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Centralized Dynamic Channel Reservation Mechanism via SDN for CR Networks Spectrum Allocation

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ABSTRACT In cognitive radio networks (CRNs), secondary users (SUs) transmission requests are fulfilled via the use of portions of the licensed bandwidth dedicated to primary users (PUs). Meanwhile, through spectrum sharing of dynamic spectrum access (DSA), the PUs gain either financial benefits or cooperative communications. Due to the fact that the spectrum bandwidth resources are restricted hence; the dynamic allocation requests have become the focus of attention in recent years. Therefore, the dynamic channel reservation (DCR) in CRNs has a significant influence on improving network performance via the adjustment of the optimal number of reserved channels. Also, the centralized control (central controller) with a software-defined network (SDN) can be employed effectively to manage configuration, simplify the complexities, and develop dynamic coordination between the users in the network. In this paper, two algorithms of DCR are investigated to determine the optimal number of reserved channels based on SU retainability or SU channel availability while taking into consideration PU's channel availability minimum limit in both cases. Performance metrics in both cases indicate the enhancement in system quality of service (QoS). Moreover, the results show a significant reduction in SU cost function and network unserviceable probability (Q_s), while meeting the QoS requirements of PU through a minor inconsiderable impact on its channel availability and throughput compared to other previous models. In this paper, a proposed DCR algorithm is designed for selecting one of the two modes of operation depending on the incoming traffic requests to attain better performance characteristics.

INDEX TERMS Cognitive radio networks, dynamic channel reservation, software defined network, retainability, SU cost function.

I. INTRODUCTION

In recent decades, the massive demand has increased rapidly for radio technologies and wireless communication services and applications despite, the limited spectrum resources. Meanwhile, the usage of the scarce spectrum assigned by the governmental regulatory authorities to the license holders causes the problem of underutilized portions of the frequency bands [1], [2]. Consequently, the emergence of cognitive radio (CR) is considered the potential design paradigm that improves the utilization of unused spectrum bands by permitting the secondary users (SUs) to exploit the vacant portions from the licensed spectrum dedicated for primary users (PUs) opportunistically according to the network status without causing harmful interference to PUs [2]. Dynamic spectrum access (DSA) scheme is employed effectively in CR through the reconfiguration capability of the system characteristics to suit the surrounding environment based on the traffic load and network topology situation. Furthermore, DSA detects intelligently the spectrum holes (idle frequency bandwidths) for SU transmission requests according to QoS requirements without a change in devices, terminals, and services in the primary system [3]. In CRN, SUs are allowed to share the spectrum with the PUs by either overlay or underlay

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models [4]. In this research, the overlay scheme is adopted where spectrum sensing recognizes the empty channels to be assigned to incoming SUs. In addition to that, it is worth mentioning that the PU has the higher privilege than the SU services [5] so, whenever PU arrives the SU will vacate the channel and perform spectrum handover to a reserved channel to resume its unfinished service if an idle channel is available, otherwise, SU will be forced terminated out of the network [6]. Therefore, the channel reservation strategy is applied extensively to allocate some channels for particular users to enhance the efficiency of the system [6], [7]. In the previous literature, the reserved channels are specialized for SUs only as in [2], [8], or PU usage as in [9]. Their utilization for both interrupted services of PUs and SUs is adopted in [7], [10]. In our proposed scheme the dynamic channel reservation (DCR) is dedicated to only SUs while preserving the accepted limit of PU channel availability. Our results confirm those shown in [10] for static channel reservation (SCR), that the rise in R (number of reserved channels) increases the SU channel availability and reduces SU blocking probability. This is contrary to the results in [11] since reserved channels are allocated for primarily interrupted SUs and under hard constraints for newly arriving SUs. Moreover, this paper is motivated by using the DCR mechanism in the DSA scheme which adjusts dynamically the optimal number of reserved channels R_{OPT} based on the traffic load occupancy by PUs and SUs. Consequently, two algorithms are proposed, one of them concerns the SU retainability and the other focuses on the SU channel availability considering in both algorithms the PU channel availability threshold which cannot be neglected as in [7]. Therefore, this approach provides more accuracy and higher flexibility while sudden PU and SU requests arrive more than stated in [7], [10], [12]. It is worth mentioning since the overlay technique of CR spectrum sharing and DCR are proposed in the model, the incentives can be maximized for both PU and SU since the PU can earn revenue or monetary benefits by allowing its traffic to be exploited by SU temporarily. However, SU utilizes this unoccupied channel to support the transmission of its service with acceptable QoS requirements [13], [14]. On the other hand, it is assumed that the submitted system has perfect spectrum sensing which determines the channel occupancy accurately without errors causing the increase in misdetection or false alarm probabilities [15]. Besides, it is supposed that each PU and SU cannot occupy the same channel concurrently [11]. Additionally, CRN architecture is managed by a centralized controller of a software-defined network (SDN) that achieves the dynamic bandwidth allocation through the DCR algorithm which manages the number of reserved channels in the system. This approach provides the optimization of network utilization in which its architecture becomes programmable to make the network more dynamic, adjustable, and cost-effective [16], [17]. On the other hand, in our proposed work, the SDN with centralized control has more smart characteristics that become more efficient, faster, and make it easier to get the network traffic load information. SDN strategy simplifies the network configuration by separating the control plane from the forwarding data plane to manage the network in a simple manner and reduce the hardware implementation complexity, cost, and the delay of response time through programming utilization [18]. On one hand, the data plane consists of network OpenFlow switches and routers, on the other hand, the control plane is managed by the SDN centralized controller. To conclude briefly, the SDN concept is applied flexibly to the SU spectrum assignment with a programmable central controller. This central controller monitors and updates the information about network traffic circumstances and receives the users' allocation requests. Subsequently, the controller manages dynamically the frequency band allocation according to a flow lookup table and executes it smartly by OpenFlow software [19], [20]. In [10], the scenario of CRN architecture is dependent on the unlicensed SUs' monitoring and performing analysis on the radio environment to obtain the network occupancy details. Contrarily, the central controller of the SDN can recognize the spectrum availability and allocation based on these observations for all PUs and SUs requests within its transmission range [21]. The contribution of this paper is to utilize the SDN protocol, which is appropriate for both static and dynamic bandwidth allocation, where the system occupancy data can be discovered by more accurate calculations and analysis. On the other hand in [10], the network data is collected based on the SUs' observations on the environment. Subsequently, the possibility of data error in our proposed model is alleviated remarkably due to the reduction of false alarm and misdetection probabilities. The increase of these two probabilities occurs due to false estimation of channels occupation status as in [22] affecting the system performance negatively. Moreover, our suggested technique does not require a common control channel to negotiate between users [23]. Thus, it reduces the excessive control messages, particularly whenever the number of arrived SUs increases [24], [25]. A continuous-time Markov chain (CTMC) model is developed to analyze the performance and the QoS evaluation of the system containing the primary and secondary networks as in [7], [10], [26]. It is observed in [27], that the dynamic channel allocation is preferred more than a static channel allocation strategy where it takes into consideration the dynamic variations of the spectrum environment and fully utilizes and allocates the spectrum channel resources effectively under the restrictions of QoS requirements. The SU dynamic channel allocation is implemented depending on either one of two fundamental access mechanisms stated in [28]. These approaches are either centralized or distributed channel allocation to determine the SU assignment in CR systems [29]. Whereas, in a centralized dynamic channel allocation scheme, a central controller takes the controlling decisions for channel access based on the collected and updated information about the radio environment also, every SU communicates with the central controller to always update its status. On the other hand, the distributed dynamic channel allocation is deployed without the presence of the central controller where each SU is responsible to gather, exchange and operate the environment data observation independently and take the access decision according to this information [30]. The performance metrics of this work, SU retainability, channel availability, handover probability, network unserviceable probability, the throughput, and cost function are deduced. In addition to that, the PU channel availability and throughput can then be calculated. Moreover, the optimal number of reserved channels can be obtained in this study and dynamically changed depending on the variation of PU traffic load. However, the selection of working mode initially affects the number of reserved channels either preferring SU retainability or SU channel availability.

The remainder of this paper is described as follows; Section 2 presents the proposed network scenario containing the DSA scheme with the DCR algorithm. The CTMC model is developed and the performance metric expressions are derived in Section 3. In Section 4, the numerical performance results are shown, also the optimal number of reserved channels is obtained based on the selected mode while considering the PU channel availability threshold. Finally, the attained conclusion from this study is presented in Section 5.

II. SYSTEM MODEL

In this section, an overview of the proposed scheme is presented with a detailed description of the CRN mechanism. Furthermore, the CTMC model is analyzed and comparisons of performance metric expressions are derived. In the proposed scheme, CR architecture involves a centralized entity (central controller) based on a software-defined network (SDN) to control the access of SUs all over its transmission range as shown in Fig. 1. Moreover, the infrastructure has a primary network (PN) and a secondary network (SN) which contains multiple PUs and SUs, respectively. The central controller senses the radio environment exclusively and does the analysis based on its observation and calculations. Consequently, it makes decisions and updates the channel availability in the spectrum according to the designed programming of SDN to provide channel allocation and reservation for arriving users.

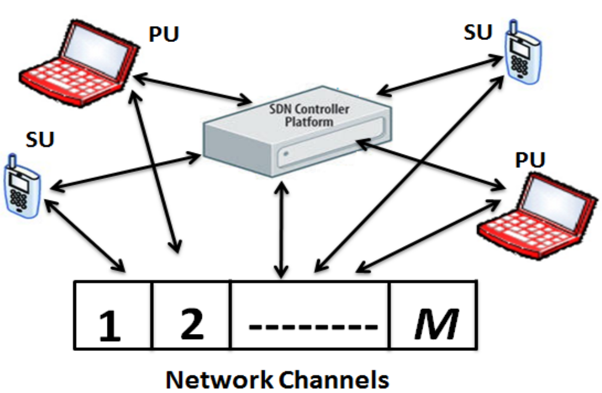

FIGURE 1. Software defined network with a centralized CRN architecture of dynamic channel reservation.

A. NETWORK SCENARIO AND ASSUMPTIONS

Consider that the total number of licensed channels in the spectrum of CRN is $M \in Z^+$ where, Z^+ is a set of positive integers and each of them has the same capacity. In the proposed scheme, the spectrum is partitioned into two parts which are non-reserved channels (N-CRN) and reserved channels (R-CRN) where N-CRN can be accessed by higher privileged PU and lower access priority is given to SU. Further, R-CRN is dedicated exclusively for new SU transmission or preempted SU from N-CRN due to abrupt PU arrival as demonstrated in Fig. 2. The number of reserved channels R is adjusted dynamically according to the active channel occupancy state.

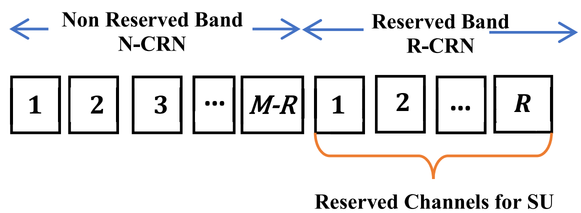

FIGURE 2. Channel allocation of reserved (R-CRN) and non-Reserved (N-CRN) channels.

Consequently, when more channels are reserved for interrupted active sessions, the SU blocking probability of new incoming users will increase. On the other hand, a certain degree of equivalence is performed between the new incoming users and the ongoing users by specifying the maximum limit number of channels that can be reserved as R_{max}. In the suggested analysis where $\leq R_{max}$, $R_{max} \in Z^+$ also, the dynamic adjustment of R is adopted corresponding to various conditions in the network. Moreover, the upper limit of R is set as $R \leq \left\lfloor \frac{M}{A} \right\rfloor$ where $A > 1$ to ensure the channel availability for new arriving users and improve the overall performance of the system and R' is defined as $\left\lfloor \frac{M}{A} \right\rfloor$. The scalar A is a parameter that restricts the part of the spectrum which would be reserved. For example, if $A = 4$ so, the system cannot reserve more than 25% from the total channels for preempted or newly arrived SUs. Each PU or SU is allocated to one channel in CRN and the model is adapted dynamically with regards to the arrival and departure traffic flow. The arrivals of PUs and SUs follow the Poisson process with rates per channel λ_p and λ_s respectively as in [7], [10]. Furthermore, the service times are distributed exponentially for PUs and SUs with corresponding service rates per channel of μ_p and μ_s respectively as in [12], [17].

B. THE PROPOSED DYNAMIC SPECTRUM ACCESS SCHEME AND DCR ALGORITHMS

This section contains an illustration of the DSA scheme, the proposed DCR approach, and the channel allocation process based on four different events: PUs/SUs arrivals

Algorithm 1 Dynamic Channel Reservation (DCR) Algorithm Based on SU Retainability and PU Channel Availability

Input: M:Total number of channels in CRN
Input: $\theta_S|_{(R=K)}$, $k = 0, 1, 2, 3$: SU Retainability when k are reserved channels in R-CRN
Input: $(\theta_S)_{MIN}$: Required minimum level of SU Retainability
Input: $A_P|_{(R=K)}$, $k = 0, 1, 2, 3$: PU channel availability when k are reserved channels in R-CRN
Input: $(A_P)_{MIN}$: Required minimum level of PU channel availability
Input: A: Parameter to determine the R_{max} which is the upper bound of R
Output: R_{OPT}: The optimal value of R

```
[1]  Calculate R' = ⌊M/A⌋
[2]  if (θS)MIN ≤ θS|(R=0) & (AP)MIN ≤ AP|(R=3) then
[3]  |  ROPT = 0
[4]  else if θS|(R=0) < (θS)MIN ≤ θS|(R=1) & (AP)MIN ≤ AP|(R=2)
[5]  |     ROPT = 1
[6]  else if θS|(R=1) < (θS)MIN ≤ θS|(R=2) & (AP)MIN ≤ AP|(R=1)
[7]  |     ROPT = 2
[8]  else if θS|(R=2) < (θS)MIN ≤ θS|(R=3) & (AP)MIN ≤ AP|(R=0)
[9]  |     ROPT = 3
[10] else
[11] |     ROPT = R' = 3
[12] end
```

Algorithm 2 Dynamic Channel Reservation (DCR) Algorithm Based on SU Channel Availability and PU Channel Availability

Input: M: Total number of channels in CRN
Input: $A_S|_{(R=K)}$, $k = 0, 1, 2, 3$: SU channel availability when k are reserved channels in R-CRN
Input: $(A_S)_{MIN}$: Required minimum level of SU channel availability
Input: $A_P|_{(R=K)}$, $k = 0, 1, 2, 3$: PU channel availability when k are reserved channels in R-CRN
Input: $(A_P)_{MIN}$: Required minimum level of PU channel availability
Input: A: Parameter to determine the R_{max} which is the upper bound of R
Output: R_{OPT}: The optimal value of R

```
[1]  Calculate R' = ⌊M/A⌋
[2]  if (AP)MIN ≤ AP|(R=3) & (AS)MIN ≤ AS|(R=0) then
[3]  |  ROPT = R' = 3
[4]  else if (AP)MIN ≤ AP|(R=2) & (AS)MIN ≤ AS|(R=1)
[5]  |     ROPT = 2
[6]  else if (AP)MIN ≤ AP|(R=1) & (AS)MIN ≤ AS|(R=2)
[7]  |     ROPT = 1
[8]  else if (AP)MIN ≤ AP|(R=0) & (AS)MIN ≤ AS|(R=3)
[8]  |     ROPT = 0
[9]  else
[13] |     ROPT = 0
[14] end
```

and PUs/SUs departures. For channel reservation, the optimum number is determined in R-CRN via submitted DCR algorithms. The proposed DCR algorithm operates in two modes considering different reliability perspectives: SU service retainability or SU channel availability. It is worth mentioning that the PU channel availability limit is considered in our two modes in contrast to other previous literature as in [7] in order to improve the QoS of the system when optimal R is selected. The optimum number of reserved channels R_{OPT} is adjusted according to the selected mode for channel allocation to new users. Initially, the SDN central controller should choose first either algorithm 1, the SU retainability, or algorithm 2, the SU channel availability, depending on the traffic load requests (λ_p and λ_s), in addition to, the performance priority represented by the specified values of the weight coefficients of the SU cost function α, β, and γ. Once, the algorithm is selected, the corresponding lookup table is implemented to determine the optimal number of reserved channels R_{OPT} as demonstrated in Fig. 3. Therefore, there is no difference in complexity for applying either algorithm. It is recognized that, when R is increased, the PU channel availability decreases, whereas the SU retainability and channel availability increase consequently. Therefore, it is necessary to develop a methodology that selects R_{OPT} which satisfies the QoS requirements. The essentials of the designed model for DCR are explained based on two proposed algorithms in the R-CRN as follows.

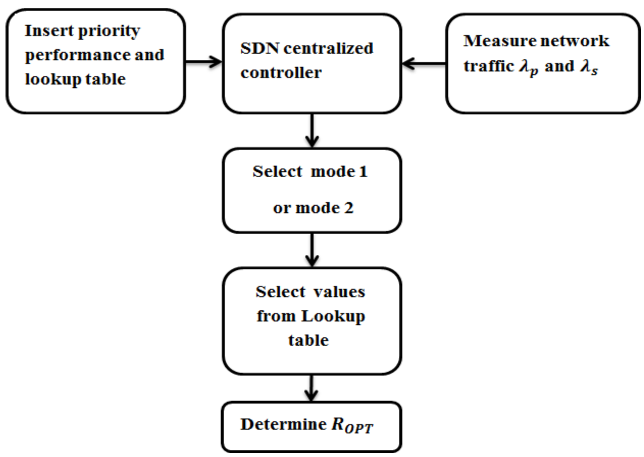

FIGURE 3. Block diagram illustration of the proposed model scheme.

Proposed algorithm 1 targets to preserve and improve the SU retainability of ongoing requests in the CRN consequently, the SU forced termination will be minimized. To guarantee the retainability, algorithm 1 assigns a higher number of reserved channels to the R-CRN when the PU ongoing traffic load λ_p becomes heavier. Moreover, PU channel availability should be ensured as PU privilege access is taken into consideration by setting the required minimum level. Therefore, when the PU arrival rate λ_p increases, SU forced termination P_{ft} increases as a result. Whereas

SU is obligated to perform hand over from N-CRN to any unoccupied channel in R-CRN otherwise, it will be exposed to forced termination out of the network. In other words, this stated algorithm is capable to select and get the optimal number of reserved channels denoted as R_{OPT} in the CRN. Further, the submitted scheme should consider the minimum level of SU retainability $(\theta_S)_{MIN}$ and the lower bound of PU channel availability $(A_P)_{MIN}$.

Conversely, **algorithm 2** aims at maximizing the SU channel availability hence; the SU blocking probability P_b^s will be reduced by lowering the number of reserved channels R when the ongoing traffic load becomes heavier. Providing more opportunities for incoming SUs services are related directly to the remaining unoccupied channels in either N-CRN or R-CRN. Therefore, in the case of the increase in traffic arrival rates of PU λ_p and SU λ_s, the SU channel availability will decrease accordingly. Once more the algorithm selects R_{OPT} for a minimum border of SU channel availability $(A_S)_{MIN}$ and a lower constraint of PU channel availability $(A_P)_{MIN}$.

As a result, using either of the two algorithms, R_{OPT} can be selected. Consequently, the number of reserved channels is readjusted and varied dynamically according to the variation in incoming trafiic, before the allocation of any new users as stored in the lookup table as illustrated in Fig. 3.

A conclusion of this study is to determine which of the two algorithms of operation is more appropriate under different operating conditions. Fig. 4 presents algorithm 1 that allocates a higher value of R when the traffic load for PU arrival rate λ_p increases while the smaller value of R is assigned to R-CRN if λ_p decreases respectively. Therefore, for achieving the demand of SU retainability, R_{OPT} should be 3 when $0.6 \leq \lambda_p \leq 0.9$ for reducing the forced termination probability. Otherwise, if the PU arrival rate is in the range $0.1 \leq \lambda_p \leq 0.3$, the system should allocate $R_{OPT} = 0$ as there is no need for reservation channels at low traffic. On the other hand, the in-between range of $0.3 < \lambda_p < 0.6$, R_{OPT} increases gradually to attain the reasonable value of reserved channel according to SDN controller management. Moreover, the system should not reserve more than $R_{max} = 3$ considering the PU channel availability does not exceed the minimum border level which is $(A_P)_{MIN} = 0.9$ where PU has the priority access in the network at $\lambda_s = 0.3$ or 0.6. Conversely, algorithm 2 targets the SU channel availability through providing idle channels for newly arrived SUs either in N-CRN or R-CRN. Subsequently, at lower λ_p, reserving more channels is proposed to R-CRN which does not affect considerably the users' occupations. Consequently, it is observed from Fig. 4, when $0.1 \leq \lambda_p \leq 0.3$ the system allocates $R_{OPT} = 3$, on the other hand for higher λ_p, when $0.6 \leq \lambda_p \leq 0.9$, $R_{OPT} = 0$ in order to avoid the increase of SU blocking probability. Whereas, the range of $0.3 < \lambda_p < 0.6$, R_{OPT} decreases dynamically to obtain the appropriate value in R-CRN. It is worth mentioning that, in mode 2 the minimum level of PU channel availability must not be less than $(A_P)_{MIN} = 0.9$ and 0.85 when $\lambda_s = 0.3$ and 0.6 respectively. For simplicity, mode 1 selects $R_{OPT} = [0, 0, 0, 1, 2, 3, 3, 3, 3]$ which satisfies the conditions, while mode 2 adopts with $R_{OPT} = [3, 3, 3, 2, 1, 0, 0, 0, 0]$ respectively.

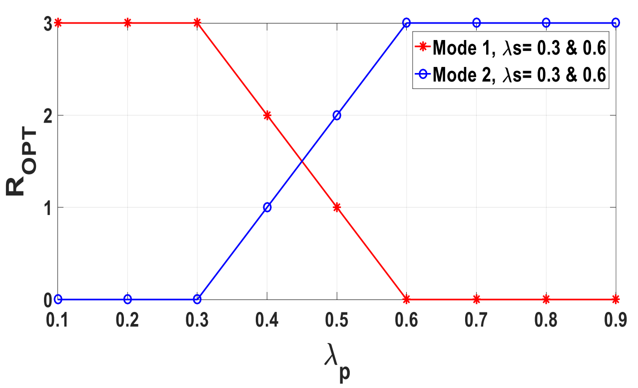

FIGURE 4. Optimum number of reserved channels R_{OPT} versus λ_p.

The presented flow chart of DCR scheme is shown with the four probable operations as explained in Fig. 5 as follows:

1) PU Arrival: First, the proposed DCR algorithm is run to find the optimum R and adjust the channels in N-CRN and R-CRN accordingly. After that, if there is an idle channel in N-CRN, a newly arriving PU will occupy that idle channel. When all channels in N-CRN are occupied, one of an ongoing SU service will be interrupted and SU will perform spectrum handover to an idle channel in R-CRN giving access to the new PU. For the situation that the interrupted SU cannot get the vacant channel in R-CRN, it will be exposed to forced termination. In the worst case that all channels in N-CRN are busy by other PUs, the new recent PU service will be blocked.
2) SU Arrival: The same as stated previously when PU arrival occurs, the system adjusts reasonable R as adopted in the proposed algorithm. Upon the arrival of an SU request, the idle channel in N-CRN will be assigned randomly to it. While all channels in N-CRN are busy, the incoming SU will occupy the available channel in R-CRN. In the case of all operational channels in N-CRN are occupied by PUs and /or SUs and the channels in R-CRN are also busy by SUs, the new SU request is blocked.
3) PU/SU Departure from N-CRN: When a PU/SU departs from N-CRN when its service is completed; the channel becomes available for occupation by another user, which could be either arrival of PU or SU. Furthermore, no spectrum handover is performed from R-CRN to N-CRN as applied in [7] to avoid more complexity in the CTMC model and more delay due to additional control traffic similar to the case in [10].
4) SU Departure from R-CRN: When SU finishes its transmission successfully in R-CRN; this vacant channel is free for allocation to the new arrival of SU. Further, a preempted SU from N-CRN can be assigned to this idle channel instead of undergoing forced termination out of the network.

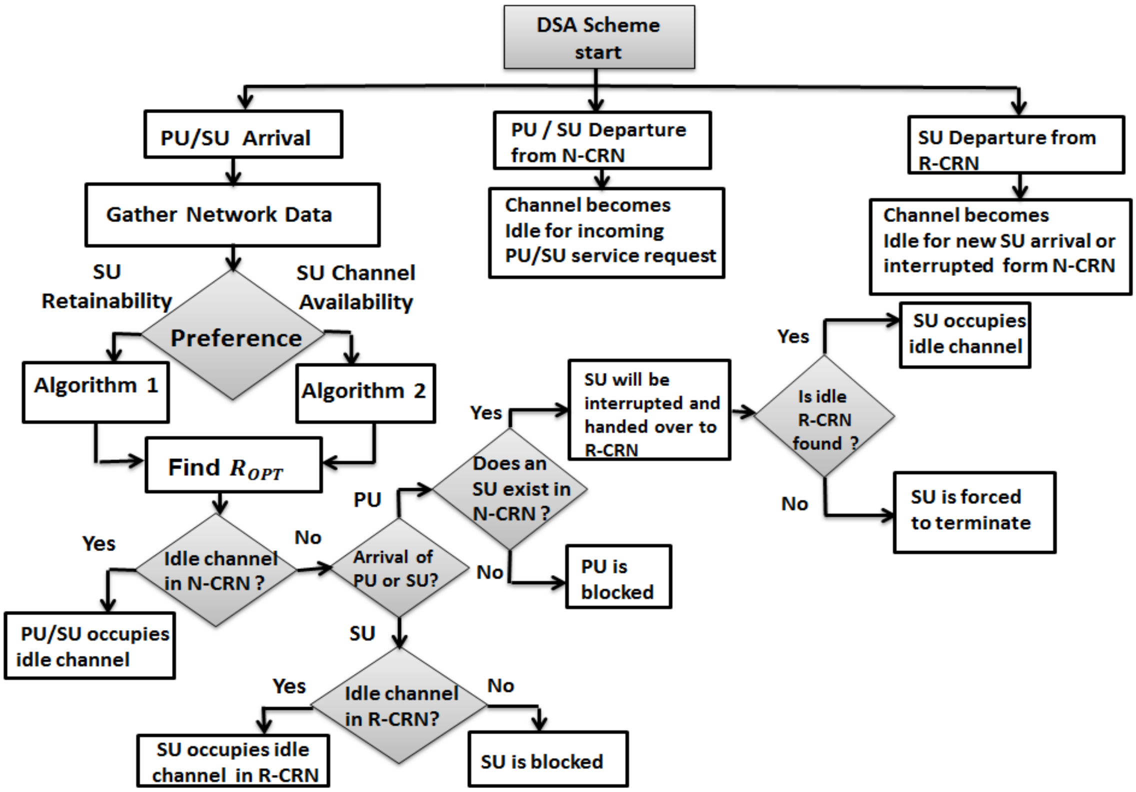

FIGURE 5. Flow chart of proposed dynamic channel reservation scheme.

III. CTMC MODELING AND PERFORMANCE METRICS

The estimated network scenario and the proposed DSA analytical model can be described under the proposed channel reservation scheme using a continuous-time Markov chain (CTMC) model.

A. CTMC MODELING

For the indicated CTMC model, it is assumed that the overall number of channels is M in CRN. These channels are divided into two parts which are non-reserved channels denoted by $(M - R)$ in the N-CRN and reserved channels denoted by (R) in the R-CRN.

While, the channel state is expressed by z where $z = (i, j, k)$ besides, i and j denote the number of SUs and PUs services in N-CRN respectively and k is the number of ongoing SUs in R-CRN. The steady-state probability is given by π_z of being in state z also the transition rate matrix. On the other hand, the steady-state probabilities can be obtained by equilibrium and normalization equation as in [7], [10] as follows

$$\pi Q = 0, \quad \sum_z \pi_z = 1, \tag{1}$$

where π is the steady-state probability vector and $\mathbf{0}$ is a row vector of all 0's. In the next section, mathematical expressions are deduced to analyze the performance metrics in the network.

B. PERFORMANCE METRICS

The QoS of the CRN using the DSA scheme and DCR can be developed and calculated based on the analytical CTMC model. The performance measures are derived such as SU retainability, PU and SU channel availability, SU network unserviceable probability, PU and SU throughput, and SU cost function.

1) CHANNEL AVAILABILITY

Upon the fact that all channels are assigned to users instantly in CRN, a newly arrived user will be blocked subsequently, the network becomes unserviceable for receiving users' requests. Consequently, the significant metric of channel availability demonstrates the opportunity of channel accessibility for both PUs and SUs in the CRN similar to [10]. In this research, channel availability of PU or SU requests is defined as the probability of the dedication of channels in CRN to new arrival for PUs or SUs without the occurrence of blocking the process of the services. Blocking of PU request happens when all the operational channels in N-CRN are busy by other active PUs' services. Contrarily, the channel availability of PU denoted by A_P is calculated as follows

$$A_P = 1 - \sum_{\forall z, i=0, j=M-R} \pi_z. \tag{2}$$

Further, an SU demand is blocked when all channels in N-CRN are utilized by PUs and/or SUs and also, all operational channels in R-CRN are employed by working SUs services thus; the channel availability of SU A_s can be obtained by

$$A_s = 1 - \sum_{\forall z, i+j=M-R, K=R} \pi_z. \tag{3}$$

The blocking probability of PU and SU, given by P_b^p and P_b^s, are attained respectively as

$$P_b^p = 1 - A_P, \quad P_b^s = 1 - A_s. \tag{4}$$

2) SU RETAINABILITY (θ_S)

Retainability is one of the most necessary metrics related to the QoS dependability of the CRN and it is known as the probability of completing the constructed service successfully within the interval time. On the contrary, SU forced termination [7] represents the probability of cutting off the active SU communication before delivering the request due to the prompt PU arrival. Correspondingly, the SU retainability θ_S can be described as

$$\theta_S = 1 - \sum_{\forall Z, (i+j=M-R), k=R} \frac{\boldsymbol{\pi}_z i \lambda_p}{\lambda_s A_s}, \tag{5}$$

Moreover, the SU forced termination P_{ft} is identical to [10] and expressed as follows

$$P_{ft} = 1 - \theta_S. \tag{6}$$

3) SU HANDOVER PROBABILITY

It is a probability that all operational channels in N-CRN are occupied by active users and at least an SU is assigned to one of these channels, so the new arrived PU will preempt randomly one of the ongoing SUs and interrupt its service. Thus, the preempted SU will perform spectrum hand over to an idle channel in R-CRN to resume its specified operation. The SU handover probability P_{hdvr} is denoted according to

$$P_{hdvr} = \sum_{\forall Z, i+j=M-R, K<R} \frac{\boldsymbol{\pi}_z i \lambda_p}{\lambda_s A_s}. \tag{7}$$

4) SU NETWORK UNSERVICEABLE PROBABILITY (Q_s)

One of the most essential system measures is the SU's network unserviceable probability Q_s which reflects the satisfactory level of the network performance. The calculation of SU blocking and forced termination probabilities help the user individually to evaluate the occupancy status and verify the retainability of the network. However, generally speaking, the metric Q_s is capable to specify the overall service completion effectively without blocking upon the user's arrival, or termination before its requested session accomplishment as in [10]. Therefore, the lower Q_s leads to better network performance. Moreover, the larger value of reserved R increases the SU retainability θ_S and channel availability A_s consequently. Q_s can be derived by deducing the proportion of the SU completion service rate with respect to the arrival rate depending on θ_S and A_s as follows

$$\begin{aligned} Q_s &= 1 - (\text{prob. of successfully accomp. SU sevices}) \\ &= P_b^s + P_{ft} - P_b^s P_{ft} = 1 - \frac{\lambda_s A_s \theta_S}{\lambda_s} = 1 - A_s \theta_S. \end{aligned} \tag{8}$$

5) THROUGHPUT

In this study, the throughput is defined as the mean number of service completions per unit time similar to [2], [8]. Therefore, this proposed model is concerned with the finished services effectively for PUs and SUs by both N-CRN and R-CRN. Hence the throughput of PU as well as SU, P_{th_PU} and P_{th_SU} respectively, are defined as follows

$$P_{th_{PU}} = \lambda_p A_P, \tag{9}$$

$$P_{th\_SU} = \lambda_s A_s \theta_S. \tag{10}$$

6) SU COST FUNCTION

This metric measures the influence of SU channel availability A_s and SU retainability θ_S also SU handover probability P_{hdvr} on the system performance and the improvement of QoS related to adopting dynamic channel reservation in the CRN. Hence, the SU Cost Function C_{SU} is given by this expression

$$C_{SU} = \alpha(1 - A_s) + \beta(1 - \theta_S) + \gamma P_{hdvr}, \tag{11}$$

where α, β, and γ are the network factors to express the cost weights of each coefficient as in [12].

IV. SIMULATION RESULTS AND SYSTEM PERFORMANCE

In this section, the simulation results are presented to examine the performance metrics and comparison is obtained according to a variation of the traffic load conditions by using MATLAB Simulink models by MATLAB software package. The proposed analysis is configured for the DSA scheme based on the DCR mechanism corresponding to the previously mentioned CTMC model. Assuming, our centralized CRN with SDN topology has the following parameter values: $M = 10$ is the total number of channels, the reserved channels is $R \in \{0, 1, \ldots, 3\}$, the parameter which limits R is $A = 3$. Moreover, the PU arrival rate of PU and SU per unit time are $\lambda_p = \{0.1, \ldots, 0.9\}$ and $\lambda_s = 0.3$ or 0.6 as stated in the previous figures respectively as well the service times of PU and SU are $\mu_p = 0.8$ and $\mu_s = 1.2$ similar to [31]. On the other hand, the cost weights are expressed by α, β, γ which are equal to 10,100, 2 sequentially representing the relative impact of the SU forced termination, blocking, and handover probabilities on the system performance as in [12]. The following figures show the comparison of performance measures between the static channel reservation and DCR according to the dynamic variation of R to select R_{OPT} based on applying the selected one of two algorithms in the CRN. For the sake of explanation clarity, the simulation results are represented with dotted and straight lines when $\lambda_s = 0.3$ and $\lambda_s = 0.6$, respectively. It is worth mentioning that, the minimum required level of SU retainability $(\theta_S)_{MIN}$ and

PU channel availability $(A_P)_{MIN}$ are assigned. Moreover, concerning algorithm 1 when $\lambda_s = 0.3$ and 0.6 the minimum border $(\theta_S)_{MIN} = 0.9$ and 0.86 respectively also $(A_P)_{MIN} = 0.9$ for both values of λ_s. However, regarding to algorithm 2 at the same mentioned λ_s, the lower limit of $(A_S)_{MIN} = 0.9$ and 0.75 for also $(A_P)_{MIN} = 0.9$ and 0.85 respectively.

Fig. 6 shows the SU retainability θ_S of SCR considering diverse channel reservation number R compared to Fig. 7 which plots θ_S with DCR according to dynamic R_{OPT} depicted in Fig. 4 for $\lambda_s = 0.3$ and 0.6 as a function of λ_p.

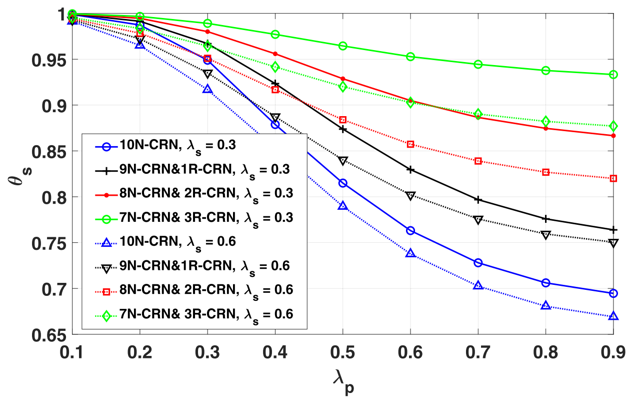

FIGURE 6. SU retainability θ_S of static channel reservation for different values of λ_p and R with $\lambda_s = 0.3$ & 0.6.

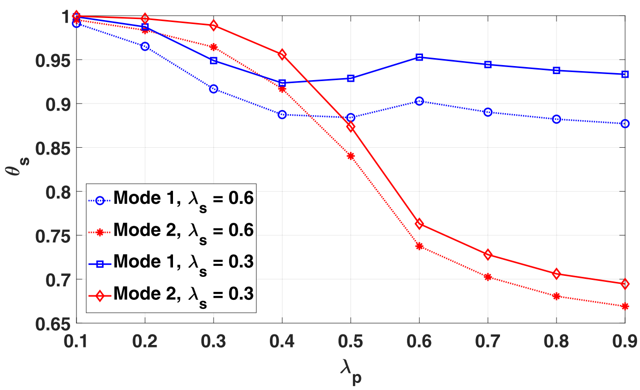

FIGURE 7. SU retainability θ_S of DCR for the two modes with various λ_p and $\lambda_s = 0.3$ & 0.6.

It is noted that, θ_S decreases with the increase of PU traffic load λ_p or λ_s at fixed R due to SU forced termination probability increasing while θ_S improves significantly when R increases in SCR as providing more opportunities in R-CRN since PU arrival occurs. For instance, at fixed higher PU traffic load when $\lambda_p = 0.8$, algorithm 1 in the DCR scheme enhances the retainability θ_S by approximately 25% and 22% with the reference to the case without channel reservation ($R = 0$) since the variation of $\lambda_s = 0.3$ and 0.6 respectively which indicates the increase of SU arrival rate does not affect the performance significantly. However, algorithm 2 has a bit improvement in comparison with $R = 0$ since at lower traffic when $\lambda_p = 0.4$, the increase of θ_S is about 8% and 7% with respect to no reservation model also regardless of the change in λ_s as previously stated in mode 1. Generally speaking, it is observed that in DCR, algorithm 1 outperforms algorithm 2 for overall performance due to its superior values of θ_S either in case $\lambda_s = 0.3$ or 0.6 specially with higher λ_p. This is because algorithm 1 assigns more reserved channels in R-CRN with higher traffic load, contrary algorithm 2 allocates fewer reserved channels with high demand on channel reservation likewise in [10]. Moreover, it is worth mentioning that for both algorithms of DCR and SCR, θ_S increases when λ_s increases from 0.3 to 0.6 as a result of the reduction of SU forced termination at lower SU arrival than higher rates.

It is observed that the DCR is more flexible and reliable than SCR for network performance quality from the view of channel availability and this observation will be pointed out in the next figures. PU channel availability A_p is illustrated in Fig. 8 with different λ_p and λ_s traffic load levels and is influenced significantly by various static channel reservation numbers of R, also in a dynamic way by applying the DCR scheme shown in Fig. 9. Further, the increase of PU traffic load λ_p decreases A_p accordingly, due to more PU arrivals that will allocate more channels in N-CRN causing blocking for new incoming PUs as shown in [10]. Meanwhile, the main

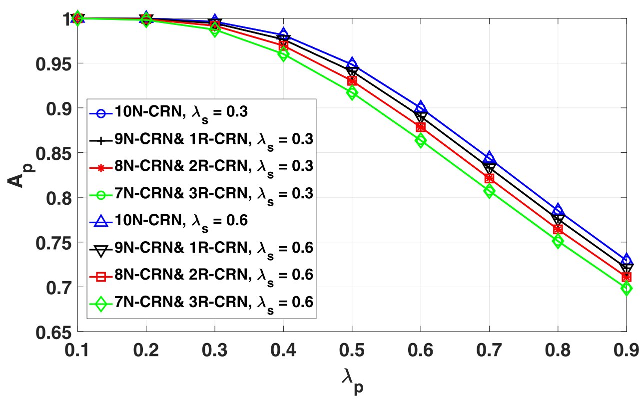

FIGURE 8. PU channel availability A_P of static channel reservation for different values of λ_p and R with $\lambda_s = 0.3$ & 0.6.

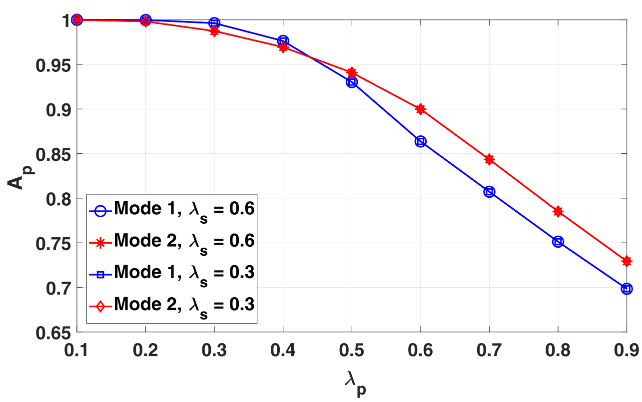

FIGURE 9. PU channel availability A_P of DCR for the two modes with various λ_p and $\lambda_s = 0.3$ & 0.6.

advantage of our proposed SCR and DCR is that A_p is not affected remarkably with a change of SU arrival rate λ_s. The reason of the aforementioned case, where with SCR the privilege is given fundamentally for the PU, so the new arrived SU will be blocked if all channels either in N-CRN or R-CRN are busy or be handed over to the vacant channel in R-CRN if available since PU arrival occurs, also it is supposed to terminate forcibly if all channels in R-CRN are occupied. Moreover, for the proposed DCR, the algorithm is designed with taking into consideration the minimum limit of A_p as a constraint to maintain PU QoS. On the other hand, the increase in R causes a minor degradation in A_p.

For example, at either fixed $\lambda_s = 0.3$ or 0.6 and when $\lambda_p = 0.5$, the system with $R = 1$, $R = 2$ and $R = 3$ has a decrease of A_p approximately with 0.8%, 2%, and 3% compared with the reference of without channel reservation ($R = 0$). Concerning Fig. 9, using either of the two algorithms we obtain the same result values at different λ_s with algorithm 2 outperforming algorithm 1 by inconsiderable improvement. For instance, at $\lambda_p = 0.8$ algorithm 2 becomes higher than algorithm 1 by about 4% which is regarded as a little change in A_p.

Fig. 10 plots SU channel availability A_s for access opportunities upon diverse PU and SU arrival rates with a variety of static reserved channel numbers. From this figure, it is demonstrated clearly that A_s decreases with the increase of λ_p at fixed λ_s and R. In addition to that, it increases with the increase of channels in R-CRN since it provids more access chances for new SU as our proposed scheme permits access for new arrived SU contrary to [10] that gives the access only for interrupted SU due to PU arrival or channel failure from N-CRN. Moreover, the increase of λ_s leads to the relative reduction in A_s due to the more utilization of channels corresponding to higher SU traffic load. On the other hand, algorithm 1 gives better results for A_s than algorithm 2 as it has more reserved channels for higher λ_p as shown in Fig. 11 regardless of λ_s.

For example, at a constant larger value of $\lambda_p = 0.8$, algorithm 1 in the DCR scheme rises A_s about 26% and

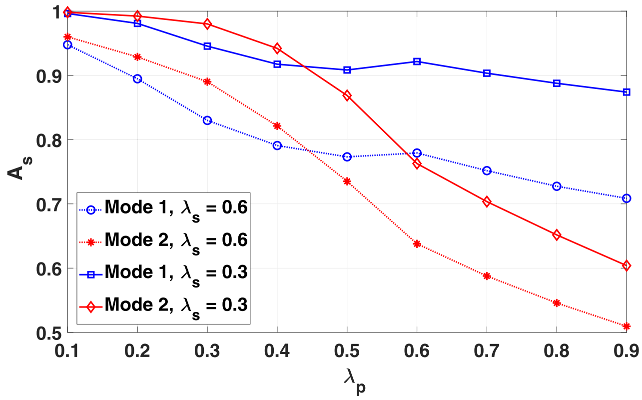

FIGURE 11. SU channel availability A_s of DCR for the two modes with various λ_p and $\lambda_s = 0.3$ & 0.6.

25% with respect to $R = 0$ while $\lambda_s = 0.3$ and 0.6 respectively. In addition, algorithm 2 improves slightly A_s at lower $\lambda_p = 0.4$ about by 5% and 7% compared to with no reservation when $\lambda_s = 0.3$ and 0.6 as mentioned before in algorithm 1. To conclude, the achieved A_s becomes more reliable if algorithm 1 is selected for developing SU higher performance. The SU throughput probability P_{th_SU} is investigated with respect to the variation of λ_p and λ_s also the change of R statically as shown in Fig. 12. It is observed from the figure that, when λ_p becomes higher that reduces A_s as illustrated in Fig. 9 which has direct proportion with P_{th_SU} as in "(10)," leading to the decrease of P_{th_SU} similar as clarified in [2]. In addition, higher λ_s causes the rising of P_{th_SU} as A_s increases accordingly. Moreover, the growth of R increases P_{th_SU} as A_s becomes larger due to providing more channel access opportunities of SU for both lower and higher λ_s. Based on the achieved DCR scheme, Fig. 13 demonstrates that algorithm 1 is preferred than algorithm 2 for higher ongoing traffic load λ_p for both cases of λ_s. Since when $\lambda_p = 0.8$ algorithm 1 improves P_{th_SU} significantly by a large rate of about 50% and 46% respectively in comparison

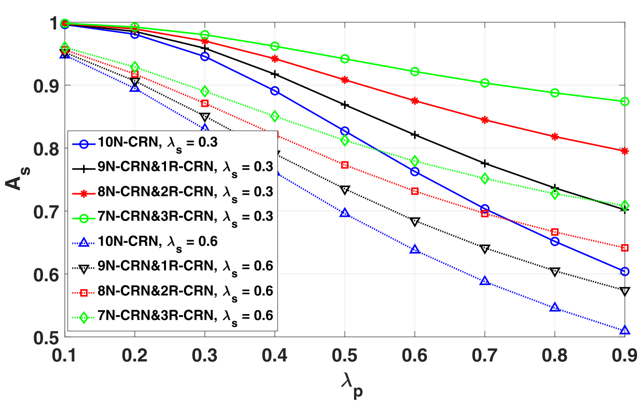

FIGURE 10. SU channel availability A_s of static channel reservation for different values of λ_p and R with $\lambda_s = 0.3$ & 0.6.

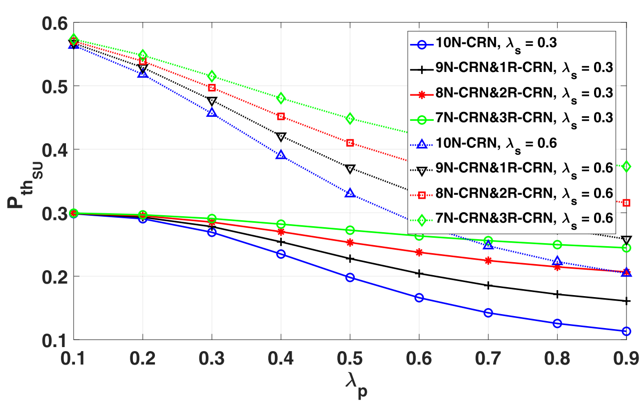

FIGURE 12. SU throughput probability P_{th_SU} of static channel reservation for different values of λ_p and R with $\lambda_s = 0.3$ & 0.6.

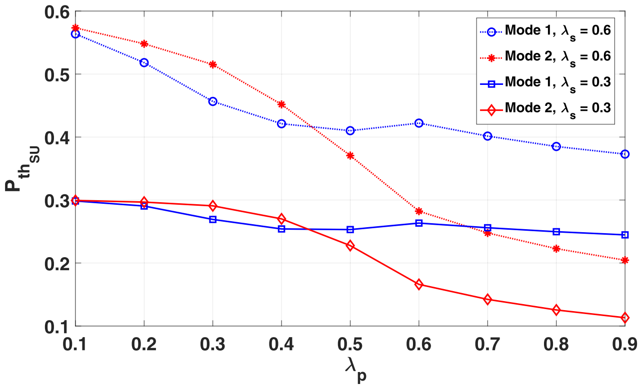

FIGURE 13. SU throughput probability P_{th_SU} of DCR for the two modes with various λ_p and $\lambda_s = 0.3$ & 0.6.

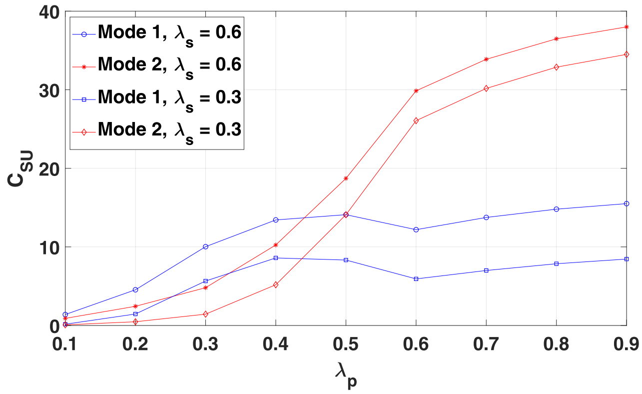

FIGURE 15. SU cost function C_{SU} of DCR for the two modes with various λ_p and $\lambda_s = 0.3$ & 0.6.

with no channel reservation configuration as it protects the working SUs services when $\lambda_s = 0.3$ and 0.6 respectively.

However, at lower $\lambda_p = 0.4$, the reserved channels are rarely accessed so, algorithm 2 serves better than algorithm 1 by 13% and 14%, respectively compared to $R = 0$. Therefore, algorithm 1 of DCR has more advantages for overall system QoS. Fig. 14 shows the SU cost function C_{SU} which is considered an important metric versus various λ_p with variation of λ_s and R. Results indicate that the rise of λ_p increases C_{SU} directly due to the consequent reduction of SU retainability θ_S and channel availability A_s and the increase of handover probability P_{hdvr} according to "(11),". The same occurs with the increase of λ_s. On the other hand, the increase of R decreases C_{SU}. Observably in Fig. 15, algorithm 1 is more reasonable for highly PU utilization as it has lower C_{SU} compared to algorithm 2. For instance, with algorithm 1 and $\lambda_p = 0.8$, $Cost_{SU}$ is less than $R = 0$ considerably by 76% and 59% for $\lambda_s = 0.3$ and $\lambda_s = 0.6$, respectively. Additionally, the other improvement is adopted through algorithm 2 which has the obvious progress by minimizing C_{SU} by 60% and 40% with the same prior recommended values of λ_s respectively. As expected clearly, the suggested DCR

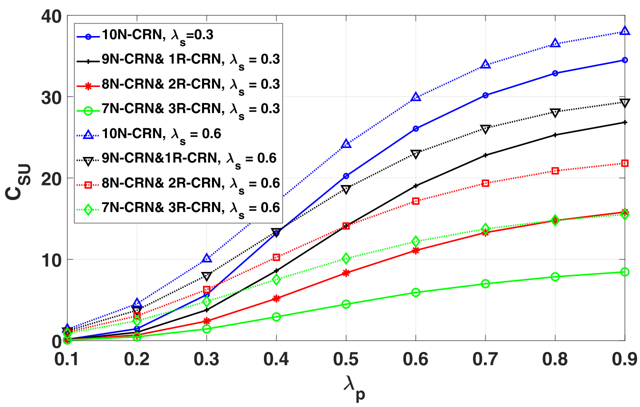

FIGURE 14. SU cost function C_{SU} of static channel reservation for different values of λ_p and R with $\lambda_s = 0.3$ & 0.6.

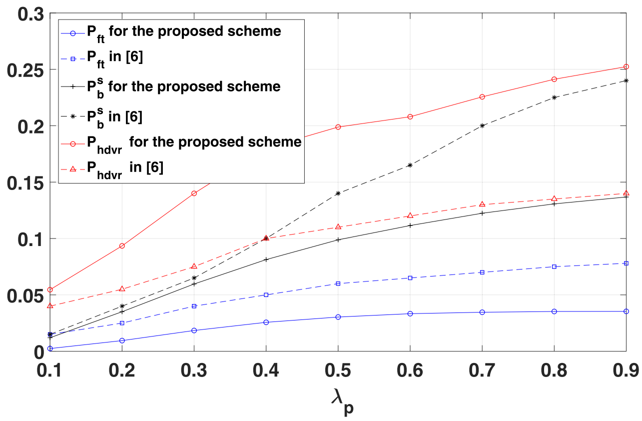

FIGURE 16. Comparison between SU metrics in our proposed DCR scheme and those in [6].

scheme reflects positively than SCR on major SU metrics with a minor inconsiderable change in PU performance.

The comparison of our proposed DCR scheme with previous literature [6], demonstrates a considerable improvement of the SU QoS.

These measures are taken by applying the referred utilized values in [6] to our DCR scheme model as $M = 9$, $\lambda_s = 0.6$, $\mu_p = \mu_s = 0.1$, and the range of λ_p from 0.1 to 1. It is expected, when λ_p rises, the corresponding values of SU forced termination P_{ft}, blocking probability P_b^s, and handover probability P_{hdvr} will increase. Fig. 16 shows the remarkable enhancement of obtained P_{ft} and P_b^s for various values of λ_p with respect to [6]. It is noted that when $\lambda_p = 0.6$, our proposed model reduces P_{ft} and P_b^s by about 49% and 32% respectively compared to [6]. On the other hand, the SU P_{hdvr} in our scheme has higher values than [6]. However, this has minor consequences on the overall SU's QoS since the whole purpose of the presence of reserved channels is to reduce P_{ft} and P_b^s.

Fig. 17 depicts the comparison of the SU unserviceable probability Q_S between the two algorithms of our proposed DCR approach and the previous literature [10] versus λ_p. It is worth mentioning that, the lower Q_S has a better performance

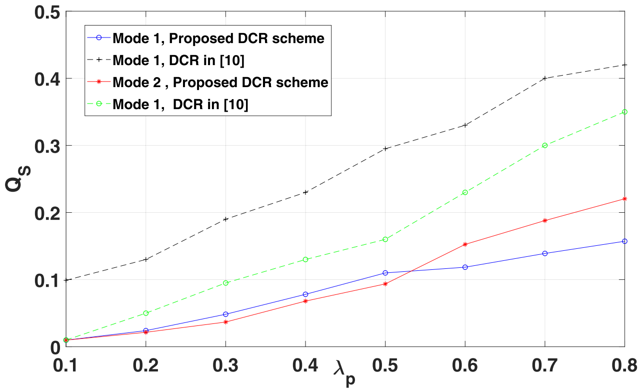

FIGURE 17. SU network unserviceable probability Q_S of DCR for proposed scheme and shown in [10].

as it preserves the SUs from being forcibly terminated or blocked as explained in "(8),". These measures are taken by applying the employed values in [10] to our DCR system model taking into in consideration the fact that the total number of channels and λ_p in [10] is taken for all the system channels in contrast with our λ_p, which is designed to be per one channel. Moreover, it is shown that Q_S increases directly with the increase of λ_p related to more PU arrivals causing the subsequent rise of P_{ft} and P_b^s. For instance, since $\lambda_p = 0.5$, Q_S for algorithm 1 and algorithm 2 is reduced compared to the values in [10] by approximately 63% and 41% respectively. Generally speaking, the SU comprehensive performance is enhanced obviously for both algorithm 1 and algorithm 2 of the proposed DCR scheme model compared to the obtained values in [10]. This reduction in Q_S demonstrates the prevalence of our DCR system results for both algorithms.

The comparison of the SU retainability θ_S is plotted against λ_p in Fig. 18, which shows the performance of the proposed two algorithms of the DCR approach and the other corresponding scheme in [10]. Further, the increase of λ_p leads to a decrease of θ_S as a result of the rise of P_{ft} accordingly. Noticeably, our proposed algorithm 1 has larger values of θ_S especially at higher λ_p. On the other hand, algorithm 2 of our proposed technique outperforms results in [10] in general, and more significantly at lower λ_p. However, when $\lambda_p = 0.5$, algorithm 1 and algorithm 2 of our submitted model increase θ_S by slightly inconsiderable rise of about 2% and 3% with compared the values achieved in [10]. Subsequently, the overall SU QoS is improved by the utilization of our proposed DCR algorithms.

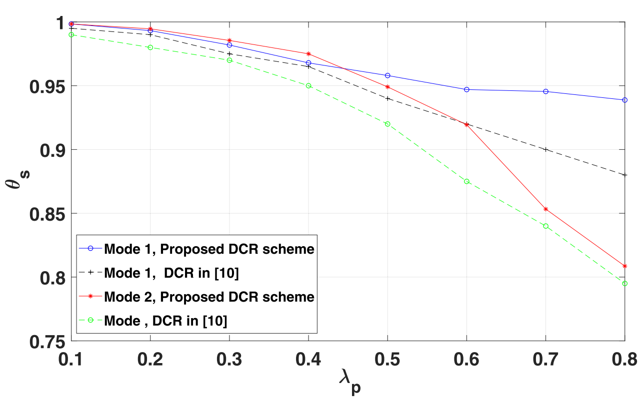

FIGURE 18. SU retainability θ_S of DCR for proposed scheme and shown in [10].

V. CONCLUSION

This paper proposes a DSA strategy embedded with the DCR scheme which targets the significant improvement of system performance in terms of PU/SU channel availability and SU retainability in CRN. This submitted strategy develops more flexibility through the selection of the optimal number of reserved channels R_{OPT} based on either SU retainability or SU channel availability while maintaining the PU channel availability. Furthermore, the coordination between users is conducted by an SDN centralized controller in the scheme. This SDN controller can manage the dynamic access allocation more effectively. As expected, the determination of SU's required algorithm of the proposed DCR algorithm is related to either fulfillment of SU's service retainability or channel availability. It is noted that from the simulation results, when the PU traffic arrival rate λ_p is low, it is recommended to utilize algorithm 2 due to its ability to provide more channel allocation opportunities for new SU arrival, increasing SU channel availability. On the other hand, when λ_p increases, algorithm 1 shows better overall performance precision and correctness through satisfying the SU service retainability requirement. Considerably, the impact of using our approach enhances the SU QoS metrics with a minor trivial change in PU perspectives at diverse traffic loads. Furthermore, the use of SDN simplifies the connectivity and the control of the network and reduces the errors caused by a false alarm and misdetection probabilities.

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