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RESEARCH ARTICLE

A Dynamic Channel Access Strategy for Underlay CRNs: Markov Modeling and Performance Evaluation

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ABSTRACT

Unlike in overlay cognitive radio networks, secondary users (SUs) in underlay cognitive radio networks can access licensed spectrum even at the presence of a primary user (PU), given that the interference caused by the secondary transmission is lower than a pre-specified threshold. Based on this underlay access principle, we propose in this paper a dynamic channel access strategy for multi-channel cognitive radio networks. Different from existing underlay access techniques, channel assembling, spectrum adaptation and restricted channel occupancy are also considered in the proposed strategy in order to achieve better performance in the secondary network. The system performance is evaluated for both primary and secondary networks and a comparison analysis is carried out to assess the cost against the gain. Numerical results demonstrate that the proposed underlay channel access strategy outperforms the corresponding overlay strategy in terms of secondary network capacity, blocking probability and dropping probability. The cost and gain analysis identifies appropriate traffic conditions under which the overall system performance could be improved by employing the proposed underlay strategy.

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1. INTRODUCTION

Cognitive radio (CR) is envisaged as one of the enabling technologies for the next generation heterogeneous wireless network [1]. Various mobile and wireless networks for intelligent transportation, public safety, emergency as well as military communications can take the advantage of the CR concepts in order to achieve more reliable communication [2]. Depending on how the licensed spectrum is accessed, the operation mode of cognitive radio networks (CRNs) can be classified into overlay and underlay [3]. In overlay cognitive radio (OCR), a channel can be accessed by an SU if and only if the primary user (PU) signal is absent [5], [6]. Consequently, SUs can only transmit during the idle periods without being subject to explicit interference constraints within the allocated band. On the other hand, given that PU signals may be successfully decoded if the interference generated by the other sources is tolerable [7], SUs can access the spectrum even when there is an active PU transmission as long as the generated interference at the PU receiver is lower than a pre-defined threshold. This fact evolved the concept of underlay cognitive radio (UCR) [8], [9]. The main advantages of the UCR techniques include further improvement of secondary network performance and efficient spectrum utilization. Additionally, recent research attempts enable also hybrid access in CRs based on both overlay and underlay paradigms [4], [10]-[12].

To provide services to SUs, the accessibility of channels and the capability to complete transmissions without interruptions are of significance. For instance, in emergency communications over the *overlay mode*, it might be unfeasible to find an idle channel for an SU service when most of the spectrum is occupied by the licensed users [13]. Generally speaking, it is difficult to find a workable solution to solve this problem in the overlay mode since SUs cannot perform simultaneous transmissions on the same channel together with PUs. This observation triggered our motivation to propose a channel access strategy based on the *underlay access mode*.

The channel access strategy proposed in this paper is a continuation of our earlier work in [14] and [15] in which we proposed several *overlay* channel access strategies for multi-channel CRNs with channel assembling and spectrum adaptation. In this paper, we extend those techniques and propose a channel access strategy for UCR networks. The main idea of this work is to jointly apply channel assembling and spectrum adaptation with underlay channel access in order to improve SU network performance.

The contributions of this work can be summarized as follows:

- A new channel access strategy is proposed for UCR networks as an extension to an existing overlay channel allocation strategy investigated in [14] and [15].
- A continuous time Markov chain (CTMC) model is developed to evaluate the system performance of *both primary and secondary networks* with respect to throughput, blocking probability, forced termination probability and the average number of commenced services.
- A cost against gain analysis* is presented and it can be used to decide the applicability of the proposed solution for a given traffic scenario.

The remainder of this paper is organized as follows. In Sec. 2, we give an overview of the related work. In Sec. 3, the system models, including the proposed channel access strategy, are explained. By providing the theoretical analysis in Sec. 4, different CTMC models are developed to analyze the system performance. Numerical results are presented in Sec. 5 while Sec. 6 features the paper's conclusion.

2. RELATED WORK

Several underlay channel access techniques have been proposed in the literature to enhance the system performance of CRNs in terms of various parameters. In [9], a channel access scheme for UCR was proposed considering PUs' interference constraints. As illustrated in the simulation results presented therein, the overall throughput of the secondary network can be increased significantly. However, other performance improvement techniques such as channel assembling or spectrum adaptation were not addressed in [9]. In [12], a hybrid strategy which combines both overlay and underlay schemes was proposed to reduce interfering probability. In that work, interfering is said to occur when the SU causes higher-than-threshold interference to the PU receiver. As depicted in the numerical results therein, the proposed strategy improves the system interfering probability performance. Anyhow, [12] does not take the multi-channel scenario into account when proposing the hybrid strategy for CRNs.

Furthermore, a resource allocation framework was presented in [16] for UCR networks. In that study,

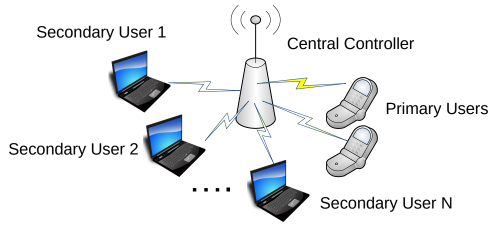

Figure 1. Network scenario of a CRN with centralized architecture.

both quality of service (QoS) for SUs and interference constraints for PUs were considered in order to provide satisfactory services for both networks. Several performance metrics such as outage probability, total throughput and the number of admitted secondary users are investigated for performance evaluation. However, the effect on dropping probability of ongoing calls has not been investigated in [16].

To summarize, most papers which study channel allocation for UCR networks did not take into account the tradeoff between interference mitigation in the primary network and the QoS improvement of the secondary network. This work combines the technique based on partial channel occupancy with channel aggregation and spectrum adaptation and studies the tradeoff between SU capacity gain and PU capacity loss under the UCR regime.

3. SYSTEM MODEL

The considered network scenario and the assumptions are explained in the following subsection.

3.1. Network Scenario and Assumptions

In this paper, we perform a flow-level analysis which captures the dynamics related to the arrivals and departures of PU and SU services. Consider a multi-channel CRN consisting of $M \in \mathbb{Z}^+$ primary channels and a number of PUs and SUs. Here $\mathbb{Z}^+$ denotes the set of positive integers. The channel allocation of the CRN is performed by a central controller [17] as shown in Fig. 1. In this network, the central controller is connected to several coordinated base stations and it makes decisions on channel allocation and spectrum handoff.

The traffic arrival of both PU and SU services is assumed to be independent Poisson processes with arrival rates λ_P and λ_S respectively. This assumption is reasonable as long as the number of users is much greater than the number of available channels [18]. The service times for PU services, and the volume of information to transfer for SU services are exponentially distributed, with corresponding service rates per channel μ_P and μ_S respectively.

While a PU service requires not more than one single channel, an SU service may assemble multiple channels if

*The cost against gain is analyzed in terms of PU capacity loss and SU capacity gain observed in the proposed strategy in comparison with the legacy system.

available. All channels are assumed to be homogeneous. Thus, the service rate of k assembled channels in a secondary network equals to $k\mu_S$ for SU traffic. Other than this, we assume that the sensing and spectrum adaptation latency is negligible in comparison with the duration between two consecutive service events. In this study, the proposed underlay channel access strategy follows the same principle as presented in [14] as discussed below, but it is tailored to the underlay CRNs. In this paper, we focus on the analysis for non-real-time services.

3.2. Dynamic Channel Access Strategy with UCR

The proposed strategy in this paper is referred to as underlay dynamic channel access (UDCA) and it includes channel aggregation, *channel sharing*[†] and spectrum adaptation for multi-channel CRNs. Those three methods are briefly explained follows.

- By *channel aggregation*, it is meant that one SU service can utilize multiple channels if available in order to provide higher data rate services for the SU flow.
- Through *spectrum adaptation*, an ongoing SU service may perform spectrum handoff to another channel once a PU activity appears on the current channel. In addition, the number of occupied channels can also be adjusted according to the availability of vacant channels.
- Channel sharing means that two SU services or one SU service and one PU service may co-exist in one channel.

Different from the overlay access paradigm, a single channel can be shared by either two SU services with half channel occupancy (HCO), or one PU and one SU service with partial channel occupancy (PCO) as mentioned below. In PCO, we define a configurable parameter, α, where $0 \leq \alpha \leq 0.5$, as a scaler indicating the channel occupancy level of an SU service when co-existing with a PU in the PCO mode. For instance, $\alpha = 0.2$ means that the exact proportion of the achievable data rate per channel (which can be translated into the fraction of μ_S) that an SU service obtains is 20% when co-existing with a PU service on the same channel. However, the specifications of the physical layer techniques underlying this PCO are beyond the interest of this study. Consequently, the service rate of a channel in a secondary network with PCO scalar α equals to $\alpha\mu_S$. In this study, an upper bound for α is imposed on purpose in order to keep the *priority access* privilege of the PUs and to minimize the interference occurred at the PU receiver. Moreover, this PCO scaler α is considered homogeneous across all channels in the considered UCR network. It is clear that, in this strategy, PUs are willing to cooperate with SUs. We can assume, for instance, that the SUs with PCO may cooperatively relay the primary data to its destination during the SU's service time. These relaying services of SUs would compensate the amount of PU network's sacrifice [19].

According to our strategy, each PU service can be accommodated with single channel by using either full channel occupancy (FCO) or PCO, depending on the channel availability. However, we do not consider any possible simultaneous transmissions of two PU services on the same channel. Furthermore, we consider another parameter $V \in \mathbb{Z}^+$ which determines the upper bound of the number of aggregated channels for an SU service. Once an SU service gets the opportunity for FCO access, channel aggregation is performed only with an integer number of channels up to V. In other words, SU services with single channel occupancy will not perform further channel aggregation with HCO or PCO. Hereafter, the details of the UDCA strategy is presented by specifying the behavior of the system after an arrival/a departure of a PU/SU event occurs.

3.2.1. PU arrival

If there is an idle channel upon a new PU arrival, PU will commence transmission on the idle channel. Otherwise, the SU service which has the maximum number of aggregated channels releases one channel for the newly arrived PU, if there is at least one SU service which occupies more than one channel. If the system has neither idle channels nor SU service with more than one channel, but there are at least two SUs each with FCO, a channel is allocated to the new PU as follows. Each of these two SUs with FCO will reduce their transmission rate by 50% and they will share one of these two channels by using HCO, thus releasing the other one to the new PU service. If there is only one SU service with FCO, the new PU service will co-exist with that SU on the same channel, however based on the PCO mode.

Furthermore, if all channels are occupied by PUs and SUs and there is no SU with FCO, then one of the SU services with HCO will perform handover to a channel in which a PU service with FCO exists and then share the channel in the PCO mode with that PU. The newly arrived PU can then share the channel with the co-existing SU service in the PCO mode. In the worst case, if all channels are occupied by PUs and SUs and none of them are with FCO, then one of the SU services with HCO is forced to terminate and the newly arrived PU service can share the channel with the co-existing SU service in the PCO mode. Moreover, if all channels are occupied by PUs with FCO or PCO, then the new PU request will be blocked. More specifically, the above mentioned PU arrival process is presented in Algorithm 1 where N_{idle} denotes the number of idle channels in the system while PU_{new} indicates the newly arrived PU service. The other notations used in this algorithm and Algorithm 2 presented in the next subsection can be introduced via the CTMC model where the states of the CTMC model are represented by

[†]It is worth mentioning that channel sharing is not considered in [14], [15] whereas it applies to both PUs and SUs in this study.

if $N_{idle} > 0$ **then**
  PU$_{\text{new}}$ is commenced on an idle channel;
else if $N_{idle} == 0$ **then**
  if $j_k > 0$ *for any* $k \geq 2$ **then**
    The SU which has the maximum number of aggregated channels releases one channel for PU$_{\text{new}}$;
  else if $j_k == 0\ \forall k \geq 2$ **then**
    if $j_1 \geq 2$ **then**
      two SUs with FCO will share one of their channels by using HCO while the other one is released to PU$_{\text{new}}$;
    else if $j_1 == 1$ **then**
      PU$_{\text{new}}$ will co-exist with the SU with FCO on the same channel, however, using PCO;
    else if *(*$j_1 == 0$ *AND* $j_h \geq 0$ *AND* $i \geq 0$*)* **then**
      One of the SUs with HCO will perform a handover to a channel in which there is a PU service with FCO and then they share the channel in the PCO mode;
      PU$_{\text{new}}$ will share the channel with the other SU in the PCO mode;
    else if *(*$j_1 == 0$ *AND* $j_h \geq 0$ *AND* $i == 0$*)* **then**
      One of the SUs with HCO is forced to terminate;
      PU$_{\text{new}}$ will share the channel with the other SU in the PCO mode;
    else if *(*$j_1 == 0$ *AND* $j_h == i == 0$*)* **then**
      PU$_{\text{new}}$ will be blocked.

Algorithm 1: UDCA channel access upon a PU arrival.

if *departed PU was in FCO* **then**
  if $i_\alpha \geq 2$ **then**
    Two PUs with PCO will be upgraded to FCO;
    Their co-existing SUs share the vacant channel with HCO;
  else if $i_\alpha == 1$ **then**
    The PU with PCO will be upgraded to FCO;
    Its co-existing SU also upgrades to FCO;
  else if *(*$i_\alpha == 0$ *AND* $j_h > 0$*)* **then**
    Two SUs with HCO upgrade to FCO;
  else if *(*$i_\alpha == 0$ *AND* $j_h == 0$*)* **then**
    The SU with the minimum number of channels ($< V$) will occupy the vacant channel;
else if *departed PU was in PCO* **then**
  if $i_\alpha > 0$ **then**
    One of the PUs with PCO upgrades to FCO;
    Its co-existing SU performs spectrum handover to the channel where the PU departs and shares the vacant channel using HCO;
  else if $i_\alpha == 0$ **then**
    The co-existing SU upgrades to FCO.

Algorithm 2: UDCA channel access upon a PU departure.

$\boldsymbol{x} = (i_\alpha, i, j_\alpha, j_h, j_1, j_2, \cdots, j_k, \cdots, j_V)$. Here i_α and j_α denote the number of PU and SU services with PCO respectively[‡]. Moreover, j_k and i denote the number of SU services that aggregate $k = 1, 2, \cdots, V$ channels, and the number of PU services with FCO respectively. The number of ongoing SU services with HCO is denoted as j_h.

3.2.2. PU departure

Once a PU service with FCO departs while there are two or more ongoing PU services existing with PCO, then two of them will be updated to full channel access by changing its transmission rate from PCO to FCO. At the same time, their co-existing SU services perform spectrum handover to the newly vacant band and share the channel with each other using HCO. On the other hand, if there is only one PU service with PCO upon a departure of a PU with FCO, the co-existing SU service can also increase its transmission rate and upgrade to FCO. Moreover when a PU service with FCO is finished while there are no other ongoing PU services with PCO, one of the SUs with HCO will access the vacant channel by channel aggregation. Moreover, if all ongoing SU services have FCO or occupy more than one channel, then the SU service with the minimum number of aggregated channels (given that it is lower than V) will occupy the newly idle channel.

When a PU service with PCO is finished while there are more ongoing PU services existing with PCO, then

[‡]Note that, in any state, $i_\alpha = j_\alpha$ since PCO mode of a channel always means the channel is occupied by one PU and one SU service. However we keep both components in our notation since they represent numeric information on two different types of users in the network.

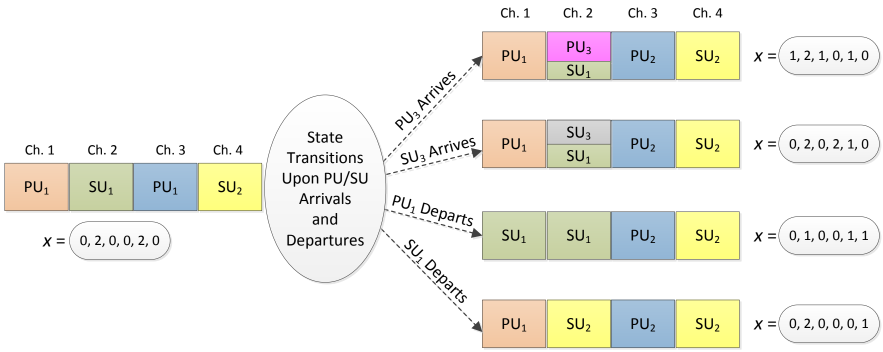

Figure 2. Possible state transitions from the original channel occupancy state $\boldsymbol{x} = (0, 2, 0, 0, 2, 0)$ under different events given that $M = 4, W = 1$ and $V = 2$. Upon a PU arrival, Ch. 2 is shared in the PCO mode by PU_3 and SU_1. Upon an SU arrival, it is shared by SU_1 and SU_3 in the HCO mode. When PU_1 departs, SU_1 could aggregate Ch. 1 together with its already occupied channel, Ch. 2, since the upper bound for channel aggregation is $V = 2$. Similarly, SU_2 aggregates Ch. 2 together with its already occupied channel, Ch. 4, if the service of SU_1 is finished.

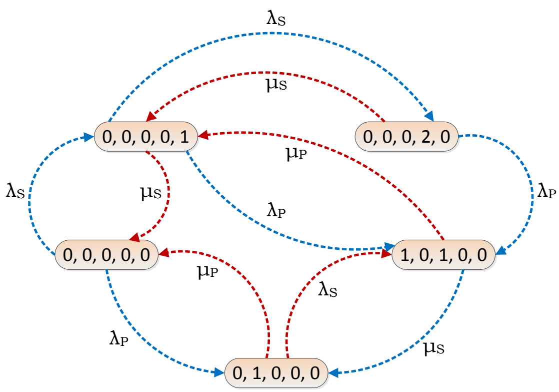

Figure 3. State transition diagram for the UDCA strategy when M=W=V=1.

one of them will be updated to full channel by changing its transmission rate from PCO to FCO and its co-existing SU service performs spectrum handover to the channel in which the PU departs and shares the channel with the other SU service under HCO. On the other hand, if there are no other PU services with PCO upon a departure of a PU with PCO, the co-existing SU service increases its transmission rate and upgrades to FCO. Algorithm 2 describes the PU departure event.

3.2.3. SU arrival

If there are multiple idle channels upon an SU arrival, the new SU service can access up to V channels. If all the channels are occupied, the ongoing SU service with the highest number of aggregated channels will donate one channel to the new SU service. This implies, correspondingly, that the donor SU must have at least 2 channels. Otherwise, one of the SU services with FCO will decrease its transmission rate as it degrades to HCO by allowing the new SU service transmit with HCO on the same channel. If all ongoing SU services are either with PCO or HCO, one of the PU services with FCO will share the channel with the new SU service. In the worst case, if none of the ongoing services (neither PUs nor SUs) are with FCO, the new SU request is blocked.

3.2.4. SU departure

The same as in the PU departure event, the first priority after a channel vacancy upon an SU departure is given to the PU services with PCO. For instance, once an SU with PCO or HCO is departed, one of the PU services with PCO will upgrade to FCO. If all ongoing PU services have FCO, then one of the ongoing SU flows with PCO or HCO will get the chance for service upgrading in sequence. On the other hand, if the departed SU service was with FCO, then the ongoing SU with the minimum number of aggregated channels (if it is $< V$) will occupy the vacant one by following the same rule as presented in Sec. 3.2.2.

4. CTMC ANALYSIS

In this section, we develop a CTMC model in order to analyze the performance of the proposed underlay strategy.

4.1. CTMC Modeling for the UDCA Strategy

As already mentioned, the states of the CTMC model can be represented by $\boldsymbol{x} = (i_\alpha, i, j_\alpha, j_h, j_1, j_2, \cdots, j_k, \cdots, j_V)$. Let $\mathcal{S}$ be the set of feasible states of the system such that $\mathcal{S} = \{\boldsymbol{x} | i_\alpha, i, j_\alpha, j_h, j_1, j_2, \cdots, j_V \geq 0; i_\alpha = j_\alpha; b(\boldsymbol{x}) \leq M\}$ where $b(\boldsymbol{x}) = i_\alpha + i + \frac{j_h}{2} + \sum_{k=1}^{V} k j_k$. As an example, Fig. 2 depicts the transition from a channel occupancy state upon different PU and SU arrival/departure events for the given scenario, $M = 4, W = 1$ and $V = 2$. In addition, the complete state transition diagram for the case, $M = W = V = 1$, can be found in Fig. 3, which illustrates the state transitions associated with different PU and SU activities.

Furthermore, the steady state probability of being in state $\boldsymbol{x}$ is denoted as $\pi_{\boldsymbol{x}}$. Given $\mathcal{S}$ and transitions in a CTMC, the global balance equations and the normalization equation can be constructed as $\boldsymbol{\pi Q} = \mathbf{0}$, $\sum_{\boldsymbol{x}\in\mathcal{S}} \pi_{\boldsymbol{x}} = 1$, where $\boldsymbol{\pi}$ is the steady state probability vector and $\boldsymbol{Q}$ denotes the transition rate matrix. $\mathbf{0}$ is a row vector of 0's of an appropriate size. Given the state probabilities, $\pi_{\boldsymbol{x}}$, the performance parameters can be derived, as presented below.

4.2. Performance Analysis of the UDCA strategy

The capacity of a service in a CRN can be defined as the average number of service completions per time unit [14]. Let ρ_{PU} and ρ_{SU} be the capacity of PU and SU services, respectively. Then, we have

$$\rho_{PU} = \sum_{\boldsymbol{x}\in\mathcal{S}} [(1-\alpha)i_\alpha + i]\mu_P \pi_{\boldsymbol{x}}, \tag{1}$$

$$\rho_{SU} = \sum_{\boldsymbol{x}\in\mathcal{S}} \left[\alpha j_\alpha + \frac{j_h}{2} + \sum_{k=1}^{V} k j_k\right] \mu_S \pi_{\boldsymbol{x}}. \tag{2}$$

A new SU service is blocked upon arrival when none of the ongoing services are with FCO. In other words, once each channel in the network is occupied by two services, i.e, the number of active services is equal to $2M$, the newly arrived SU will be blocked. Therefore the blocking probability of an SU service is given as

$$P_B = \sum_{\substack{\boldsymbol{x}\in\mathcal{S} \\ (i_\alpha + j_\alpha + j_h) = 2M}} \pi_{\boldsymbol{x}}. \tag{3}$$

A forced service termination of an ongoing SU would happen when all channels are occupied by PUs and SUs upon a PU arrival and there is no SU service with FCO. The forced termination probability can therefore be expressed as the ratio between the mean forced termination rate, R_{FT}, and the rate of commenced SU services, λ_{CSU}. Since $\lambda_{CSU} = (1 - P_B)\lambda_S$, we have

$$P_{FT} = \frac{R_{FT}}{\lambda_{CSU}} = \frac{\lambda_P}{(1-P_B)\lambda_S} \sum_{\substack{\boldsymbol{x}\in\mathcal{S} \\ (i_\alpha + j_\alpha + j_h) = 2M,\ i_\alpha < M}} \pi_{\boldsymbol{x}}. \tag{4}$$

Other than the above mentioned performance parameters, the average number of SU services in the system, N_{SU}, is also of interest. N_{SU} is defined as the number of SU services which start transmissions in the CRN, obtained by

$$N_{SU} = \sum_{\boldsymbol{x}\in\mathcal{S}} \left[j_\alpha + j_h + \sum_{k=1}^{V} j_k\right] \pi_{\boldsymbol{x}}. \tag{5}$$

4.3. Revisit the CTMC Model for the Overlay Strategy

In order to compare the performance of the proposed underlay strategy with that of the earlier studied overlay strategy which supports neither PCO nor HCO allocations, we revisit briefly the overlay strategy presented in [14] in which PU and SU services always occupy an integer number of channels using FCO. In addition to the upper bound, a lower bound $W \in \mathbb{Z}^+$ channels was also defined for channel assembling of SU services. Therein the states of the CTMC model corresponding to this overlay scheme can be represented by $\boldsymbol{y} = (i_P, j_W, j_{W+1}, \cdots, j_k, \cdots, j_V)$ where i_P denotes the number of PU services with single channel occupancy and j_k represents the number of SU services that aggregate $k = W, W+1, \cdots, V$ channels respectively. In this overlay strategy, $\mathcal{S}'$, $b(\boldsymbol{y})$ and $\pi_{\boldsymbol{y}}$ hold the corresponding meanings as $\mathcal{S}, b(\boldsymbol{x})$ and $\pi_{\boldsymbol{x}}$ in the underlay strategy. Therefore $\mathcal{S}' = \{\boldsymbol{y} | i_P, j_W, j_{W+1}, \cdots, j_V \geq 0; b(\boldsymbol{y}) \leq M\}$ where $b(\boldsymbol{y}) = i_P + \sum_{k=W}^{V} k j_k$. Similarly the mathematical expressions to calculate performance parameters in the overlay strategy are expressed as follows.

The capacity of PU and SU services is given by,

$$\rho'_{PU} = \sum_{\boldsymbol{y}\in\mathcal{S}'} i\mu_P \pi_{\boldsymbol{y}} \text{ and } \rho'_{SU} = \sum_{\boldsymbol{y}\in\mathcal{S}'} \sum_{k=W}^{V} k j_k \mu_S \pi_{\boldsymbol{y}} \tag{6}$$

respectively. According to the overlay strategy in [14], a new user is blocked when the number of idle channels plus the total number of channels that can be donated by ongoing users is fewer than W channels. Thus the blocking probability of new SU arrivals is given by

$$P'_B = \sum_{\substack{\boldsymbol{y}\in\mathcal{S}' \\ [M - b(y) + \sum_{k=W+1}^{V} (k-W) j_k] < W}} \pi_{\boldsymbol{y}}. \tag{7}$$

The forced termination probability can be expressed as

$$P'_{FT} = \frac{R'_{FT}}{\lambda'_{CSU}} = \frac{\lambda_P}{(1-P'_B)\lambda_S} \sum_{\substack{\boldsymbol{y}\in\mathcal{S}',\ b(y)=M \\ j_W > 0,\ j_n = 0,\ \forall n > W}} \pi_{\boldsymbol{y}}, \tag{8}$$

where R'_{FT} and λ'_{CSU} denote the mean forced termination rate and the rate of commenced SU services respectively. Similarly, the average number of SU services in the system is obtained as

$$N'_{SU} = \sum_{\boldsymbol{y}\in\mathcal{S}'} \sum_{k=W}^{V} j_k \pi_{\boldsymbol{y}}. \tag{9}$$

4.4. Cost and Gain Analysis

Conceptually, the proposed underlay access strategy can provide higher capacity for SUs, however, at the cost of lower capacity for PUs. Therefore, it is of interest to assess the gain against the cost when employing UDCA. Correspondingly, we define two parameters, ρ_{cost} as the

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capacity that the *primary network* loses due to PCO compared with the overlay strategy, and ρ_{gain} as the capacity that the *secondary network* gains due to PCO compared with the overlay strategy, as

$$\rho_{cost} = \rho'_{PU} - \rho_{PU} \quad \text{and} \quad \rho_{gain} = \rho_{SU} - \rho'_{SU} \tag{10}$$

Moreover, we introduce a cost-gain indicator (CGI) which is defined as the ratio between the capacity gain and the capacity cost functions, i.e.,

$$CGI = \frac{\rho_{gain}}{\rho_{cost}}. \tag{11}$$

The value of the CGI varies according to different traffic conditions such as service and arrival rates of users as well as α. When the CGI value is greater than one, it indicates that the proposed scheme outperforms the overlay scheme. The impact of such conditions upon CGI is analyzed in the numerical results presented below.

5. NUMERICAL RESULTS AND DISCUSSIONS

This section evaluates the performance of the proposed underlay strategy in comparison with the existing overlay strategy proposed in [14]. Unless otherwise stated, the following reference scenario is deployed for performance evaluation. Consider a CRN with $M = 6$ channels. The upper bound for channel assembling, $V = 2$ is configured for both strategies while the lower bound $W = 1$ is meant only for the overlay strategy. The default values of the arrival and service rates are set as $\lambda_P = 1$, $\lambda_S = 2$, $\mu_P = 0.5$ and $\mu_S = 1$ respectively. The units of these parameters could be services or flows per unit of time. We vary one of those parameters to evaluate the behavior of the performance metrics while keeping the other parameters constant.

5.1. SU and PU Network Capacity

Fig. 4 and Fig. 5 illustrate the secondary network and primary network capacity respectively as a function of the PU arrival rate under different configurations of the PCO scaler, α. Jointly considering both figures, it is clear that the SU capacity becomes higher and the PU capacity becomes lower with higher values of α. Since α indicates the channel occupancy level of an SU service under the PCO mode, the SU network completes a larger number of services per time unit when α becomes higher. The impact of α is dominant when the PU arrival rate is high. In comparison with the overlay strategy, the SU network capacity can be increased tremendously when adopting the proposed underlay strategy. For instance, when $\lambda_P = 5$, the underlay SU capacity is about 4 times as high as the overlay SU capacity when $\alpha = 0.2$, and it is about 3 times as high as when $\alpha = 0.1$. Consequently, the PU capacity becomes lower, however, the capacity degradation is not more than 25%.

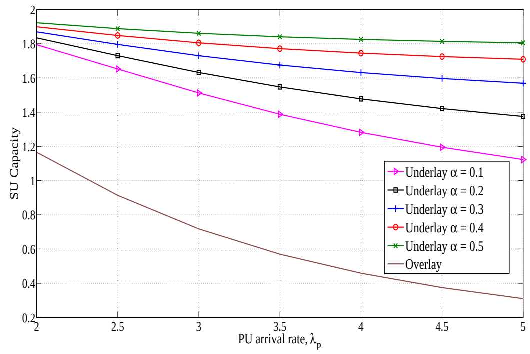

Figure 4. SU capacity as a function of PU arrival rate.

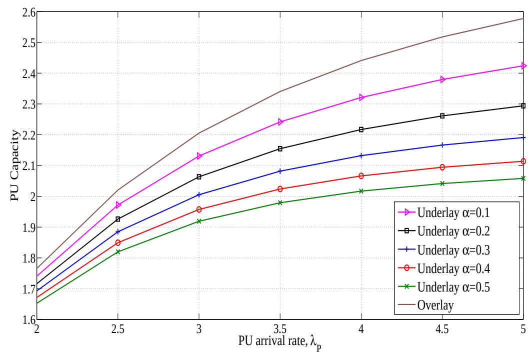

Figure 5. PU capacity as a function of PU arrival rate.

5.2. Cost against Gain Comparison

Fig. 6 illustrates the SU capacity gain and the PU capacity loss as a function of the SU service rate, μ_S, for $\alpha = 0.2$ and $\alpha = 0.5$ respectively. At a first glance, it is shown that the capacity gain is improved when α is increased, however at a cost of PU capacity loss. Moreover, in the CRN with $\alpha = 0.2$, capacity gain outweighs capacity loss when $\mu_S > 0.09$. Note that when $\alpha = 0.5$, in order to achieve the benefit, i.e., $\rho_{gain} > \rho_{cost}$, the service rate of the secondary network has to be greater than 0.18. This is expected since a higher value of the PCO scaler leads to lower PU capacity in the proposed strategy. Hence, an optimal selection of α for a given scenario is recommended. From another perspective, if the primary network is not willing to undergo more than 0.01 capacity loss when $\alpha = 0.2$, then the proposed underlay strategy cannot be recommended when $\mu_S < 0.35$, as shown in Fig. 6.

In order to further analyze this tradeoff, we observe the cost-gain indicator, CGI, given by (11) as a function of the PU arrival rate in Fig. 7. From this figure we can observe how the CGI value increases with a decreasing α and how it decreases with an increasing λ_P. When λ_P becomes higher, the capacity of the primary network also increases as observed in Fig. 5 in both strategies. However,

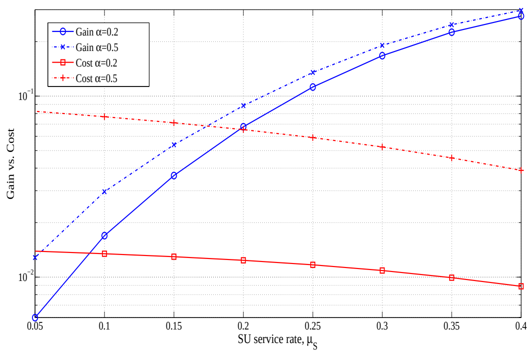

Figure 6. SU capacity gain versus PU capacity cost as a function of SU service rate.

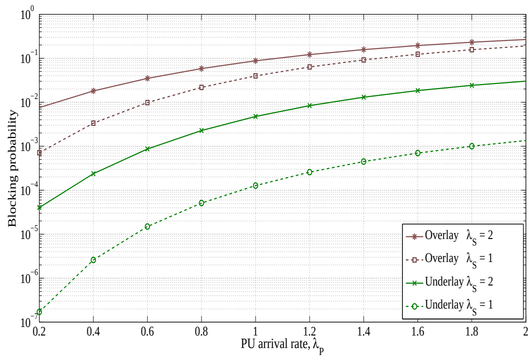

Figure 8. Blocking probability as a function of PU arrival rate when $\alpha = 0.5$.

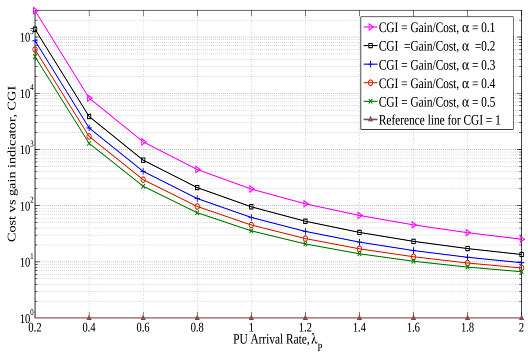

Figure 7. The cost-gain indicator, CGI, as a function of PU arrival rate.

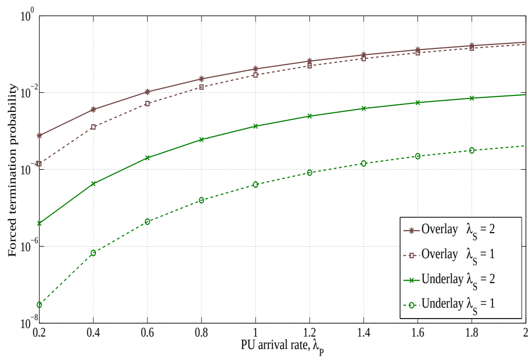

Figure 9. Forced termination probability as a function of PU arrival rate when $\alpha = 0.5$.

the rate of capacity increase is lower in the overlay strategy. This observation implies that ρ_{cost} will obtain a higher value when λ_P is increased. Similarly, even though the SU capacity decreases as observed in Fig. 4 in both strategies, the descending rate is sharper when the overlay strategy is employed, implying that ρ_{gain} is getting lower with an increasing λ_P. Therefore the resulting CGI value monotonically decreases as λ_P increases. Once the system is configured with a small α, the capacity loss occurred in the PU network becomes less significant. Conversely, it is higher at a larger α. Then, CGI becomes larger as α decreases.

5.3. Blocking and Forced Termination Probabilities

Fig. 8 and Fig. 9 demonstrate the benefit of adopting the underlay channel access strategy with respect to blocking probability and forced termination probability. In Fig. 8, we provide the new user blocking probability as a function of the PU arrival rate, for two different SU arrival rates. As expected, the blocking probability of the new SU services exhibits a monotonic increasing trend when more PUs arrive per time unit and it becomes higher for a higher SU arrival rate. This is due to the fact that higher channel occupancy by PUs diminishes the chances for channel access by new SU requests. In this case, we also observe that the proposed underlay strategy outperforms significantly the existing overlay strategy, represented by lower blocking probability for SUs.

It is known that dropping ongoing calls is more annoying than blocking new call arrivals. Therefore, minimizing the forced terminations of the secondary services should be an important principle for designing channel access schemes. The forced termination probability of the ongoing SU sessions in Fig. 9 also exhibits a similar trend as observed in blocking probability with varying λ_P. With the overlay strategy, the interrupted SUs which cannot perform spectrum handover are forced to terminate their sessions. Using the underlay strategy, however, they can access channels which are occupied by other users with FCO instead of being terminated. Thus the forced termination probability is also greatly reduced. According to the obtained numerical results, the proposed UDCA strategy results in a remarkable performance improvement due to the significant decrements of blocking and forced termination probabilities, although there is a capacity drop

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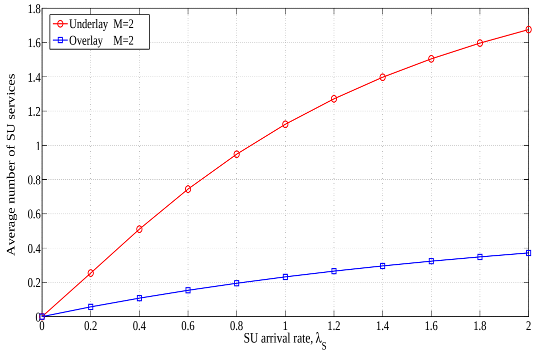

Figure 10. Average number of SU services as a function of SU arrival rate.

in the primary network. However this capacity cost can be bounded by selecting appropriate values for α in the PCO mode as discussed in Sec. 5.2.

5.4. Average Number of SU Services in the System

Fig. 10 compares the average number of SU services that would be commenced in the proposed scheme in comparison with the existing overlay scheme. As λ_S increases, the underlay strategy performs much better than the overlay scheme. For instance, at $\lambda_S = 2$, the number of SU services that can be commenced with the underlay strategy is four times larger than that of the overlay scheme. However, both schemes can admit new sessions only up to a certain limit since they have a capacity upper bound due to the finite number of resources.

6. CONCLUSIONS

In this paper, we have proposed a novel channel access strategy for underlay CRNs. We examine when as well as to what extent a multi-channel CRN obtains benefits by adopting the proposed strategy. Depending upon the maximum allowable interference level, SUs can select an appropriate partial channel occupancy parameter, α, which directly determines the transmission opportunity of an SU service in a channel. We model this underlay strategy by using CTMCs and evaluate its performance in terms of several system-centric parameters. For the identified scenarios, the gain of the proposed strategy outweighs the cost. This is especially evident when α is small, or the primary network is lightly loaded.

REFERENCES

1. Hossain E, Niyato D, Han Z. Dynamic spectrum access and management in cognitive radio networks. Cambridge University Press 2009, 1st Ed: 39-74.
2. Inage K, Fujii T, Muraoka K, Ariyoshi M. Capacity conservation ratio: a novel interference constraint for spectrum sharing. *Transactions on Emerging Telecommunications Technologies* Jul. 2013; **24**(7-8): 672-682.
3. Pischella M, Ruyet DL. Adaptive resource allocation and decoding strategy for underlay multi-carrier cooperative cognitive radio systems. *Transactions on Emerging Telecommunications Technologies* Jul. 2013; **24**(7-8): 748-761.
4. Khoshkholgh MG, Navaie K, Yanikomeroglu H. Access strategies for spectrum sharing in fading environment: Overlay, underlay, and mixed. *IEEE Transactions on Mobile Computing* Dec. 2010; **9**(12): 1780-1793.
5. Joshi DR, Popescu DC, Dobre OA. Joint spectral shaping and power control in spectrum overlay cognitive radio systems. *IEEE Transactions on Wireless Communications* Sep. 2012; **60**(9): 2396-2401.
6. Pereira RC, Souza RD, Pellenz ME. Overlay cognitive radio with multiple secondaries and its application to wireless mesh networks. *in Proc. IEEE VTC Spring*, Barcelona, Spain, Apr. 2009.
7. Federal Communications Commission (FCC), Spectrum policy Task force report, *Technical report*, Nov. 2002, available at http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf
8. Hussain SI, Abdallah MM, Alouini M.-S., Qaraqe K, Hasna M. Relay selection in underlay cognitive networks with fixed transmission power nodes. *Transactions on Emerging Telecommunications Technologies* Jul. 2013; **24**(7-8): 734-747.
9. Hu H, Zhu Q. Dynamic spectrum access in underlay cognitive radio system with SINR constraints. *in Proc. Wireless Commun., Networking and Mobile Comput. (WiCOM)*, Beijing, China, Sep. 2009.
10. Oh J, Choi W. A hybrid cognitive radio system: A combination of underlay and overlay approaches. *in Proc. IEEE VTC Fall*, Ottawa, ON, Canada, Sep. 2010.
11. Bansal G, Hossain J, Bhargawa VK, Le-Ngoc T. Subcarrier and power allocation for OFDMA-based cognitive radio systems with joint overlay and underlay spectrum access mechanism, *IEEE Transactions on Vehicular Technology* May 2013; **62**(3): 1111-1122.
12. Jiang X, Wong K-K, Zhang Y, Edwards D. On hybrid overlay-underlay dynamic spectrum access: Double-threshold energy detection and Markov model, *IEEE Transactions on Vehicular Technology* Oct. 2013; **62**(8): 4078-4083.
13. Younis O, Kant L, Chang K, Young K, Graff C. Cognitive MANET design for mission-critical networks, *IEEE Communications Magazine* Oct.

DOI: 10.1002/ett

2009; **47**(10): 64-71.

14. Jiao L, Li FY, Pla V. Modeling and performance analysis of channel assembling in multi-channel cognitive radio networks with spectrum adaptation, *IEEE Transactions on Vehicular Technology* Jul. 2012; **61**(6): 2686-2697.
15. Jiao L, Li FY, Pla V. Dynamic channel aggregation strategies in cognitive radio networks with spectrum adaptation", *in Proc. IEEE GLOBECOM*, Houston, TX, USA, Dec. 2011.
16. Le LB, Hossain E. Resource allocation for spectrum underlay in cognitive radio networks, *IEEE Transactions on Wireless Communications* Dec. 2008; **7**(12): 5306-5315.
17. Hoang AT, Liang Y-C. Downlink channel assignment and power control for cognitive radio networks, *IEEE Transactions on Wireless Communications* Aug. 2008; **7**(8): 3106-3117.
18. Tang S, Mark BL. Modeling and analysis of opportunistic spectrum sharing with unreliable spectrum sensing, *IEEE Transactions on Wireless Communications* Apr. 2009; **8**(4): 1934-1943.
19. Hafeez M, Elmirghani JMH. Analysis of Dynamic Spectrum Leasing for Coded Bi-Directional Communication, *IEEE Journal on Selected Areas in Communications* Sep. 2012: **30**(8): 1500-1512.