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Channel availability for mobile cognitive radio networks

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ABSTRACT

Channel availability is defined as the probability of a licensed channel being available for the communications of unlicensed users. Channel availability is a key parameter for an effective design of channel selection strategies as well as routing metrics in cognitive radio networks. In static scenarios, the availability of a channel depends only on the primary user's activity. Differently, in mobile scenarios, the availability of a channel dynamically varies in time due to the changes of the users' relative positions. In this paper, we design a channel-availability estimation strategy by explicitly accounting for the features of mobile scenarios. The simulation results reveal the benefits of adopting the proposed strategy in cognitive radio networks.

1. Introduction

Channel availability is defined as the probability of a channel licensed to a Primary User (PU) being available for the communications of unlicensed users, referred to as Cognitive Users (CUs). Channel availability is a key parameter for an effective design of channel selection strategies as well as routing metrics (Caleffi et al., 2012; Abdelaziz and ElNainay, 2014) in cognitive radio networks. In fact, the knowledge of the channel availabilities enables a CU to select the channel providing the highest communication opportunities. Moreover, it enables the CU to effectively measure the quality of a route through a routing metric.

In static scenarios, the availability of a channel depends only on the PU activity probability, i.e., on the probability of the channel being occupied by the PU transmissions. Differently, in mobile scenarios, the availability of a channel dynamically varies in time due to the changes of the relative positions between the PUs and the CUs. Let us consider the example in Fig. 1a and b. At time t, since the CU is outside the PU *protection range*,[1] the channel availability is independent of whether the PU is active or not. Differently, at time t', the CU is inside the PU protection range due to the mobility. Hence, the channel availability is not anymore independent of the PU activity. Therefore, in mobile scenarios, the knowledge of the PU activity probability is not enough for an actual channel-availability estimation.

In this paper, we design a channel-availability estimation strategy by explicitly accounting for the features of mobile scenarios. Specifically, we propose a channel-availability estimation strategy based on the relative distances between PUs and CUs. The proposed strategy takes advantage of the non-stationarity of the network topology induced by the user mobility. Thus, with reference to mobile scenarios, such a strategy is expected to outperform the traditional methods, based only on the PU activity. The simulation results confirm the benefits of the proposed strategy in cognitive radio networks.

The rest of the paper is organized as follows. In Section 2 we introduce the problem statement. In Section 3 we describe the network model. In Section 4 we present the proposed channel-availability estimation strategy, and we evaluate the performance through numerical simulations in Section 5. Finally, Section 6 concludes the paper.

2. Problem statement

In this section, we describe how the channel availability in static scenarios differs from the mobile scenarios and then we discuss our proposal. Finally, we present the related work.

2.1. Challenges

In static scenarios, the geographic location of each user is fixed (i.e., both PU and CU). Therefore, the relative distance between PU and CU does not vary on time. In this case, the channel-availability

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[1] The CUs are able to detect active PUs within a range, referred to as *protection range*, determined by the PU transmission range and by the CU interference range (Cacciapuot et al., 2013; Ghasemi and Sousa, 2007).

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estimation, referred to as *static method*, depends only on the PU inactive probability (Jha et al., 2011; Xue et al., 2010; Caleffi et al., 2012). This probability can be *a priori* known or simply estimated according to the channel occupancy history (Chowdhury and Akyildiz , 2011).

In mobile scenarios, the geographic location of each user is not fixed. Therefore, the relative distances between PU and CU vary in time. Consequently, the channel availability is affected by the time variant nature of the network topology.

We clarify this issue with an example. As shown in Fig. 2a, let us assume that at time t_0 a CU, denoted as u_i, is inside the protection range of two different PUs, denoted as v_l and v_n, transmitting on channel a and b, respectively. Moreover, we assume that the inactivity probability of v_l on channel a is higher than the inactivity probability of v_n on channel b. At time $t_0+\Delta$, due to v_n movement, u_i is inside the protection range of only v_l, as shown in Fig. 2b.

According to the *static method*, since the inactivity probability of v_l is greater than the inactivity probability of v_n, u_i would choose always channel a as the channel with the highest availability. However, since at time $t_0+\Delta$ u_i is out of v_n protection range, the channel providing the effective highest availability is channel b. In fact, u_i can freely transmitting on channel b without causing harmful interference to the primary network, independently from the v_n activity.

Hence, from the above example, it is evident that in mobile scenarios it is necessary for a proper estimation of channel availability by explicitly accounting for the features of mobile scenarios.

2.2. Channel-availability estimation design in mobile scenarios

In this paper, we propose a novel channel-availability estimation for cognitive radio networks that explicitly accounts for the features of mobile scenarios. More in detail:

- We derive a closed-form expression of the channel availability in mobile scenarios by accounting for two different PU spectrum occupancy models.
- We analyze the impact of the localization error on the channel-availability estimation.
- We verify through numerical simulations that the proposed method is able to take advantage from the dynamic variation of the channel availability caused by the user mobility.

2.3. Related work

Most of the works available in the literature propose to estimate the channel availability basing only on the PU activity probability. In Jha et al. (2011), the authors propose an opportunistic multi-channel Medium Access Control (MAC), according to which the CUs estimate the channel availability basing on the previous channel scanning results. In Xue et al. (2010), the authors propose another MAC protocol by assuming that each CU obtains the channel availability from the physical layer. In Chowdhury and Akyildiz(2011), the authors introduce a routing metric that aims to minimize the interference of the CUs against the PUs, by estimating the channel availability through the channel history. In Salameh and Badarneh(2013), the authors propose a probabilistic channel quality- and availability-aware cognitive radio MAC, whereas they assume that the spectrum sensing method is in place for determining the list of idle channels. Based on the same assumption, in Talay and Altilar (2013), the authors propose a self adaptive routing for dynamic spectrum access on cognitive radio networks. In Parvin et al. (2013), the security issues on cognitive radio networks are addressed. In Ning et al. (2014), a channel estimation technique is proposed, however, this approach is not suitable in cognitive paradigm due to the PU activities. In Avokh and Mirjalily (2014). an interference-aware routing solution is provided including channel diversity features, which is not also suitable due to the same reasoning. Finally, in Caleffi et al. (2012), the authors propose an optimal routing metric for both static and mobile cognitive radio scenarios, according to which the channel availability depends again on the channel occupancy history. Unlike all the aforementioned works, in this paper we design a channel-availability estimation strategy by explicitly accounting for the main features of mobile scenarios.

3. Network model

In this section, we describe both the PU and CU network models.

3.1. PU network model

The PUs move according to the well-known Random Way Point Mobility (RWPM) model (Camp et al., 2002) inside a network region $\mathcal{A}$, assumed as a square for the sake of simplicity. $v_l(t)$ denotes the position of the l-th PU at time instant t. The l-th PU traffic on the

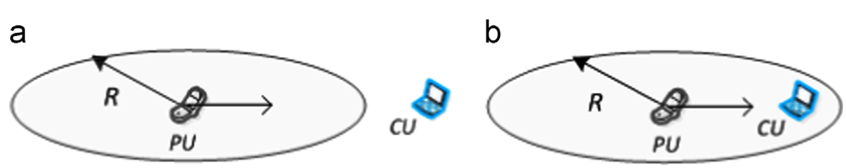

Fig. 1. Channel availability in mobile scenarios.

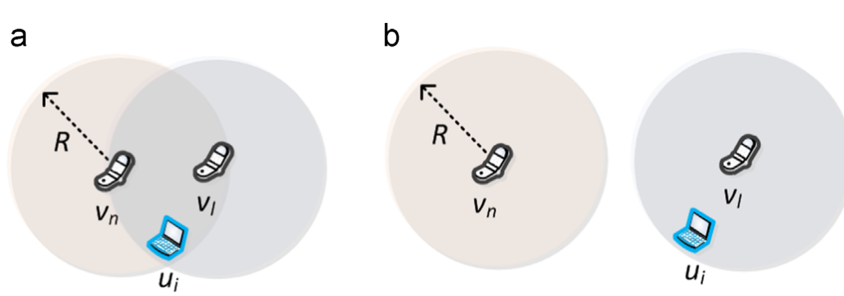

Fig. 2. Channel with the highest availability.

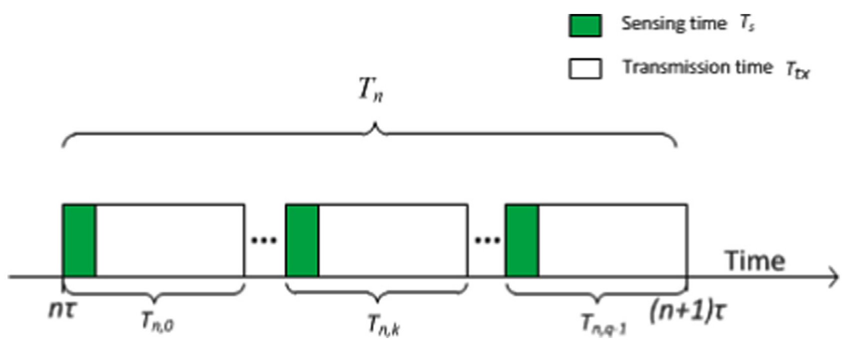

Fig. 3. CU time organization.

m-th channel is modeled as a two-state birth-death process (Cacciapuoti et al., 2013a, 2011; Cacciapuoti et al., 2014), with death rate $\alpha_{l,m}$ and birth rate $\beta_{l,m}$. In the *on* state, the l-th PU is active on channel m with probability $P^{on}_{l,m} = \beta_{l,m}/(\alpha_{l,m}+\beta_{l,m})$ whereas in the *off* state it is inactive with probability $P^{off}_{l,m} = 1 - P^{on}_{l,m}$. Moreover, we consider two different PU spectrum occupancy models (Cacciapuoti et al., 2011). In the first model, called Single PU for Channel (SPC), the PUs roaming within the network region use different channels. In the second model, called Multiple PUs for Channel (MPC), different PUs roaming within the network region share the same channel.

3.2. CU network model

The CUs are assumed static[2] and u_i denotes the fixed position of the i-th CU. As well known, the CU activity is organized into fixed-sized slots of duration T, as shown in Fig. 3. Each time slot T is further organized in a sensing period T_s (Cacciapuoti et al., 2013b, 2011), which measures the portion of the time slot assigned to the spectrum sensing, and in a transmission period T_{tx}, which measures the portion of the time slot devoted to the CU packet transmissions. Each CU is aware of its position,[3] whereas it can acquire the PU positions periodically[4] with a *PU position update interval* $\tau = qT$, as shown in Fig. 3. We note that, in Fig. 3, $T_{n,k}$ denotes the k-th time slot in the n-th arbitrary PU position update interval, i.e., $T_{n,k} = [n\tau + kT, n\tau + (k+1)T)$.

4. Channel-availability estimation

In this section, with reference to scenarios characterized by PU mobility, we derive estimates of the channel availability which exploit the PU position information. More in detail, we present the channel-availability expression in both SPC (Theorem 1) and MPC (Theorem 2) scenarios.

4.1. Channel-availability estimation in SPC scenarios

In this subsection, we derive the expression of the channel availability with reference to SPC scenarios (Theorem 1). To this aim, we first present Proposition 1.

Proposition 1. *At the time instant $t_0 = n\tau$, the i-th CU estimates the probability $p^{SPC}_{i,m,l}(T_{n,k})$ of the m-th channel licensed to the l-th PU being available in the subsequent time slot $T_{n,k} = [n\tau + kT, n\tau + (k+1)T)$ with $k = 0, \ldots, q-1$, as*

$$\tilde{p}^{SPC}_{i,m,l}(T_{n,k}) = \begin{cases} 1 & \text{if } \tilde{d}_{i,l}(t) > R_{i,l} \;\; \forall t \in T_{n,k} \\ P^{off}_{l,m} & \text{otherwise} \end{cases} \tag{1}$$

where $R_{i,l}$ denotes the protection range of the l-th PU, $P^{off}_{l,m}$ has been defined in the Section 3.1, $\tilde{d}_{i,l}(t)$ denotes the distance between the i-th CU and the l-th PU at time $t \in T_{n,k}$, estimated at time t_0, and $\tilde{p}^{SPC}_{i,m,l}(T_{n,k})$ denotes the estimation of $p^{SPC}_{i,m,l}(T_{n,k})$.

Proof 1. See Appendix Appendix A. □

Remark 1. In Proposition 1, we estimate a channel as fully available in an arbitrary time slot if and only if the CU is outside the protection range in the whole time slot. This choice is reasonable since it agrees with the policy of minimizing the interference on the PU transmissions.

Remark 2. In SPC scenarios, the channel-availability estimation $\tilde{p}^{SPC}_{i,m,l}(T_{n,k})$ in the arbitrary time slot $T_{n,k}$ depends on both the activity and the position of the unique PU active on such a channel.

Theorem 1. *At the time instant $t_0 = n\tau$, the i-th CU estimates the probability $\overline{P}^{SPC}_{i,m,l}(T_n)$ of the m-th channel licensed to the l-th PU being available in the next PU position interval $T_n = [n\tau, (n+1)\tau)$ as*

$$\tilde{\overline{P}}^{SPC}_{i,m,l}(T_n) = \frac{1}{q}\sum_{k=0}^{q-1} \tilde{p}^{SPC}_{i,m,l}(T_{n,k}) \tag{2}$$

where $\tilde{p}^{SPC}_{i,m,l}(T_{n,k})$ is given in (3), and $\tilde{\overline{P}}^{SPC}_{i,m,l}(T_n)$ denotes the estimation of $\overline{P}^{SPC}_{i,m,l}(T_n)$.

Proof 2. It follows by averaging on the PU position updating interval the result of Proposition 1. □

4.2. Channel-availability estimation in MPC scenarios

In this subsection, we derive the expression of the channel availability with reference to MPC scenarios (Theorem 2). To this aim, we first give a definition and present Proposition 2.

Definition 1 (*PU Set*). The PU set L denotes the set of PUs roaming within the network region and using the same channel, according to the MPC model.

Proposition 2. *At the time instant $t_0 = n\tau$, the i-th CU estimates the probability $p^{MPC}_{i,m,L}(T_{n,k})$ of the m-th channel licensed to the PU set L being available in the next time slot $T_{n,k} = [n\tau + kT, n\tau + (k+1)T)$ with $k = 0, \ldots, q-1$, as*

$$\tilde{p}^{MPC}_{i,m,L}(T_{n,k}) = \begin{cases} 1 & \text{if } \tilde{d}_{i,l}(t) > R_{i,l} \;\; \forall l \in L, t \in T_{n,k} \\ \prod_{l \in L} P^{off}_{l,m} & \text{otherwise} \end{cases} \tag{3}$$

[2] It is straightforward to prove that the derived expressions hold also if we assume mobile CUs and static PUs.

[3] Either directly through dedicated positioning systems such as Global Positioning System (GPS), or indirectly through location estimation algorithms.

[4] It is reasonable to assume that the CU cannot access the PU location in each time instant t, since the PU location is time-variant and it is obtained through either location estimation algorithms (Liu et al., 2009) or dedicate databases (Caleffi and Cacciapuoti, 2014).

where $R_{i,l}$ denotes the protection range of the l-th PU, $\tilde{d}_{i,l}(t)$ denotes the distance between the i-th CU and the l-th PU at time $t \in T_{n,k}$, estimated at time t_0, and $\tilde{p}^{\mathrm{MPC}}_{i,m,L}(T_{n,k})$ denotes the estimation of $p^{\mathrm{MPC}}_{i,m,L}(T_{n,k})$.

Proof 3. It can be proved by following the same reasoning adopted in Proposition 1. □

Remark 3. In MPC scenarios, the channel-availability estimation $\tilde{p}^{\mathrm{MPC}}_{i,m,L}(T_{n,k})$ of the m-th channel licensed to the PU set L in the arbitrary time slot $T_{n,k}$ depends on both the activity and the position of all the PUs in the set L.

Theorem 2. *At the time instant $t_0 = n\tau$, the i-th CU estimates the probability $\overline{P}^{\mathrm{MPC}}_{i,m,L}(T_n)$ of the m-th channel licensed to the PU set L being available in the next PU position interval $T_n = [n\tau, (n+1)\tau)$ as:*

$$\tilde{\overline{P}}^{\mathrm{MPC}}_{i,m,L}(T_n) = \frac{1}{q}\sum_{k=0}^{q-1} \tilde{p}^{\mathrm{MPC}}_{i,m,L}(T_{n,k}) \quad (4)$$

where $\tilde{\overline{P}}^{\mathrm{MPC}}_{i,m,L}(T_n)$ denotes the estimation of $\overline{P}^{\mathrm{MPC}}_{i,m,L}(T_n)$

Proof 4. It follows by averaging on the PU position updating interval the result of Proposition 2.

5. Simulation results

In this section, we numerically evaluate the performance of the proposed estimation method through 10^6 Monte Carlo runs with reference to both the SPC (Experiment 1) and the MPC (Experiment 2) scenarios. Moreover, in Experiment 3, we analyze the impact of localization error on the channel-availability estimation. Finally, in Experiment 4 we evaluate the channel availability as a function of the CU time for both SPC and MPC scenarios.

In all the considered experiments, we analyze the performance of three estimation strategies for the channel availability: (i) the static estimation, i.e., the traditional estimation based only on the PU activity probability (Chowdhury and Akyildiz , 2011); (ii) the proposed estimation when the distance $d_{i,l}(t)$ between the i-th CU and the l-th PU at time t is perfectly known; (iii) the proposed estimation when the distance $d_{i,l}(t)$ between the i-th CU and the l-th PU at time t is estimated as described in the proof of Proposition 1.

5.1. Experiment 1

In this experiment, the PUs move in a squared network region of side $a = 2000$ m according to the RWPM model, with velocity uniformly distributed in the interval [5, 10] m/s. The simulation set is as follows: sensing time $T_s = 1$ s, transmission time $T_{tx} = 3$ s, PU position update interval $T_n = 36$ s, and, finally, PU inactive probability $P^{off}_{l,m} = 0.6 \ \forall l, m$.

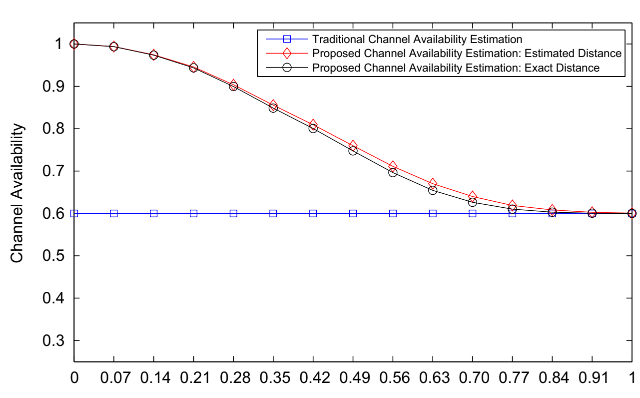

Fig. 4. Channel availability vs. PU protection range in SPC scenarios.

In Fig. 4, we report the channel availability as a function of the normalized PU protection range $R_{i,l}/a$ for the SPC scenario. Clearly, the traditional estimation does not depend on the PU protection range. Differently, the proposed estimation strategy is deeply affected by the PU protection range. This behavior is reasonable since the proposed strategy takes into account the mobile nature of the PU network. More in detail, the channel availability decreases as the normalized PU protection increases, and it collapses in the traditional estimation when the normalized PU protection range goes to 1, since the CU is always inside the PU protection range. We underline that for PU protection range values of practical interest, the proposed strategy provides a significantly more accurate estimation of the channel availability with respect to the traditional

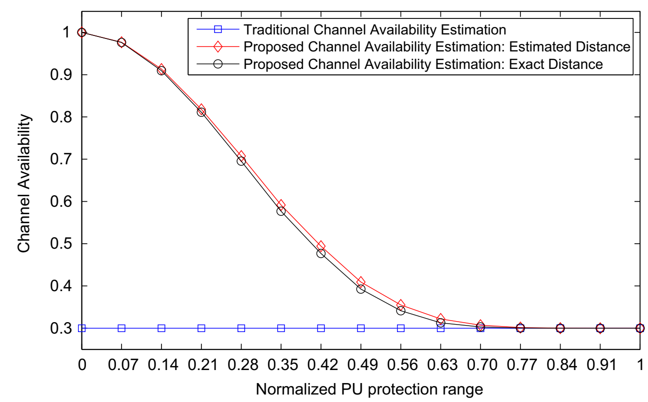

Fig. 5. Channel Availability vs. PU protection range in MPC scenarios.

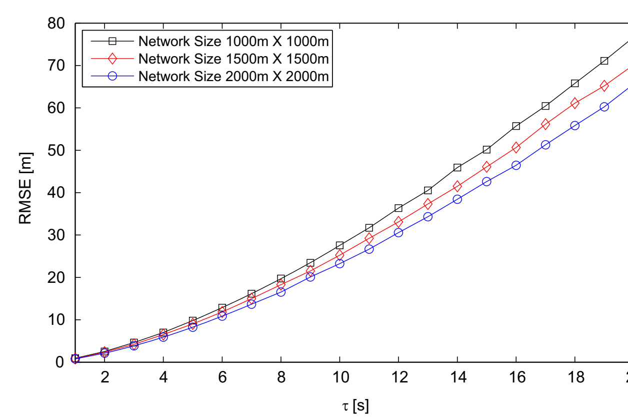

Fig. 6. RMSE vs. τ for different network region sizes.

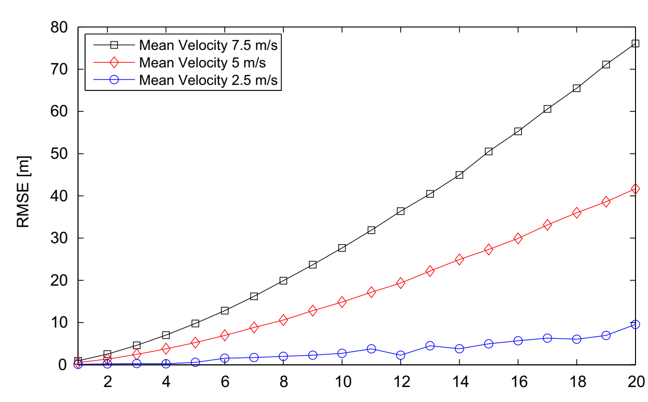

Fig. 7. RMSE vs. τ for different average PU velocities.

channel-availability estimation, since it is able to account for the non-stationarity of the PU network topology. Clearly, the additional cost the proposed scheme has to pay with respect to the traditional scheme is constituted by the periodic acquisition of the PU positions that as underlined in the footnote 7 can be obtained through either location estimation algorithms (Liu et al., 2009) or dedicate databases (Caleffi and Cacciapuoti, 2014).

We finally observe a good match between the curve obtained when the distance is perfectly know and the curve obtained through distance estimation.

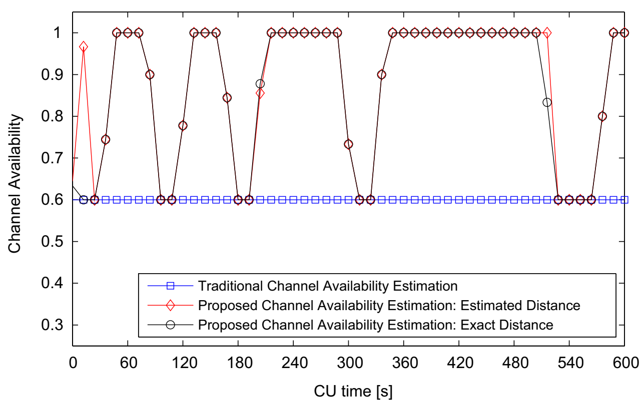

Fig. 8. Channel availability vs. CU time in SPC scenarios.

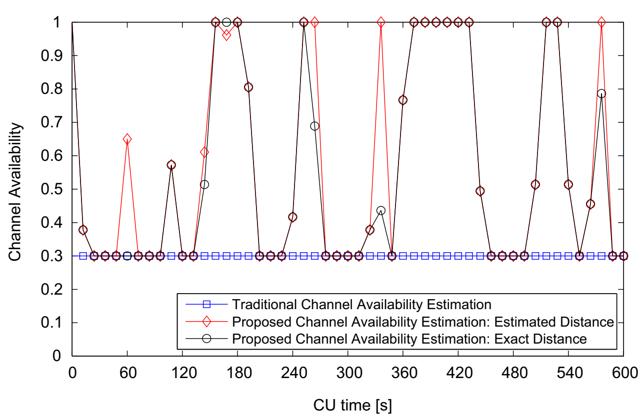

Fig. 9. Channel availability vs. CU time in MPC scenarios.

5.2. Experiment 2

In this experiment, we adopt the same simulation set of Experiment 1, and we consider two PUs affecting the CU transmissions, with PU inactive probability equals to 0.6 and 0.5, respectively.

In Fig. 5, we report the channel availability as a function of the normalized PU protection range $R_{i,l}/a$ for the MPC scenario. All the considerations made for the SPC scenario hold also in the MPC scenario. Moreover, we observe that the channel availability in the MPC scenario is lower than the SPC scenario. This is reasonable and in agreement with Proposition 2, since the probability of a CU being inside the protection range of the PU increases with the number of active PUs on a given channel.

5.3. Experiment 3

In this experiment, we evaluate the impact of the localization error on the channel-availability estimation. More in detail, we note that the larger is the PU position update interval τ, the lower is the updating rate of the PU position, i.e., the lower is the network overhead and energy consumption. However, the larger is τ, the less accurate is the estimation of the distance described in the proof of Proposition 1. In particular, when τ increases, the error increases as well, and it has an impact on the accuracy of the estimation model which can be assessed in terms of Root Mean Square Error (RMSE).

By adopting the same simulation set of Experiment 1 and by setting the PU protection range to 500 m, in Fig. 6 we report the RMSE of the estimated distance as a function of τ for different network region sizes. In particular, the RMSE increases when the network size decreases, since the smaller is the network size, the more likely the PU changes its direction in a given time interval, in according to the random waypoint mobility model (Camp et al., 2002).

Moreover, in Fig. 7 we report the RMSE of the estimated distance as a function of τ for different average PU velocity. Specifically, the PUs move according to the RWP model with velocity uniformly distributed in the intervals $[0,5]$, $[2.5,7.5]$, and $[5,10]$ m/s. In particular, the RMSE increases when the average PU velocity increases, since the higher is the PU velocity, the less accurate is the distance estimation used to evaluate the channel availability (see the proof of Proposition 1).

5.4. Experiment 4

Finally, in Figs. 8 and 9 we report the channel availability as a function of the CU time for both the SPC and MPC scenarios.

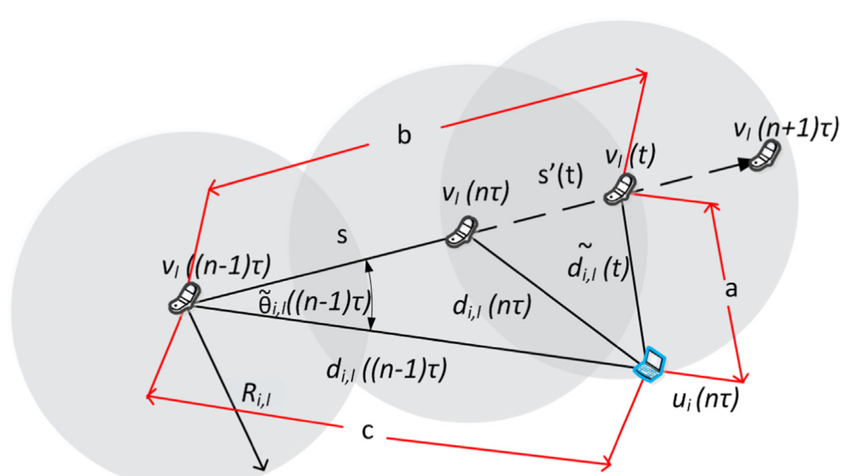

Fig. 10. Distance estimation procedure.

We observe that the channel-availability estimation changes in time. This is reasonable and it agrees with Propositions 1 and 2. We finally observe that the mismatch between the curve obtained when the distance is perfectly know and the curve obtained through distance estimation is due to the error of the distance estimation procedure.

6. Conclusion

In this paper, we design a strategy for estimating the channel availability in mobile cognitive radio networks. The proposed strategy takes advantage of the non-stationarity of the network topology induced by the users' mobility. Numerical results reveal the benefits of adopting the proposed strategy in mobile cognitive radio networks.

Appendix A

A.1. Proposition 1

At time instant $t_0 = n\tau$, CU u_i estimates the trajectory of ν_l in the time interval $[n\tau, (n+1)\tau)$ by accounting for the position information received at time instants $t_{-1} = (n-1)\tau$ and t_0.

More specifically, by assuming that the PU does not change its direction and velocity during the interval $[n\tau, (n+1)\tau)$ (this assumption is reasonable for small values of τ and/or small values of the average PU velocity, as confirmed by simulations in Section 5 of the PU mobility model), u_i estimates the distance $\tilde{d}_{i,l}(t)$ from ν_l at time $t \in (n\tau, (n+1)\tau)$ by applying the law of cosines to the triangle shown in Fig. 10:

$$\tilde{d}_{i,l}(t) = \sqrt{(s+s'(t))^2 + (d_{i,l}((n-1)\tau))^2 - 2(s+s'(t))d_{i,l}((n-1)\tau)\cos(\tilde{\theta}_{i,l}((n-1)\tau))} \tag{5}$$

where s denotes the traveled distance of ν_l during the interval $[(n-1)\tau, n\tau]$, $s'(t) = (s(t-n\tau))/\tau$ denotes the estimated traveled distance of ν_l during the interval $[n\tau, t]$ with $t \in (n\tau, (n+1)\tau)$, and $d_{i,l}((n-1)\tau)$ denotes the distance between u_i and ν_l at time instant $(n-1)\tau$. Moreover, $\tilde{\theta}_{i,l}((n-1)\tau)$ denotes the estimated relative movement direction of ν_l with respect to u_i at time $((n-1)\tau)$ and it can be estimated by applying again the law of cosines as follows:

$$\tilde{\theta}_{i,l}((n-1)\tau) = \cos^{-1}\left(\frac{s^2 + d_{i,l}^2((n-1)\tau) - d_{i,l}^2(n\tau)}{2sd_{i,l}((n-1)\tau)}\right) \tag{6}$$

Once the estimated distance $\tilde{d}_{i,l}(t)$ between u_i and ν_l at time t is available, if $\tilde{d}_{i,l}(t) > R_{i,l}$, then u_i can freely use the channel since it is outside of ν_l protection range, i.e., the channel is available with probability $\tilde{p}^{SPC}_{i,m,l}(T_{n,k}) = 1$. Differently, if $\tilde{d}_{i,l}(t) \le R_{i,l}$, u_i is inside ν_l protection range and, hence, the channel is available with probability $\tilde{p}^{SPC}_{i,m,l}(T_{n,k}) = P^{off}_{l,m}$.

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