MCAST: Mobility-aware Channel-Availability based Channel Selection Technique

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***Abstract*—A key issue in cognitive radio networks is the design of a channel selection technique that guarantees to utilize the highest available channel in presence of the dynamic activity of primary users. Usually, the channel selection techniques that operate in this kind of network are based on the channel-availability probability. In the static primary user's scenario, this probability can be *a priori* known or simply estimated from the channel occupancy history. However, in the mobile primary user's scenario, this probability dynamically varies in time due to the changes of the primary user's position. In order to exploit the dynamic variation of the channel availability, in this paper we design a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) that ensures the selection of the channel with the highest channel availability probability in a given temporal interval. The simulation results highlight the benefits of the proposed technique in presence of primary user's mobility. Moreover, we evaluate the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric designed for this network.**

***Index Terms*—Cognitive Radio, PU Mobility, Channel Availability Probability.**

I. Introduction

In Cognitive Radio Networks (CRNs), the channel selection techniques are usually based on the knowledge of the Channel-Availability Probability (CAP), i.e., the probability that the channel is available for the unlicensed users, referred to as Cognitive Users (CUs), without causing interference against the licensed users, referred to as Primary Users (PUs). In fact, this knowledge enables the CU to select the channel with the highest availability. Usually, the CAP coincides with the probability that at a certain time the PU is inactive, and can be *a priori* known or simply estimated from the channel occupancy history [1]. However, this assumption is valid when the PU is static.

On the other hand, in the mobile PU scenario, the CAP dynamically varies in time due to the changes of the PU position. For instance, if at a certain time the CU is outside the *protection range* (i.e., it is defined as the maximum distance between the PU and the CU at which the CU transmission does not interfere the PU communication on an arbitrary channel. It is determined by the PU transmission range and by the CU interference range [2]) of an arbitrary PU, then the CAP is independent from whether the PU is inactive or not. Due to the PU mobility, after a certain interval of time, the CU might be inside the protection range of the PU, then the CAP depends on the probability that the PU is inactive. Since the best performance is guaranteed by the channel with the highest CAP assumed at a given time, a fundamental key issue in CRNs is the *design of a channel selection technique that ensures the selection of the best channel by exploiting the dynamic variation of the channel availability caused by the PU mobility*.

Basically, most of the works in literature consider the static PU scenario where the CAP does not vary in time. In [3], Jha et al. propose an opportunistic multi-channel Medium Access Control (MAC) with QoS provisioning for distributed CRNs, where CUs use the previous channel scanning results to select those channels with the highest CAP. In [4], Xue et al. propose an opportunistic periodic MAC protocol where the CUs cooperate each wit other to share the channel-availability information. In [1], Chowdhury et al. propose a routing metric that aims to minimize the interference caused by the CUs against the static PUs. In [5], Caleffi et al. propose an optimal routing metric for CRNs where the channel is selected based on channel occupancy history. Finally, there are some other channel selection strategies that have been proposed in literature by using the assumption of static PU activity [6][7][8].

However, the design of a channel selection technique that accounts for the CAP in presence of PU mobility has not yet been addressed in literature. Cacciapuoti et al. [2] addressed the concept of CAP in mobile scenario. For this reason, we design a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) that ensures the selection of the channel with the highest CAP in a given temporal period.

Specifically, the contribution of this work can be summarized as follows. First, we derive the channel-availability estimation method in presence of PU mobility. Then, we prove that the proposed channel selection technique takes advantage of the dynamic variation of channel-availability caused by the PU mobility and, consequently, outperforms the traditional method which is only based on the PU temporal activity. The simulation results highlight the benefits of the

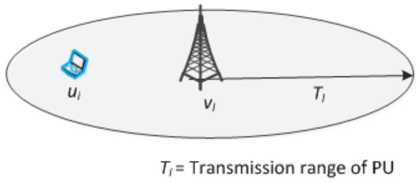

Fig. 1: CAP in presence of static PU.

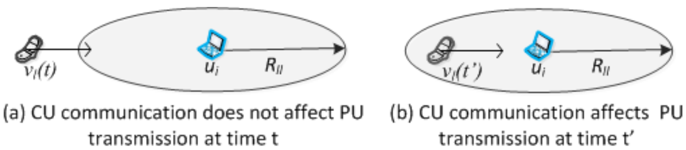

Fig. 2: CAP in presence of mobile PU.

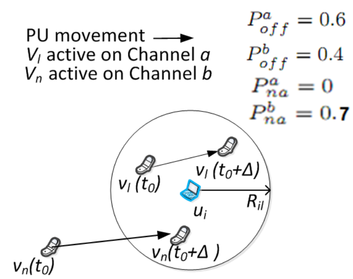

Fig. 3: Static method fails in selecting the channel with highest CAP between a and b. It selects channel a, although channel b is the highest one.

proposed technique. Moreover, we evaluate the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric, referred to as Optimal Primary-aware routE quAlity (OPERA) [5], designed for CRNs.

The rest of the paper is organized as follows. In Section II, we introduce the problem statement. In Section III, we discuss about the network model, while in Section IV, we describe the channel-availability estimation process. We describe the proposed MCAST in Section V, while the performances are evaluated through simulations in Section VI. Finally, in Section VII, we conclude the paper.

II. Problem Statement

In this section, we describe how the CAP in static PU scenario differs from the Mobile PU scenario and then, we present our proposal to overcome the adverse effects of PU mobility.

A. Static PU Scenario

In the static PU scenario, the geographic location of each PU is fixed, as shown in Figure. 1. In this case, the channel selection strategy, referred to as *static method*, considers PU inactive probability, denoted as P^m_{off}, for selecting the channel with the highest CAP [3][4][5]. This probability can be *a priori* known or simply estimated based on the channel occupancy history [1]:

$$P^m_{off} = \frac{\alpha^m}{\alpha^m + \beta^m} \tag{1}$$

where $\frac{1}{\alpha^m}$ and $\frac{1}{\beta^m}$ are the average *on* and *off* times for the *m-th* channel, respectively. The *on* time refers to the period where the *m-th* channel is occupied by the PU, while the *off* time indicates the channel is free for CU transmission.

B. Mobile PU Scenario

On the other hand, in the mobile PU scenario, the geographic location of each PU is not fixed and the channel availability dynamically varies in time. In fact, in Figure. 2 (a), the transmission of the *i-th* CU, denoted as u_i, does not affect the PU receiver at time t, since u_i is outside the *protection range* of the *l-th* PU transmitter, denoted as v_l. However, v_l is moving toward u_i at time t, then after a certain interval of time, in Figure. 2 (b), the transmission of u_i might affect the PU receiver at time instant t', since u_i is inside the protection range of v_l. Therefore, the CAP varies in the interval $[t, t']$.

In this scenario, if the CU selects the channel according to the *static method*, it will not achieve the channel with the highest CAP. We discuss this issue with an example. As shown in Figure. 3, there are two PUs, denoted as v_l and v_n, which are communicating on channel a and b, respectively. Due to the PU mobility, in a certain interval of time $[t_0, t_0 + \Delta]$, the CAP depends on two factors: *i)* The PU inactive probabilities, i.e., P^m_{off}; *ii)* The probability that the CU transmission does not affect the PU while it is active, i.e., P^m_{na}. The *static method* selects the best channel considering only the first factor. Since P^a_{off} is greater than P^b_{off}, the best channel with the highest CAP according to the *static* method is channel a, since $P^a_{off} > P^b_{off}$. However, in presence of PU mobility, the selection of channel a does not assume the best choice in terms of channel availability. According to the procedure which considers both factors, referred to as *mobility-aware method*, the channel with the highest CAP is channel b, since in this method the $CAP^a = P^a_{off} + (1 - P^a_{off})P^a_{na} = 0.6 + 0.4 \times 0 = 0.6$ is less than $CAP^b = P^b_{off} + (1 - P^b_{off})P^b_{na} = 0.4 + 0.6 \times 0.7 = 0.82$. As a result, at a certain time t_0, the *mobility-aware method* achieves the best channel in presence of PU mobility selecting it with the highest CAP for the next interval of time $[t_0, t_0 + \Delta]$.

From the above example, it is evident the need for designing a proper channel selection technique that ensures the selection of the best channel by exploiting the dynamic variation of the CAP caused by the PU mobility.

C. Proposed Method

The proposed channel selection technique is based on the channel-availability estimation method in order to estimate the channel-availability for a given interval of time. The method is described as follows.

- Firstly, it estimates the distance between PU and CU at time instant t where t belongs to the next temporal interval (See Section IV-A);

- Based on the estimated distance, it estimates the CAP for each channel at time t ;
- Then, it estimates the average CAP for each channel in the next temporal interval;
- Finally, MCAST selects the channel based on the highest average CAP for the next temporal interval.

The proposed channel selection technique is designed for mobile PU scenario with the objective to overcome adverse effects of PU mobility.

III. Network Model

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

A. PU Network Model

The PUs move according to the Random WayPoint Mobility (RWPM) model [9] inside a square network region $\mathcal{A}$. Each PU randomly chooses a destination point in $\mathcal{A}$ according to a uniform distribution, and it moves towards this destination with a velocity modeled as a random variable uniformly distributed in $[v_{min}, v_{max}]$ m/s and, statistically independent of the destination point. During each PU movement period, it is assumed that the PU does not change its direction and velocity. The PU traffic on the *m*-th channel is modeled as a two-state birth-death process [10]. Moreover, we consider two different PU spectrum occupancy models [11]. In the first model called Single PU for Channel (SPC), the PUs roam within the network region using different channels. In the second model called Multiple PUs for Channel (MPC), different mobile PUs can use the same channel.

B. CU Network Model

The CUs are assumed static (it is straightforward to prove that the derived expressions hold also if we assume mobile CR users and static PUs), where $u_i(t)$ denotes the position of the *i-th* CU that is constant in time. Each CU obtains its location information once during the network initialization, (the CU can obtain its location either directly through dedicated positioning systems such as Global Positioning System (GPS) or indirectly through location estimation algorithms) whereas it can update the PU position every τ seconds, referred to as *PU position updating interval*. 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 [12][13][14] or dedicate databases.

IV. Channel-Availability Estimation

Since the CU does not know the effective PU position during τ, a distance estimation method should be derived to estimate the channel availability during this temporal interval, with the aim to select the channel with the highest CAP. Thus, in this section we single-out the distance estimation procedure (Section. IV-A) and the estimated CAP expression in both Single PU for Channel (Section. IV-B) and Multiple PUs for Channel (Section. IV-C) scenarios. Finally, we discuss the trade-off that exists between the PU position updating interval τ and the distance estimation error (Section. IV-D). The CAP estimation process of [2] is adopted in this paper. For the details about CAP estimation, we refer the reader to [2].

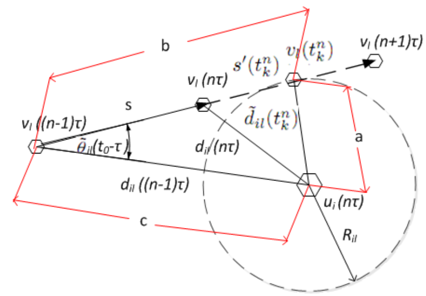

Fig. 4: Distance Estimation Procedure.

A. Distance Estimation Procedure

The distance estimation procedure is depicted in Figure. 4 where the *i-th* CU and the *l-th* PU are denoted with u_i and v_l, respectively, and R_{il} denotes the *protection range*. The PU v_l is mobile and its position at a generic time instant t is denoted, for simplicity of notation, as $v_l(t)$, and the distance between u_i and v_l is denoted as $d_{il}(t)$. At the time instant t_0, the CU can calculate several parameters related to the previous interval $[t_0 - \tau,\, t_0]$, such as $d_{il}(t_0 - \tau)$ and $d_{il}(t_0)$, the traveled distance of v_l during the interval $[t_0 - \tau,\, t_0]$ denoted as s, the estimated movement direction of v_l toward u_i at time $(t_0 - \tau)$ denoted as $\tilde{\theta}_{i,l}(t_0 - \tau)$. Based on these information, along with the estimated traveled distance of v_l during the interval $[t_0,\, t]$ denoted as $s'(t)$, u_i can estimate the distance $\tilde{d}_{il}(t)$ when t belongs to the next temporal period $[t_0,\, t_0 + \tau]$.

B. CAP estimation in Single PU for Channel (SPC) scenario

In this subsection, we derive (Theorem 1) the estimation $\tilde{p}^m_{il}(t)$ of the CAP when $t \in [t_0, (t_0 + \tau)]$ in SPC scenario under the following assumptions: i) The CU knows the PU position at the actual time instant t_0 and at the previous time instant $t_0 - \tau$; ii) The PU does not change its direction and velocity during the interval $[t_0 - \tau, t_0 + \tau]$ (this assumption is reasonable beacuse of the PU mobility model). Since the proof of Theorem 1 requires an intermediate result, we first present it in Lemma 1.

Lemma 1. *The estimated distance $\tilde{d}_{il}(t)$ between the i-th CU and the l-th PU at time instant $t \in [t_0, (t_0 + \tau)]$ is given by:*

$$\tilde{d}_{il}(t) = \sqrt{a^2 + b^2 - 2ab\cos(\tilde{\theta}_{il}(t_0 - \tau))} \tag{2}$$

where $a = (s + s'(t))$ is the distance traveled by the l-th PU during the temporal intervals $[t_0 - \tau, t]$ and $\tilde{\theta}_{il}(t_0 - \tau)$ is the estimated movement direction of the l-th PU towards the i-th CU at the time instant $(t_0 - \tau)$.

Proof. We refer the reader to [2], for the proof of Lemma 1. □

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By means of Lemma 1, we can now derive the expression of the estimated CAP $\tilde{p}_{il}^{m}(t)$ when $t \in [t_0, (t_0 + \tau)]$ in the SPC scenario.

Theorem 1. *The estimated CAP $\tilde{p}_{il}^{m}(t)$ at time $t \in [t_0, (t_0+\tau)]$ assume the following expression:*

$$\tilde{p}_{il}^{m}(t) = \begin{cases} 1 & \text{if } \tilde{d}_{il}(t) > R_{il} \\ P_{off}^{m} & otherwise \end{cases} \quad \forall\, t \in [t_0, (t_0 + \tau)] \quad (3)$$

Proof. From the Lemma 1, we can estimate distance at time t. Utilizing $\tilde{d}_{il}(t)$, the theorem can proof directly. □

Remark. *The estimated CAP $\tilde{p}_{il}^{m}(t)$ depends on the estimated distance $\tilde{d}_{il}(t)$. Since it is assumed that the l-th PU does not change the velocity and direction during the interval $[t_0 - \tau, t_0 + \tau]$, the estimation procedure will encounter an error that depends on the PU mobility parameters and the temporal period τ. The trade-off is discussed in the subsection IV-D.*

C. CAP estimation in Multiple PUs for Channel (MPC) scenario

In this subsection, we derive (Theorem 2) the expression of the estimated CAP when $t \in [t_0, (t_0 + \tau)]$ in the MPC scenario, under the same assumptions of the Theorem 1.

Theorem 2. *If a number N of PUs, which are the elements of a primary user set V^m, use the same channel m simultaneously, then the estimated CAP $\tilde{p}_{iV}^{m}(t)$ at time $t \in [t_0, (t_0+\tau)]$ assume the following expression:*

$$\tilde{p}_{iV}^{m}(t) = \begin{cases} 1 & \text{if } \tilde{d}_{il}(t) > R_{il} \quad \forall\, l \in V^m \\ P_{off}^{m} & otherwise \end{cases} \quad \forall\, t \in [t_0, (t_0 + \tau)] \quad (4)$$

Proof. It is similar to the Theorem 1. □

Remark. *When the i-th CU is outside the protection range of all the N PUs belong to V^m then the CAP is equal to one, otherwise it depends on the PU inactive probability. Since the probability that the i-th CU is inside the protection range of the arbitrary PU increases when N increases, then the CAP in the MPC scenario is lower than the SPC scenario.*

D. Trade-off between the PU position updating interval τ and distance estimation error

It is worth noticing that the larger is τ, the smaller is the updating rate of the PU position, i.e., the lower is the network overhead and energy consumption. However, the estimation of the distance for the next temporal period becomes less accurate. We explain this concept with an example, as shown in Figure. 5. Here, the non-dashed line is the exact PU movement pattern, and $v_l(t)$ and $\tilde{v}_l(t)$ represent the exact and estimated PU position at time t, respectively. Since the distance at time t is estimated assuming that the PU does not change its velocity and direction during the interval $[(t_0 - \tau), (t_0 + \tau)]$, the estimation procedure will encounter an error when the PU changes these parameters during this interval. 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

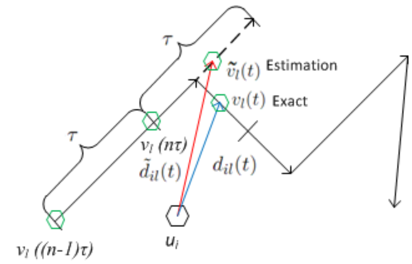

Fig. 5: PU movement pattern.

assessed in terms of Root Mean Square Error (RMSE). The RMSE increases with the increasing value of τ. In particular, the RMSE increases when the network size decreases, since the smaller is the network size, the greater is the frequency that the PU change its direction, in according to the random waypoint mobility model [2]. In Section. VI, we will assess the impact of τ on the estimation of the CAP.

V. Mobility-Aware Channel-Availability Based Channel Selection Technique

In this section, we discuss about proposed Mobility-aware Channel-Availability based channel Selection Technique. Based on the estimation model derived in the previous section, the CU selects the best channel in both the SPC (Theorem 3) and MPC (Theorem 4) scenarios with the highest value of the estimated CAP averaged over the next temporal period $[t_0, t_0 + \tau]$.

Theorem 3. *The expression of the MCAST in SPC scenario is the following:*

$$m_{opt}^{SPC} = \arg\max_{m} \tilde{q}_{il}^{m}(t_0, \tau) = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \tilde{p}_{il}^{m}(t)dt \quad (5)$$

where $\tilde{q}_{il}^{m}(t_0, \tau)$ denotes the estimated CAP averaged on $[t_0, t_0 + \tau]$ in the SPC scenario, that depends on the time instant t_0 and the period τ.

Proof. It follows by accounting for Theorem 1. □

Theorem 4. *The expression of the MCAST in MPC scenario is the following:*

$$m_{opt}^{MPC} = \arg\max_{m} \tilde{q}_{iV}^{m}(t_0, \tau) = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \tilde{p}_{iV}^{m}(t)dt \quad (6)$$

where $\tilde{q}_{iV}^{m}(t_0, \tau)$ denotes the estimated CAP averaged on $[t_0, t_0 + \tau]$ in the MPC scenario, that depends on the time instant t_0 and the period τ.

Proof. It follows by accounting for Theorem 2. □

Remark. *The value of $\tilde{q}_{il}^{m}(t_0, \tau)$ and $\tilde{q}_{iV}^{m}(t_0, \tau)$ equal to one when the estimated distance during $[t_0, t_0 + \tau]$ is always greater then the protection range, it is equal to P_{off}^{m} when the estimated distance is always less than or equal to the protection range during $[t_0, t_0 + \tau]$, while it is comprised between one and P_{off}^{m} in the intermediate case.*

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By exploiting the dynamic variation of the channel availability caused by the PU mobility, the proposed technique is able to outperform the static method that considers only the PU temporal activity. The simulation results in Section. VI highlight the benefits of using the proposed technique for selecting a channel in presence of PU mobility.

VI. Simulation Results

In this section, first we evaluate via numerical experiments the performance of the proposed channel selection technique (MCAST). Then we prove its effectiveness by adopting MCAST in a routing metric, recently proposed in literature, referred to as OPERA [5].

A. Performance evaluation

Figure. 6 (a-d) shows the performance comparison between the *mobility-aware method* (MCAST) and the *static method* in terms of maximum CAP (CAP_{max}), i.e., every τ seconds we consider the maximum CAP achievable from the best selected channel among the others, then we average it over the total number of periods considered in the simulation.

Experiment 1: It is plotted the exact and the estimated CAP_{max} in the SPC scenario, along with the CAP_{max} corresponding to the static method, versus the normalized PU protection range where $R_{il} = \{500m, 600m, 700m, ..., 1400m\}$. The adopted simulation set is defined as follows: the CU transmission range is $T_i = 100m$, CU interference range is $I_i = 200m$, the PU transmission range is $T_l = 300m$, the number of channels is $M = 5$, the PU inactive probability vector is $\{0.6, 0.2, 0.3, 0.5, 0.4\}$, the PU spectrum occupancy model is SPC, i.e., each channel is used by a single PU. The PUs move in a square region of side $a = 2000m$ according to the RWPM model, where the minimum velocity is $v_{min} = 5m/sec$ and maximum velocity is $v_{max} = 10m/sec$.

In Figure. 6 (a), we note that there is a very good agreement between the estimated and exact CAP_{max} when $\tau = 10s$. The CAP_{max} decreases in both methods when the PU protection range increases, and achieves the minimum value (given by the static method) when the normalized PU protection range is equal to one. This is reasonable because the greater is the protection range, the lower is the percentage of time in which the PUs are outside the protection range. For the static method, the CAP_{max} is always 0.6 since it selects the channel according to the maximum PU inactive probability P^m_{off}.

In Figure. 6 (b), we note that the average error of the estimated CAP_{max} increases by increasing τ. This is because in the estimation model we assume that the PU does not change its velocity and direction during the interval $[(t_0-\tau), (t_0+\tau)]$. This error have an impact on the performance evaluation that means a trade-off between the effectiveness for the spectrum utilization and network overhead caused by the updating PU position mechanism.

Experiment 2: In this experiment, we consider the MPC scenario, i.e., each channel is used by multiple PUs, as shown in Figure. 6 (c, d). The adopted simulation set is the same defined in experiment 1, but we consider two PUs for each channel. We compare the CAP_{max} in the SPC and MPC scenarios. Specifically, we note that the CAP_{max} in the MPC scenario is lower than the SPC scenario. This is reasonable because, according to Theorem 2, the probability that the CU is inside the protection range of the PU increases when there are more PUs for each channel. The same considerations about the estimation model drawn for the SPC scenario are valid for the MPC scenario.

B. Effectiveness

In this subsection, we evaluate the effectiveness of MCAST in a scenario of practical interest. Specifically, we adopt MCAST in a recently proposed routing metric designed for CRNs, referred to as OPERA, and analyze the network performance in terms of packet delay [5].

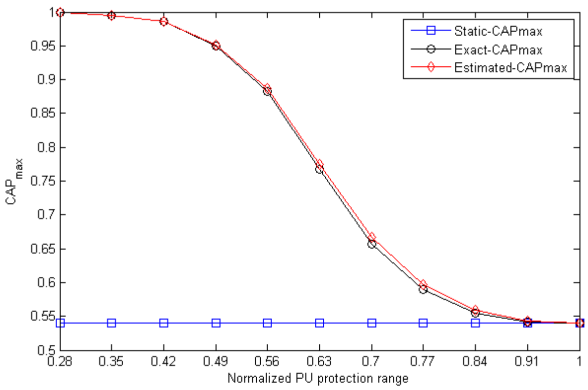
The network topology is shown in Figure. 6 (e) and it is similar to the one used in [1], with 64 CUs spread in a square region of side 1000m. The CU transmission standard is IEEE 802.11g, the packet length is L = 1500 bytes, the expected link throughput is $\bar{\psi}$ = 54Mbps, the transmission range of CU is equal to 200m, the transmission range of PU is equal to 166m and the number of channels is M = 2. Unlike the experiment in [1], we assume that the PUs are mobile and they are moving according to the RWPM.

Experiment 3: The experiment shows two different routes with the same source and destination, where the routes singled out by OPERA and OPERA with mobility-aware method (OPERA-MA), as shown in Figure. 6 (e). In the case of OPERA, where the static channel selection method is utilized, the delay is 0.57s. On the other hand, in the case of OPERA-MA we observe that the delay is significantly decreased to 0.34s, as it counteracts the adverse effect of PU mobility.

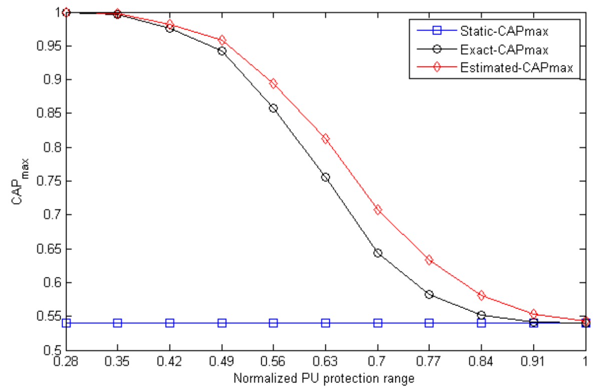
Experiment 4: In this experiment, we report the packet delay versus the distance between source and destination nodes for both the cases, as shown in Figure. 6 (f). First, we observe that the delay computed by both OPERA and OPERA-MA increases with the distance. This result is reasonable, because the longer is the path, the more is the number of PUs affecting it. However, we observe that OPERA-MA exhibits a significant improvement compared to OPERA when the distance increases, since more favorable paths are available by accounting for PU mobility.

VII. Conclusion

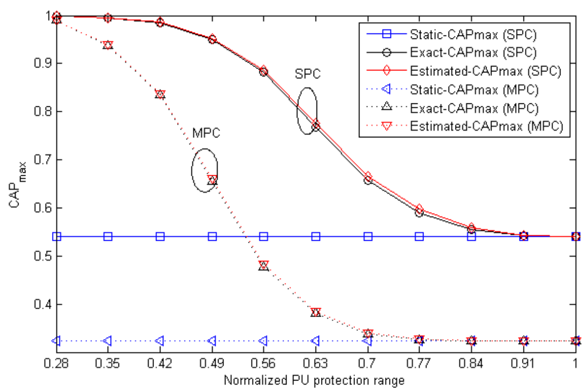
In this paper, we proposed a novel mobility-aware channel-availability based channel selection technique for CRNs that ensures the selection of the channel with the highest CAP in a given temporal period. In fact, this technique takes advantage of the dynamic variation of channel-availability caused by the PU mobility and consequently outperforms the static method which is only based on the PU temporal activity. The numerical experiments corroborate the theoretical results. Moreover, we evaluate the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric designed for CRNs. The



(a) Experiment 1: τ = 10s.



(b) Experiment 1: τ = 30s.



(c) Experiment 2: τ = 10s.

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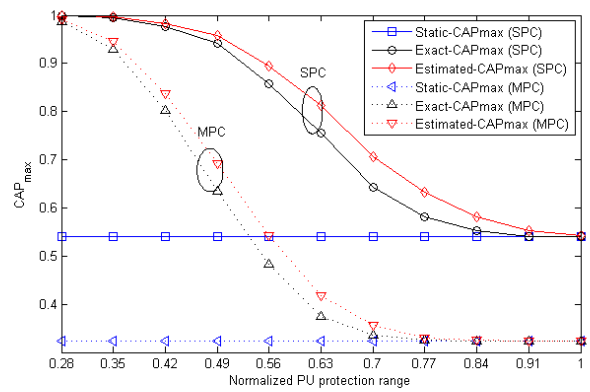
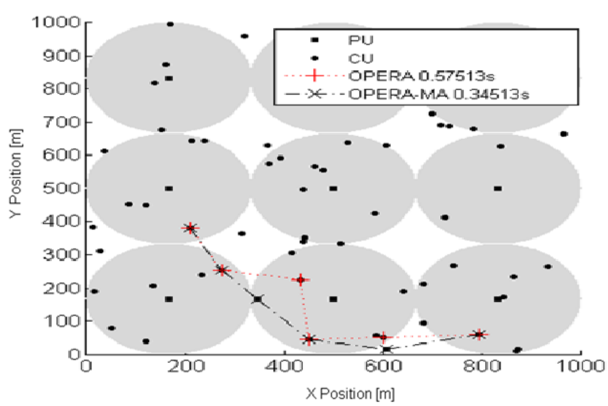
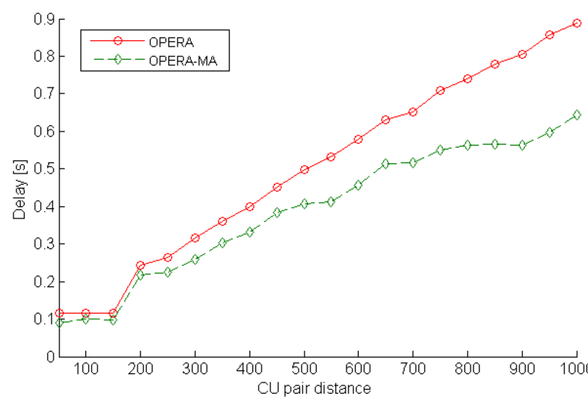


(d) Experiment 2: τ = 30s.



(e) Experiment 3



(f) Experiment 4

Fig. 6: (a, b) Maximum CAP vs normalized PU protection range in SPC scenario; (c, d) Maximum CAP vs normalized PU protection range in both SPC vs MPC scenario; (e) Two different routes and the respective delays between the same pair source-destination, the routes singled out by OPERA and OPERA-MA; (f) Delay vs. CU pair distance for OPERA and OPERA-MA.

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future research development foresee the design of a MAC protocol based on the proposed channel selection method.

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