Performance Analysis of Cognitive Radio Spectrum Access with Prioritized Traffic

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Abstract—Dynamic spectrum access (DSA) is an important design aspect for the cognitive radio networks. Most of the existing DSA schemes are to govern the unlicensed user (i.e., secondary user) traffic in a licensed spectrum without compromising the transmissions of the licensed users, in which all the unlicensed users are typically treated equally. In this paper, prioritized unlicensed user traffic is considered. Specifically, the unlicensed user traffic is divided into two priority classes (i.e., high and low priority). We consider a general setting in which the licensed users’ transmissions can happen at any time instant. Therefore, the DSA scheme should perform spectrum handoff to protect the licensed user’s transmission. Different DSA schemes (i.e., centralized and distributed) are considered to manage the prioritized unlicensed user traffic. These DSA schemes use different handoff mechanisms for the two classes of unlicensed users. We also study the impact of sub-channel reservation for the high priority secondary users in both DSA schemes. Each of the proposed DSA schemes is analyzed using a continuous time Markov chain. For performance measures, we derive the blocking probability, the probability of forced termination, the call completion rate and the mean handoff delay, for both high and low priority unlicensed users. The numerical results are verified using simulations.

Index Terms—Cognitive radio, spectrum handoff, quality-of-service (QoS), Markov chain analysis, dynamic spectrum access.

I. INTRODUCTION

In the recent years, there has been tremendous increase in the demand for spectrum due to the rapid proliferation of wireless technologies and wireless markets. For example, the Internet broadband markets are expanding despite the limited spectrum (around the 2.4 GHz band) due to the competition between the 3G cellular networks and the WiFi networks [1]. Such trends endanger the quality-of-service (QoS) that must be achieved for the future wireless services. According to the recently published report [2] by the Federal Communications Commission (FCC), the spectrum regulatory authority in the United States, the traffic distribution across the radio spectrum is extremely uneven. It is observed that the unlicensed portions of the spectrum (2.4GHz and 5GHz bands) in which most wireless networks operate (e.g. WiFi and WiMAX), are heavily occupied whereas the licensed portions of the spectrum (e.g. UHF band) are sporadically used. The above observation motivates the design of wireless networks in which the unlicensed users can explore and exploit unused portions of the licensed spectrum while safeguarding the transmissions of the licensed users. Such wireless networks are referred to as the cognitive radio networks (CRNs) [4]. Recently, the FCC approved the deployment of CRNs in the TV spectrum, subject to specific operating constraints which were determined based on a series of experiments [3]. Similar experiments were conducted to classify other portions of the licensed spectrum for the deployment of CRNs (e.g. public safety bands [5] and cellular bands [6]).

The channel availability for the unlicensed users varies both temporally and spatially, due to the licensed user’s activity. This phenomenon is called spectrum heterogeneity [7]. Spectrum heterogeneity complicates coordination among the unlicensed users during data transmission. In order to cope with spectrum heterogeneity, the unlicensed users in the CRN implement two basic functions, namely spectrum sensing and dynamic spectrum access (DSA) [4]. While spectrum sensing is responsible for identifying idle channels in the licensed spectrum, the DSA scheme is used to facilitate the unlicensed users’ transmissions over the detected idle channels. An important aspect of a DSA scheme is to give higher priority to the licensed users during spectrum access compared to the unlicensed users. Due to this reason, the licensed user is also known as the primary user (PU) and the unlicensed user is known as the secondary user (SU).

In the following, we give an overview of how DSA is addressed for different CRN architectures, namely centralized and distributed, from the literature.

A. Related Work

1) DSA in Centralized CRN: In a centralized CRN, a central controller manages the spectrum sensing and DSA for the SUs associated with it. The DSA can be implemented either as frame-level scheme (e.g., [9], [10]) or as call-level scheme (e.g., [11]-[15]).

In the frame-level DSA schemes, a central controller implements medium access control (e.g., MAC protocol) on every vacant licensed channel on a frame-by-frame basis to handle the packet transmissions of the SUs associated with it. In the

1 A licensed user is a device which can legitimately operates in a licensed spectrum.
2 A licensed spectrum can be divided into several channels (i.e., frequency bands) which can be specified by their center frequency and bandwidth.
IEEE 802.22 network [9], expected to provide DSA for SUs in the TV spectrum, the MAC protocol is divided into uplink (i.e., SUs to central controller) and downlink (central controller to SUs) subframes. In each frame, the central controller broadcasts the uplink and downlink schedules. The central controller assigns exclusive bandwidth (portions of an idle TV channel) to the SUs based on their bandwidth requests for the uplink transmission. In [10], the central controller uses a scheduling algorithm to assign SUs to the licensed channels at the beginning of each frame such that the aggregate throughput is maximized. In [10], the channel status varies within the frame duration.

In the call-level DSA schemes ([11]-[15]), the SU and PU transmissions are treated as calls which are assigned dedicated frequency bands. However, an SU should relinquish its frequency band when a PU call claims it, because the PU call assignment is oblivious of any ongoing SU calls. The central controller admits an SU call if the requested bandwidth is available, and performs spectrum handoff (i.e., reassigning an SU call to another vacant frequency band when it interferes with a new PU call). According to the DSA scheme in [11], an incoming SU call was queued till a new transmission opportunity was found. Also, the SUs which experienced handoff failure were dropped. In [12], the effect of a buffer for SU call arrivals was considered. SUs which experienced handoff failure were dropped. In [13], the SUs were queued upon handoff failure and reassigned to channels when they are available. Thus, the SU transmissions were prevented from forced termination due to a PU arrival in [13]. In [14], Zhu et al. proposed a DSA scheme which considered channel reservation for SU handoff. According to [14], an incoming SU call was assigned a channel only when the number of idle channels in the licensed spectrum exceeds the number of channels reserved for SU handoff. According to the DSA scheme in [15], the central controller assigned as much as possible bandwidth to the SUs to improve the spectrum utilization. This bandwidth assignment was performed whenever the system state changed.

In all the above call-level DSA schemes, the performance was analyzed using continuous time Markov chain (CTMC). The performance was evaluated in terms of the blocking probability and probability of forced termination for the SU calls.

2) DSA in Distributed CRN: Most distributed CRNs have also used frame-level DSA approach [16]-[22]. However, the MAC protocol is managed by the SUs as there is no central controller. A frame may be further divided into several slots. During a frame, multiple SUs sharing the same idle channel use contention mechanisms to transmit their packets (e.g., using CSMA/CA). Most distributed CRNs assume a common control channel for coordination among the SUs (e.g., [17], [18]). The MAC protocol in a distributed CRN is expected to address issues including spectrum sensing, synchronization, hidden/exposed nodes and group coordination.

According to the MAC protocol for the ECMA-392 standard [16], proposed for providing DSA for SUs in TV spectrum, an SU can transmit on a frame shared by several SUs using two methods, namely PCA (prioritized contention access) or CRP (channel reservation protocol). Under the PCA, an SU transmits its packets on a channel based on its random backoff time. The higher an SU’s priority, the shorter is the interval from which it chooses the backoff value randomly. Under the CRP, an SU reserves a few slots of the frame for contention-free access. In [16], SUs perform handoff when they detect a PU activity during the frame. In [17], all SUs participate in detecting the idle channels in the current frame. However, in [17], the winner of the contention phase in the previous frame transmits on the detected idle channels in the current frame. For analysis, the packet arrival and channel availability at an SU were modeled as a M/G/1 queue in [17]. In [18], the SUs form clusters or groups and each group is headed by a leader. The leaders took responsibility for scheduling the contention process and data transmissions within the respective groups during the MAC frame. In [19], an SU modeled the PU occupancy within a frame using a partially observable Markov decision process (POMDP). Based on the state of the POMDP, the expected rate of transmission for the winning SU pair was analyzed. In [20]-[22], the IEEE 802.11 DCF (distributed coordination function) mechanism [26] was adopted for the contention process. For analysis, the saturation throughput of the secondary user was calculated in [20]-[22].

In few works [23]-[25], the DSA was implemented without SU coordination (i.e., no MAC protocol was considered). The SU used slotted transmission. In these works, whenever the SU sensed and accessed a channel successfully for a slot (i.e., SU transmits data without causing collisions to the PU transmissions) a reward was accrued. The objective of these works was to maximize the expected reward over a finite number of slots subject to the constraint on the interference permissible to the PUs. This objective was achieved in [23]-[25] using constrained partially observable Markov decision process (CPOMDP).

B. Contribution of the Paper

The major contributions of this paper are summarized below:

In a real scenario, the SU traffic can be prioritized based on QoS requirements (e.g., real-time traffic has higher priority than non real-time traffic). To date, very few works [16], [27]-[29] considered SU traffic prioritization. In these works, the SUs’ priorities are used for packet transmission during a frame. However, the SU priority does not affect spectrum handoff. On the other hand, in our paper, SUs’ priorities play an important role during spectrum handoff (e.g., a high priority SU gets handoff before a low priority SU, in a two priority class case). Our DSA schemes are particularly helpful when multiple SU transmissions (ongoing or those on hold) require handoff simultaneously.

Our DSA schemes work at a call-level, similar to other existing call-level DSA schemes [11]-[15]. However, there are several key differences with [11]-[15]: 1) we consider priority-based spectrum handoff, 2) we propose distributed call-level DSA schemes, and 3) we analyze the effect of handoff buffer under both the centralized and distributed CRNs.

The rest of the paper is organized as follows. In Section II, we present the system model and the proposed call-level
DSA schemes for the centralized and distributed CRNs. In Section III, we provide analytical models based on continuous time Markov chain (CTMC) for the centralized and distributed CRNs with respect to the proposed DSA schemes. The performance measures including the blocking probability, the probability of forced termination, the successful call completion rate and mean handoff delay, for both high and low priority SUs are derived. In Section IV, we present the numerical and simulation results under the proposed DSA schemes. Finally, Section V gives the concluding remarks.

II. SYSTEM MODEL

The system (Fig. 1) is composed of \( M \) licensed channels, each of which is further divided into \( N \) sub-channels (this system model was also considered in [11], [12], [14], [15]). The PU and SU transmissions are treated as calls which use dedicated sub-channels. A PU call requires one channel whereas an SU call requires one sub-channel\(^1\). A PU call assignment depends on the number of ongoing PU calls (denoted by \( k \)) in the system (i.e., a PU call is admitted if \( k < M \)). A PU call assignment is oblivious of the ongoing SU calls. Therefore, an ongoing SU call interfering the new PU call should be handed-off to another vacant sub-channel. The SUs are classified into two priority classes. The high priority SUs are denoted as \( SU_1 \) while the low priority SUs are denoted as \( SU_2 \). We assume a fully connected CRN, i.e., all SUs observe the same channel status (i.e., PU/SU activity). Perfect sensing is assumed to detect the PU activity. A common control channel is assumed to exist for the coordination among the SUs.

1) Handoff Mechanism for DSA-C1: Handoff for DSA-C1 is done according to the following steps.

1) Randomly assign a displaced \( SU_1 \) call to a unique idle sub-channel (if available).
2) For the remaining displaced \( SU_1 \) calls, terminate the required number of ongoing \( SU_2 \) calls and assign each resulting idle sub-channel to a displaced \( SU_1 \) call.
3) If there are no ongoing \( SU_2 \) calls, terminate the remaining displaced \( SU_1 \) calls.
4) After handoff for all the displaced \( SU_1 \) calls, if there are still idle sub-channels, randomly assign a displaced \( SU_2 \) call to a unique idle sub-channel.
5) When there is no idle sub-channel, terminate the remaining displaced \( SU_2 \) calls.

2) Handoff Mechanism for DSA-C2: The handoff in DSA-C2 is the same as DSA-C1 except for steps (2) and (3). No ongoing \( SU_2 \) calls are terminated for the sake of \( SU_1 \) handoff. When there is no idle sub-channel, the displaced \( SU_1 \) calls are terminated.

3) Handoff Mechanism for DSA-C3: For DSA-C3, handoff is done according to the following steps.

1) Randomly assign a displaced \( SU_1 \) call to a unique idle sub-channel (if available).

Under all the proposed DSA schemes, a number of sub-channels are reserved for new high priority SU calls (\( SU_1 \)). That is, if the total number of idle sub-channels is less than \( \zeta \) which is the number of sub-channels reserved for \( SU_1 \), the new \( SU_2 \) call will be rejected. In this way, we provide higher priority for the \( SU_1 \) calls over the \( SU_2 \) calls.\(^5\)

Call arrivals occur independently as Poisson processes with mean arrival rates \( \lambda_p \), \( \lambda_1 \) and \( \lambda_2 \) for PU, \( SU_1 \) and \( SU_2 \), respectively. The service times independently follow exponential distributions with mean service rates of \( \mu_p \), \( \mu_1 \) and \( \mu_2 \) for PU, \( SU_1 \) and \( SU_2 \) calls, respectively. During a call (PU or SU), the data traffic is disassembled into packets and the packet transmissions are slotted. We assume the slot duration \( (T_s) \) to be very small compared to a call duration. We assume the packet delivery mechanism exists for each call (e.g., modulation and packet acknowledgement).

A. DSA Schemes for Centralized CRN

For the centralized CRN, we assume that a central controller performs spectrum sensing, sub-channel assignment and spectrum handoff for the SU calls. The central controller tracks all the ongoing calls (i.e., PU, \( SU_1 \) and \( SU_2 \) calls). Let \( Y \) denote the total number of busy sub-channels at a given time instant. New \( SU_1 \), \( SU_2 \) and PU calls are dropped when \( Y = MN \), \( Y = MN - \zeta \) and \( k = M \), respectively. When a PU starts transmission on a given channel, the central controller performs handoff for any ongoing SU calls associated with the sub-channels corresponding to this channel. These displaced SU calls can belong to different priorities (\( SU_1 \) and \( SU_2 \)), and the central controller does handoff for displaced \( SU_1 \) calls followed by handoff for displaced \( SU_2 \) calls (i.e., due to the priority). Our centralized DSA schemes only differ in their handoff mechanism (explained below).

1) Handoff Mechanism for DSA-C1: Handoff for DSA-C1 is done according to the following steps.

1) Randomly assign a displaced \( SU_1 \) call to a unique idle sub-channel (if available).
2) For the remaining displaced \( SU_1 \) calls, terminate the required number of ongoing \( SU_2 \) calls and assign each resulting idle sub-channel to a displaced \( SU_1 \) call.
3) If there are no ongoing \( SU_2 \) calls, terminate the remaining displaced \( SU_1 \) calls.
4) After handoff for all the displaced \( SU_1 \) calls, if there are still idle sub-channels, randomly assign a displaced \( SU_2 \) call to a unique idle sub-channel.
5) When there is no idle sub-channel, terminate the remaining displaced \( SU_2 \) calls.

2) Handoff Mechanism for DSA-C2: The handoff in DSA-C2 is the same as DSA-C1 except for steps (2) and (3). No ongoing \( SU_2 \) calls are terminated for the sake of \( SU_1 \) handoff. When there is no idle sub-channel, the displaced \( SU_1 \) calls are terminated.

3) Handoff Mechanism for DSA-C3: For DSA-C3, handoff is done according to the following steps.

1) Randomly assign a displaced \( SU_1 \) call to a unique idle sub-channel (if available).

Note that this assumption is made for the simplicity of presentation. Our DSA schemes can be applied to handle SU calls having different bandwidth requirements.

Note that these are simply the names of our proposed DSA schemes which will be explained later.

Note that the PU calls are not affected by such sub-channel reservation due to the highest priority of PU.
2) For the remaining displaced SU1 calls, place the required number of ongoing SU2 calls on hold and assign each resulting idle sub-channel to a displaced SU1 call.
3) If there are no ongoing SU2 calls, place the remaining displaced SU1 calls on hold.
4) After handoff for all the displaced SU1 calls, if there are still idle sub-channels, randomly assign a displaced SU2 call to a unique idle sub-channel.
5) When there is no idle sub-channel, place the remaining displaced SU2 calls on hold.

When an ongoing SU call is placed on hold, new SU calls (i.e., SU1 and SU2) are not accepted. When an ongoing call (SU1/ SU2/PU) completes service, the SU calls put on hold are reassigned to the resulting idle sub-channels according to their priority. These reassigned SU calls resume transmissions for their remaining service times. The act of the central controller placing a SU call on hold and reassigning an idle sub-channel can be viewed as putting the displaced SU call in a virtual buffer till transmission opportunity is available.

4) Handoff Mechanism for DSA-C4: For DSA-C4, handoff is the same as DSA-C3 except for steps (2) and (3). No ongoing SU2 calls are put on hold for the sake of SU1 handoff, when there is no idle sub-channel the displaced SU1 calls are put on hold.

B. DSA Schemes for Distributed CRN

In a distributed CRN, the SU calls independently perform spectrum sensing, sub-channel selection and spectrum handoff. During an SU call, the sender and destination exchange control messages on the common control channel (e.g., handoff messages). A new SU call performs full spectrum sensing at the beginning of the slot which occurs after its arrival time. Then, the new SU call randomly picks an idle sub-channel for transmission. New SU calls are dropped depending on the number of detected busy sub-channels (e.g., a new SU2 call is dropped if it sensed less than $\zeta$ idle sub-channels). An ongoing SU call senses its own sub-channel in every slot to avoid interference to the PU. If a PU call is detected, the ongoing SU call must perform spectrum handoff. The handoff mechanisms of the distributed DSA schemes are discussed below.

1) Handoff Mechanism for DSA-D1: Having detected the PU call, at the commencement of the next slot, a displaced SU (i.e., sender) determines the idle sub-channels through full spectrum sensing. If idle sub-channels are found, the displaced SU randomly selects only one idle sub-channel and claims it using a contention process because there could be other displaced SU calls also choosing the same sub-channel. As the displaced SU calls can have different priorities, we adopt the idea of contention resolution from the EDCF (enhanced distributed coordination function) protocol in IEEE 802.11e network [30]. Note that unlike in the IEEE 802.11e network [30] we allow only the winner of the contention process (explained later) to stay on the sub-channel. In other words, at most one displaced SU gets successful handoff on a chosen idle sub-channel. The duration of the contention process ($T_c$) is smaller compared to the slot period.

During the contention process, the displaced SUs use an arbitration inter-frame space (AIFS) and contention window (CW) depending on their priority class (similar to [30]). A displaced SU1 call uses shorter AIFS and CW than those of a displaced SU2 call, as SU1 calls have higher priority than SU2 calls. We denote the AIFSs corresponding to the SU1 calls and SU2 calls as $AIFS_1$ and $AIFS_2$, respectively. The CW corresponding to the SU1 calls and SU2 calls are denoted as $[1, W_1]$ and $[1, W_2]$, respectively. Each displaced SU senses its chosen idle sub-channel for a duration equal to $AIFS_x + backoff_x$ depending on its priority $x \in \{1, 2\}$, where $backoff_x$ is the time spent for backoff based on the random integer number chosen from the corresponding CW. The handoff for a displaced SU is treated as successful if it chose the lowest $AIFS_x + backoff_x$ among all displaced SUs contending for the same idle sub-channel. An SU call which achieves successful handoff resumes its transmission for the remaining service time. A displaced SU call experiences handoff failure under two scenarios: 1) the chosen sub-channel becomes busy before its $AIFS_x + backoff_x$ expires (i.e., other SU access the sub-channel first or a collision occurs), 2) if idle sub-channels are not available. The displaced SU calls experiencing handoff failure are dropped (i.e., treated as force terminated by the incoming PU call).

2) Handoff Mechanism for DSA-D2: Unlike the DSA-D1 scheme, in the DSA-D2 scheme, displaced SU calls experiencing handoff failures are not terminated, but allowed to retry in the subsequent slots till they get successful handoff. Therefore, in the subsequent slot, such displaced SU calls perform spectrum sensing and repeat the contention process. The displaced SU calls can be viewed as being in a virtual buffer and contending for the idle sub-channels to get successful handoff.

Additionally, in the DSA-D2 scheme, the displaced SU calls are given higher priority over the new SU arrivals. A new SU call (SU1/ SU2) must sense all idle sub-channels at the beginning of the slot to ascertain any ongoing contention process. Only when handoff SUs are not present (i.e., no contention process is detected), the new SU call will be admitted. This is accomplished by letting the handoff SUs transmit a jamming signal at the beginning of the slot on their selected idle sub-channels before the commencement of the contention process.

III. PERFORMANCE ANALYSIS

A. Analytical Models for Centralized CRN

In this section, we develop analytical models for the centralized CRN under each DSA scheme using a continuous time Markov chain (CTMC). A CTMC can be described by its state transition characteristics.

1) Centralized DSA Schemes without Buffer: The state of the CTMC for the centralized DSA schemes without buffer (DSA-C1 and DSA-C2) is denoted as $[i,j,k]$, where $i \in \{0,1,\ldots, MN\}$, $j \in \{0,1,\ldots, MN - \zeta\}$ and $k \in \{0,1,\ldots,M\}$ represent the number of ongoing $SU_1$, $SU_2$, and PU calls in the system, respectively. For a valid state $[i,j,k]$, $Y = i + j + kN$ should not exceed $MN$.

Let $l$ (where $l \in \{0,1,\ldots,N\}$) and $m$ (where $m \in \{0,1,\ldots,N\}$) respectively denote the number of $SU_1$ call and $SU_2$ calls
displaced by an incoming PU call when the state is \([i, j, k]\). \(l\) and \(m\) should satisfy the following conditions:

\[
l \leq i, m \leq j \quad \text{and} \quad l + m \in \{0, 1, \ldots, N\}
\]

\[
r := MN - Y - \left( N - (l + m) \right) \quad \text{and} \quad r \geq 0
\]

\[
s := (l + m) - \min (r, l + m).
\]

In Eq. (1), the first condition defines the maximum number of SU calls that can be displaced upon a PU call arrival. The second condition defines the number of sub-channels available for handoff (denoted as \(r\)) for the displaced SU calls. Accordingly, the total number of unsuccessful handoff calls (denoted as \(s\)) is calculated in the third condition.

### TABLE I

**QUICK REFERENCE OF FREQUENTLY USED SYMBOLS WITH DESCRIPTIONS.**

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>Number of ongoing SU(_1) calls</td>
</tr>
<tr>
<td>(j)</td>
<td>Number of ongoing SU(_2) calls</td>
</tr>
<tr>
<td>(k)</td>
<td>Number of ongoing PU calls</td>
</tr>
<tr>
<td>(Y = i + j + kN)</td>
<td>Number of busy sub-channels</td>
</tr>
<tr>
<td>(l) and (m)</td>
<td>Number of displaced SU(_1) and SU(_2) calls</td>
</tr>
<tr>
<td>(r)</td>
<td>Number of sub-channels available for handoff</td>
</tr>
<tr>
<td>(l') and (m')</td>
<td>Number of SU(_1) and SU(_2) calls in buffer</td>
</tr>
<tr>
<td>(s = l' + m')</td>
<td>Number of unsuccessful SU(_1) and SU(_2) handoff calls</td>
</tr>
<tr>
<td>(l_s) and (m_s)</td>
<td>Number of successful SU(_1) and SU(_2) handoff calls</td>
</tr>
</tbody>
</table>

The evolution of the state \([i, j, k]\) of the CTMC is presented under three cases of \(Y\):

1. \(Y \leq N(M - 1)\): The system has at least \(N\) idle sub-channels.
2. \(N(M - 1) < Y < MN\): The number of idle sub-channels in the system is in the range \(\{1, \ldots, N - 1\}\).
3. \(Y = MN\): The system has no idle sub-channel.

For the case \(Y \leq N(M - 1)\), all displaced SU\(_1\) and SU\(_2\) calls get successful handoff (i.e., \(s = 0\)) when displaced by a PU call arrival. In other words, no calls are terminated (under DSA-C1 and DSA-C2) due to an incoming PU call. For the case \(N(M - 1) \leq Y < MN\), \(s = \{1, \ldots, N - 1\}\) number of SU calls experience unsuccessful handoff whereas, when \(Y = MN\), \(s = N\) SU calls experience unsuccessful handoff. The exact number of terminated SU\(_1\) and SU\(_2\) calls under each centralized DSA scheme are explained later. Let \(l'\) and \(m'\) denote the number of terminated SU\(_1\) and SU\(_2\) calls, respectively. Thus, \(l' + m' = s\). For convenience, a quick reference of the symbols with descriptions frequently used in this paper is given in Table I.

#### a) State Transitions under DSA-C1 Scheme

Under the DSA-C1 scheme, the transitions for the state \([i, j, k]\) for different cases of \(Y\) are explained using Fig. 2. State transitions from/to the state \([i, j, k]\) occur due to any of the six possible events, namely PU call arrival, SU\(_1\) call arrival, SU\(_2\) call arrival, PU call departure, SU\(_1\) call departure and SU\(_2\) call departure. Each state transition is represented by its corresponding rate. Taking as an example, a SU\(_2\) call arrival in state \([i, j, k]\) causes a transition to state \([i, j, k]\) with a rate \(\delta_{1} \cdot \lambda_{2}\), where \(\delta_{1} = 1(i + (j - 1) + kN < MN - \zeta)\) specifies the condition for sub-channel reservation (i.e., a new SU call is accepted by the system only when the condition \(i + (j - 1) + kN < MN - \zeta\) holds), where \(1(\cdot)\) is the indicator function which returns the value 1 when the condition given inside the parenthesis is true and returns 0 otherwise. In Fig. 2, \(\delta_{2} = 1(i + (j + kN < MN - \zeta)\) (condition for sub-channel reservation in state \([i, j, k]\)) and \(\delta_{3} = 1(i + (j + (k-1)N < MN - \zeta)\) respectively.

#### b) State Transitions under DSA-C2 Scheme

Fig. 2 also represents the state transitions under the DSA-C2 scheme for the following cases of \(Y\):

1. Transition from state \([i, j + j', k - 1]\) to state \([i, j, k]\) occurs with rate \(\gamma_{i,j,j',k-1}\), where \(j > 0\) and \(0 < j' < N\). The rate \(\gamma_{i,j,j',k-1}\) is calculated using Eq. (2) corresponding to the state \([i, j + j', k - 1]\). During this state transition, SU\(_2\) calls are terminated.

2. Transition from state \([i + (j' - j), j + j', k - 1]\) to state \([i, j, k]\) occurs with rate \(\gamma_{i,j,j',k-1}\), where \(j > 0\) and \(0 < j' < N\). The rate \(\gamma_{i,j,j',k-1}\) is calculated using Eq. (2) corresponding to the state \([i + (j' - j), j + j', k - 1]\). During this state transition, SU\(_1\) calls and SU\(_2\) calls are terminated.

The transition rate \(\gamma_{i,j,j',k-1}\) from state \([i - l', j - m', k + 1]\) to state \([i, j, k]\) is calculated as follows.

1. Let \(N_{l', m'}\) denote the set containing the valid combinations of \((l', m')\).

2. For every valid pair of \((l', m')\) in the set \(N_{l', m'}\), find \(R_{l', m'}p\) which represents the number of valid combinations of \(l, m, r\) and \(s = l' + m'\). Valid \(l, m, r\) and \(s\) for given \([i, j, k]\) can be found using Eq. (1).

3. Then, the transition rate \(\gamma_{i,j,j',k-1}\) is given by

\[
\gamma_{l', m', i, j, j', k-1} = \sum_{(l', m') \in N_{l', m'}} R_{l', m'} p\lambda_{p}.
\]
the various cases of $Y$. According to the handoff mechanism under DSA-C2 scheme, the number of terminated $SU_1$ and $SU_2$ calls are given as $t' = l - \min(r,l)$ and $m' = \max(0, m - \max(0, r - l))$, respectively. All state transitions shown in Fig. 2 occur similar to those of the DSA-C1 scheme. Apart from the state transitions given in Fig. 2, transitions occur from states $[i+j', j'+j, k-1]$ (in which $i+j+(k-1)N = (N(M-1))$ to the state $[i,j,k]$ when $Y = MN$, where $0 \leq i', j' < N$ and $0 < i' + j' < N$.

2) Centralized DSA Schemes with Buffer: The state of the CTMC for the centralized DSA schemes with buffer (DSA-C3 and DSA-C4) is denoted as $[i, j, k, l, m]$, where $i \in \{0, 1, \ldots, MN\}$, $j \in \{0, 1, \ldots, MN - \zeta\}$ and $k \in \{0, 1, \ldots, M\}$ represent the number of ongoing $SU_1$, $SU_2$, and PU calls in the system, respectively. The variables $i_q \in \{0, 1, \ldots, MN\}$ and $m_q \in \{0, 1, \ldots, MN - \zeta\}$ represent the number of $SU_1$ and $SU_2$ calls waiting in the buffer due to unsuccessful handoff. Here also, $Y = i+j+kN$. For a valid state $[i, j, k, l, m_q]$, the following conditions must hold:

$$Y \leq MN, \quad i + j + l + m_q \leq MN \quad \text{and} \quad j + m_q \leq MN - \zeta. \quad (3)$$

As in Section III-A1, the same three cases of $Y$ are considered to explain the state transitions. The state transitions are also classified according to the buffer status (empty and non-empty).

a) State Transitions under DSA-C3 Scheme: Fig. 3 shows the transitions of state $[i, j, k, l, m_q]$ for the DSA-C3 scheme when the buffer is empty (i.e., $i_q + m_q = 0$). For $i_q + m_q = 0$, except for the transitions between the states $[i, j, k, 0, 0]$ and $[i - t', j - m', k + 1, l', m']$ for $Y = MN$, the state transitions under the DSA-C3 scheme and the DSA-C1 scheme (as shown in Fig. 2) are the same for all cases of $Y$. Here, $t' = s - \min(j, s)$ and $m' = m - \min(j, s)$. During a PU call arrival for $Y = MN$, $t'$ $SU_1$ calls and $m'$ $SU_2$ calls are placed in the buffer. As a result, $[i, j, k, 0, 0]$ changes to $[i - t', j - m', k + 1, l', m']$ with rate $\lambda_{\delta i j k}$. As $\lambda_{\delta i j k}$ is independent of buffer status, it is calculated using Eq. (2). A PU departure in state $[i - t', j - m', k + 1, l', m']$ reassigns all the $SU_1$ and $SU_2$ calls in the buffer and hence, state changes to $[i, j, k, 0, 0]$.

Fig. 4 shows the state transitions under the DSA-C3 scheme when the buffer is non-empty (i.e., $i_q + m_q > 0$) which occurs only for the case $Y = MN$. A new $SU_1$ or $SU_2$ call arrival cannot be accommodated when the buffer is non-empty. A PU call arrival adds $t' + m'$ $SU_1$ to the buffer. $SU_2$ calls in the buffer are reassigned sub-channels following a departure event (PU/$SU_1$/$SU_2$) according to their priority (refer Section II-A3).

For the variables $i$, $m'$, $t'$ and $m''$ shown in Fig. 4, when a $SU_1$ call (or $SU_2$) departs $l = \min(l, l_q)$ and $m_q = m - (1 - \min(l, l_q))$. When a $SU_1$ call departs $l' = \min(l, l_q)$ and $m' = m - (1 - \min(l, l_q))$. When transition occurs from state $[i, j, k, 0, 0]$, $l_q = 0$ and $m_q = j'$ where $j > 0$ and $0 < j' < N$. Similarly, for the transition occurring from state $[i - s', j', k - 1, 0, 0]$, $l_q = s' - j'$ and $m_q = j'$ where $j = 0$, $0 < s' < N$ and $0 \leq j' < s'$. In Fig. 4, $\delta_l = 1_{\{(N(M-1)-1)l+1(j+1)+k-1; N < MN\}}$ and $\delta_q = 1_{\{(N(M-1)-1)(s'+j'+1)+k-1; N < MN\}}$.

b) State Transitions under DSA-C4 Scheme: Fig. 3 and Fig. 4 also represent the state transitions under the DSA-C4 scheme. However, for the DSA-C4 scheme, $t' = l - \min(r,l)$ and $m' = \max(0, m - \max(0, r - l))$. The order of reassignment of $SU$ calls from the buffer is the same in the DSA-C3 and DSA-C4 schemes.

![State transitions for centralized DSA schemes with buffer, $l_q = 0$ and $m_q = 0$.](image1)

![State transitions for centralized DSA schemes with buffer, $l_q > 0$ and $m_q > 0$.](image2)

B. Analytical Models for Distributed CRN

In this section, we develop the analytical models for the distributed DSA schemes (DSA-D1 and DSA-D2) using two different CTMCs.

1) DSA-D1 Scheme: Similar to the DSA-C1 and DSA-C2, the state of the CTMC under the DSA-D1 scheme (i.e., without buffer case) is denoted as $[i, j, k]$ where $i$, $j$ and $k$ have the same meanings as those defined in Section III-A1.

The state transitions for the state $[i, j, k]$ under the DSA-D1 scheme are shown in Fig. 5, where $t' \in \{0, \ldots, N\}$, $m' \in \{0, \ldots, N\}$ and $t' + m' \in \{s, \ldots, N\}$ ($s$ is determined by Eq. (1)). Similar to Section III-A1, the state transitions can be explained on the basis of $Y$ (some transitions are ignored depending on $Y$). For the cases $Y \leq N(M-1)$ and $N(M-1) < Y < MN$, all the state transitions shown in Fig. 5 occur. For the case $Y = MN$, the transitions between the states $[i, j, k]$ and $[i, j + 1, k]$ do not occur, and the transitions between the states $[i, j, k]$ and $[i + 1, j, k]$ also do not occur.

The transition rate $\lambda_{i,j,k}$ from state $[i, j, k]$ to state $[i - t', j - m', k + 1]$ in Fig. 5 is calculated as $P_d(t', m'[i, j, k] \cdot \lambda_p$, where $P_d(t', m'[i, j, k]$ denotes the probability that $t'$ $SU_1$ and $m'$ $SU_2$ calls are dropped following a PU call arrival. $P_d(t', m'[i, j, k]$ is expressed as follows:

$$P_d(t', m'[i, j, k] = \sum \forall m \{P_d(t', m'[l, m, i, j, k] \cdot P(l, m[i, j, k) . \quad (4)$$

In the above equation, $P(l, m[i, j, k]$ is calculated as

$$P(l, m[i, j, k] = \frac{\left(\frac{N}{i,j} \cdot \frac{(M-k-1)N}{i,j} \right)}{\left(\frac{N(M-k-1)N}{i,j}\right)} \quad (5)$$
where \( l, m, r \) and \( s \) are determined by Eq. (1) for state \( z \). The notation \( \binom{a}{b} \) denotes the number of ways of arranging \( a \) \( SU \) cells, \( b \) \( SU \) cells in \( e = a + b \) sub-channels without repetition.

As \( l' + m' = s \) depends only on \( l, m \) and \( r \) corresponding to state \( [i,j,k] \), \( P_d(l', m', [i,j,k]) \) can be rewritten as \( P_d(l', m', [l,m,r]) \). Accordingly, Eq. (4) is modified as

\[
P_d(l', m', [i,j,k]) = \sum_{l,m,r} P_d(l', m', [l,m,r]) \cdot P(l, m[i,j,k]). \tag{6}
\]

In Fig. 6, the rate \( P_{i,j,k,l,q,m,q}^{i,j,k,l,q,m,q} \) is equal to \( P(l, m[i,j,k]) \cdot \lambda_p \), where \( P(l, m[i,j,k]) \) is calculated using Eq. (5). The rate \( P_{i,j,k,l,q,m,q}^{i,j,k,l,q,m,q} \) is given by \( P(l, m[i,j,k], m_q, r') \cdot \lambda_p \), where \( P(l, m[i,j,k], m_q, r') \) is also calculated using Eq. (7), by replacing \( l, m \) and \( r \) in \( P_d(l, m, r) \).

D. Performance Measures

The performance measures for each DSA scheme are expressed using the steady state probability distribution of its corresponding CTMC. We derive performance measures (for both \( SU_1 \) and \( SU_2 \) cells) such as blocking probability, probability of forced termination, successful call completion rate and mean handoff delay.

Let \( \Pi_a \) denote the steady state distribution of a CTMC whose state is denoted as \( z \). For the DSA-C1, DSA-C2 and DSA-D1 schemes, \( z = [i,j,k] \) whereas for the DSA-C3, DSA-C4 and DSA-D2 schemes \( z = [i,j,k,m_q] \). To simplify the presentation, we use the same notations under all DSA schemes. For any DSA scheme, the corresponding steady state probability distribution \( \Pi_a \) is obtained by finding the corresponding transition rate matrix \( Q \) and applying the Gauss-Seidel algorithm [31]. Each row of \( Q \) represents the transitions with respect to a specific state \( z \), as a balance equation. For example, referring to Fig. 3, one balance equation with respect to the state \( [i,j,k,0,0] \) under the DSA-C3 scheme is expressed as in Eq. (10), where \( \Pi_{[i,j,k,0,0]} \) represents the steady state probability for state \( [i,j,k,0,0] \) under the DSA-C3 scheme.

1) Blocking Probability: The blocking probability represents the probability with which an incoming SU call (\( SU_1 \) or \( SU_2 \)) is not permitted to enter the system due to the lack
of sub-channels or due to SU calls on hold. The blocking probability of SU1 calls denoted as \( P_{B1} \) is expressed as

\[
P_{B1} = \sum_{\forall z, \, Y = MN} \Pi_{z}.
\]

The blocking probability of SU2 calls denoted as \( P_{B2} \) is expressed as

\[
P_{B2} = \sum_{\forall z, \, Y \geq MN - \zeta} \Pi_{z}.
\]

2) Probability of Forced Termination: The probability of forced termination represents the probability with which an ongoing SU call (SU1 or SU2) is terminated by an incoming PU call. Note that forced termination occurs only with DSA-C1, DSA-C2 and DSA-D1 schemes (i.e., without buffer cases). The probability of forced termination for the SU1 calls denoted as \( P_{F1} \), is expressed as

\[
P_{F1} = \sum_{\forall z, \, i \geq j, \, m} \lambda(z) \cdot \Pi_{z}.
\]

where \( Q_{z} \) denotes the transition rate from state \( z = [i, j, k] \) to state \( z' = [i - t', j - m', k + 1] \). In Eq. (13), the numerator denotes the probability that \( t' \) SU1 calls are terminated in state \( z \) whereas the denominator denotes the effective rate with which a new SU1 call is assigned a sub-channel.

Similarly, the probability of forced termination for the SU2 calls denoted as \( P_{F2} \), is expressed as

\[
P_{F2} = \sum_{\forall z, \, i \geq j, \, m} \lambda(z) \cdot \Pi_{z} \cdot \sum_{l \geq 1} \frac{m}{l} \cdot Q_{z}.
\]

4) Mean Handoff Delay: The mean handoff delay for SU1 (SU2) calls is defined as the mean time taken by the SU1 (SU2) calls to perform successful handoff. Let \( HD_1 \) and \( HD_2 \) denote the handoff delays for SU1 and SU2 calls, respectively. For the DSA-C3, DSA-C4 and DSA-D2 schemes (i.e., with buffer cases), the mean handoff delays corresponding to SU1 and SU2 calls is given as follows:

\[
HD_1 = \frac{\bar{P}}{\bar{T}} \sum_{l, \, m, \, z} l \cdot Q_{z} \cdot \Pi_{z}
\]

\[
HD_2 = \frac{\bar{m}}{\bar{T}} \sum_{l, \, m, \, z} m \cdot Q_{z} \cdot \Pi_{z}
\]

where \( Q_{z} \) represents the transition rate from state \( z = [i, j, k, l, m] \) to state \( z' = [i - t', j - m', k + 1] \). In the above equations, \( \bar{T} \) and \( \bar{m} \) denote the mean number of SU1 and SU2 calls displaced during a PU call arrival, respectively. They are calculated as \( \bar{T} = \sum_{i, \, m, \, z} l \cdot P(l, i, m, z) \Pi_{z} \) and \( \bar{m} = \sum_{i, \, m, \, z} m \cdot P(l, i, m, z) \Pi_{z} \) where \( P(l, i, m, z) \) is equal to \( l' \) if \( i \) and \( m' \) are valid for the given \( l \) and \( m \) corresponding to the state \( z \), otherwise \( P(l, i, m, z) = 0 \). Here, \( P(l, i, m, z) \) is equivalent to \( P(l, i, j, k, l, m) \) as \( l \) and \( m \) are independent of \( l' \) and \( m' \). Therefore, \( P(l, i, j, k, l, m) \) is also calculated using Eq. (5).

For the DSA-C1, DSA-C2 and DSA-D1 schemes (i.e., without buffer cases) as the unsuccessful handoff calls are dropped immediately, \( HD_1 = 0 \) and \( HD_2 = 0 \).

IV. RESULTS AND DISCUSSION

In this section, we evaluate the performance of the CRN under each proposed DSA scheme using the performance measures derived in the Section III. The accuracy of the analysis is verified through simulations. In our experiments, we use the following parameter settings, \( M = 3, \, N = 4, \, \lambda_1 = 1, \, \lambda_p = 1, \, \lambda_p \in \{0.4, \ldots, 1\}, \, \mu_1 = 0.5, \, \mu_2 = 0.5, \, \mu_p = 1.8, \, \zeta = 1, \, T_0 = 1.8 \) and \( T_e = 0.02 \) (Table II gives the description for the parameter settings). For convenience, the arrival rates and service rates are expressed in calls/second. For the DSA-D1
and DSA-D2 schemes, \( AIFS_1 = 1 \), \( AIFS_2 = 2 \), \( W_1 = 2 \) and \( W_2 = 3 \). The symbols \(< a >\) and \(< s >\) in the figures indicate analytical and simulation results, respectively.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>( M )</td>
<td>Number of channels in the system</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of sub-channels per channel</td>
</tr>
<tr>
<td>( \lambda_1, \lambda_2 ) and ( \lambda_p )</td>
<td>Mean arrival rate of ( SU_1 ), ( SU_2 ) and PU calls</td>
</tr>
<tr>
<td>( \mu_1, \mu_2 ) and ( \mu_p )</td>
<td>Mean service rate of ( SU_1 ), ( SU_2 ) and PU calls</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>Number of sub-channels reserved for ( SU_1 ) call arrival</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Slot duration</td>
</tr>
<tr>
<td>( T_c )</td>
<td>Maximum contention duration</td>
</tr>
<tr>
<td>( AIFS_1 ) and ( AIFS_2 )</td>
<td>Arbitrary inter-frame space for ( SU_1 ) and ( SU_2 ) calls</td>
</tr>
<tr>
<td>( W_1 ) and ( W_2 )</td>
<td>Contention window size for ( SU_1 ) and ( SU_2 ) calls</td>
</tr>
</tbody>
</table>

### A. Call Completion Rate

Fig. 7(a) and Fig. 7(b) show the effect of PU call arrival rate (\( \lambda_p \)) on call completion rate of the \( SU_1 \) and \( SU_2 \) calls under the different proposed DSA schemes, respectively. The call completion rate corresponding to the DSA-C4 scheme is the same as that corresponding to the DSA-C3 scheme and hence, it is not shown. It can be seen from Fig. 7(a) and Fig. 7(b) that as \( \lambda_p \) increases, the call completion rate of the SU calls (\( n_1 \) and \( n_2 \)) decreases under all the DSA schemes. This is because the number of busy sub-channels increases with an increase in \( \lambda_p \), causing higher blocking probabilities for the SU calls and subsequently lower call completion rate.

![Fig. 7. Effect of PU call arrival rate on call completion rate for (a) \( SU_1 \) calls and (b) \( SU_2 \) calls, under all DSA schemes.](image)

It can also be seen that the DSA schemes using handoff buffer give higher call completion rate (\( n_1 \) and \( n_2 \)) compared to those without buffer. This is because the forced termination of SU calls is prevented in the DSA schemes with buffer (i.e., DSA-C3, DSA-C4 and DSA-D2). The call completion rate of the DSA-D2 scheme is less than those of the centralized DSA schemes which use buffer, because the handoff calls wait longer time in the buffer due to contention process, resulting in a longer service time for SU calls. It is observed that the DSA-D1 scheme gives the lowest values of \( n_1 \) and \( n_2 \) among all the DSA schemes. This is because some \( SU_1 \) and \( SU_2 \) calls are terminated due to collision during handoff. It is also observed that the DSA-C1 scheme gives higher value of \( n_1 \) than the DSA-C2 scheme. Further, the DSA-C2 scheme has higher value of \( n_2 \) than the DSA-C1 scheme. The reason for both these behaviors is the same, i.e., some \( SU_2 \) calls are terminated by the displaced \( SU_1 \) calls during handoff under the DSA-C1 scheme but no such termination occurs under the DSA-C2 scheme. This fact is confirmed by the Fig. 8(a) and Fig. 8(b) which show the effect of PU call arrival rate on the probability of forced termination for the \( SU_1 \) and \( SU_2 \) calls, respectively.

![Fig. 8. Effect of PU call arrival rate on forced termination probability of (a) \( SU_1 \) calls and (b) \( SU_2 \) calls, under DSA schemes without buffer.](image)

It can be seen that the \( P_{TF} \) for the DSA-C1 scheme is lower than that of the DSA-C2 scheme, and \( P_{TF} \) for DSA-C2 scheme is lower than that of the DSA-C1 scheme. Fig. 8(a) shows that the distributed case (DSA-D1) has the highest value of \( P_{TF} \). Similarly, Fig. 8(a) shows the distributed case having the highest \( P_{TF} \). Further, it is intuitive that an increase in \( \lambda_p \) causes an increase in both \( P_{TF} \) and \( P_{TF} \), as shown in Fig. 8(a) and Fig. 8(b). The analysis and simulation results match well for the successful call completion rates (\( n_1 \) and \( n_2 \)) and probability of forced termination (\( P_{TF} \) and \( P_{TF} \)), under all the DSA schemes.

### B. Mean Handoff Delay

Fig. 9(a) shows the effect of the PU call arrival rate (\( \lambda_p \)) on the mean handoff delay of \( SU_1 \) calls (\( HD_1 \)) under the centralized and distributed schemes using handoff buffer. It can be seen that as \( \lambda_p \) increases \( D_1 \) also increases. This is because the channels mostly carry PU traffic as \( \lambda_p \) increases. Fig. 9(a) shows that the DSA-C3 scheme has the lowest value of \( HD_1 \). This is because under this scheme, the \( SU_1 \) calls get immediate handoff as long as some ongoing \( SU_2 \) calls are present (i.e., in such scenario, handoff delay is zero). As a result, the mean handoff delay (\( HD_1 \)) is smaller. Fig. 9(a) shows the DSA-D2 scheme having higher value of \( HD_1 \) than that of the centralized DSA schemes. This is because the contention and collision during handoff lead to longer handoff times.

Fig. 9(b) shows the effect of the PU call arrival rate (\( \lambda_p \)) on the mean handoff delay of \( SU_2 \) calls (\( HD_2 \)) under the centralized and distributed schemes which use handoff buffer. It can be seen that as \( \lambda_p \) increases \( HD_2 \) also increases. The
reason is the same as that given for \( HD_1 \). Fig. 9(b) shows the DSA-C3 scheme having higher value of \( HD_2 \) than that of the DSA-C4 scheme. This is because under DSA-C3 scheme, the number of displaced \( SU_2 \) calls is more than that in the DSA-C4 scheme (as some \( SU_2 \) calls are also displaced due to \( SU_1 \) handoff). Fig. 9(b) also shows that the DSA-D2 scheme gives the highest value for \( HD_2 \). This reason is the same as that explained for \( HD_1 \). Again, the simulation results and analytical results match well for both \( HD_1 \) and \( HD_2 \) under all the DSA schemes with buffer.

The results can be summarized as follows.

The distributed DSA schemes are relatively complex compared to the centralized DSA schemes. However, the centralized DSA schemes incur infrastructure cost. While the DSA schemes with handoff buffer improve the SU call completion rate, they introduce handoff delay which consequently increases the blocking of incoming SU calls. In our future work, we will analyze the effect of sensing errors on the performance of our DSA schemes. For instance, it can be observed from Figs. 10(a) and 10(b) corresponding to DSA-C2 and DSA-C4 schemes (simulation results) show that the sensing error causes degradation in the call completion rate of the \( SU_1 \) and \( SU_2 \) calls. In the Figs. 10(a) and 10(b), \( P_f \) denotes the probability of false alarm (i.e., probability of wrongly sensing an idle channel) and \( P_m \) denotes the probability of miss detection (i.e., probability of wrongly sensing an active PU call).

C. Optimal Sub-channel Reservation

As mentioned in Section II, some sub-channels (\( \zeta \)) are reserved for the \( SU_1 \) call arrivals. Using the sub-channel reservation, some low priority SU calls are blocked to improve the performance of the high priority SU calls. Based on the given parameter settings and blocking probability requirement of the \( SU_1 \) calls, an optimal number of sub-channels (\( \zeta \)) to be reserved under the DSA schemes can be determined from our analysis. Here, optimal number means the minimum number of sub-channels to be reserved to guarantee that the blocking probability requirement of the \( SU_1 \) calls is satisfied. For instance, consider the following parameter setting: \( \lambda_1 = 1.8, \lambda_2 = 1.8, \lambda_p = 0.06, \mu_1 = 0.8, \mu_2 = 0.3, \mu_p = 0.009 \) and a desired blocking probability of 5\% for the \( SU_1 \) calls under the DSA-C1 scheme. The analysis results can be verified from simulation. Fig. 11 shows the simulation results for the above parameter settings under different values of \( \zeta \) with DSA-C1 scheme. Fig. 11 shows that the desired blocking probability of 5\% for the \( SU_1 \) calls satisfied when \( \zeta = 4 \) sub-channels. Similarly, the optimal \( \zeta \) can be found for the other DSA schemes.

Fig. 9. Effect of PU call arrival rate on the mean handoff delay of (a) \( SU_1 \) calls and (b) \( SU_2 \) calls, under DSA schemes with buffer.

Fig. 10. Call completion rate for different sensing errors for \( SU_1 \) and \( SU_2 \) calls under (a) DSA-C2 scheme and (b) DSA-C4 scheme.

V. CONCLUSION

We have investigated the spectrum handoff prioritization using various novel DSA schemes under different CRN architectures (i.e., centralized and distributed). For simplicity, we have considered two levels of prioritization in the SU traffic. The analytical models for the CRN under all the proposed DSA schemes have been presented. For performance evaluation, we have derived the blocking probability, the forced termination probability, the call completion rate and the mean handoff delay for the two priority classes in the SU traffic. We have also investigated the case of sub-channel reservation for the high priority SUs and obtained the optimal sub-channel reservation. The analytical results have been verified through simulations. In the future, we will analyze the optimal number of channels and sub-channels required for the design. We will also study the effects of sensing errors on the performance of our DSA schemes.
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