans. on Vehic. Technol., Vol. 54 , NO. 1, pp. 62-81, Jan. 2005.

[14] Won-Yeol Lee and I.F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks", IEEE Transactions on Wireless Communications, vol. 7, no. 10, pp. 1536-1276, Oct. 2008.