IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 9 January 2024, accepted 18 February 2024, date of publication 29 February 2024, date of current version 14 March 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3371884

APPLIED RESEARCH

Performance Analysis in the Presence of Channel Failure in Cognitive Radio Networks With Dynamic Spectrum Reservation

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ABSTRACT In wireless networks, there are two prominent challenges. The first challenge is ensuring that users have opportunities to access channels and request new services. The second challenge is maintaining connections for data flows. These challenges are compounded by the occurrence of channel failures, which often occur due to characteristics of radio transmission such as signal attenuation, signal blockage or device and power outages. Channel failures can significantly impact the effectiveness of both the primary and secondary networks. Therefore, it becomes crucial to prioritize retainability which denotes the need to maintain uninterrupted user connections even during network disruptions. This paper proposes an analytical model that evaluates performance of cognitive radio networks in the context of random channel failure rates. Additionally, the dynamic channel reservation (DCR) scheme is introduced. It can be integrated into dynamic spectrum access (DSA) strategies. This integration aims to give priority to existing services over requests from users to provide cognitive networks with more opportunities to allocate idle channels or maintain their current services. Moreover, the cost functions for both the primary user (PU) and the secondary user (SU) are calculated. This calculation considers the failure rate specifically in either reserved channels (RCN) or non-reserved channels (N-RCN) to meet different performance requirements. The results show a decrease in the SUs cost function, which guarantees that the quality of service (QoS) requirements for the PU are fulfilled. Importantly, this reduction in SU cost leads to an enhancement in SU channel availability or throughput when compared to previous models.

INDEX TERMS Licensed shared access, cognitive radio network, dynamic channel reservation, dynamic spectrum access, secondary user, primary user, quality of service, retainability, channel availability.

I. INTRODUCTION

The significant growth in wireless communication in recent decades has created a high demand on the rapidly crowded radio spectrum. A main challenge for the future of 5G wireless systems centers on improving the availability and dependability of communication services. Current cellular networks are constrained by their limited bandwidth and fixed spectrum allocations, necessitating a shift toward more flexible and dynamic spectrum access to achieve these objectives. Cognitive radio (CR) stands as a prospective technology that could be incorporated within the 5G framework, providing a promising technological approach to handle the challenges encountered during the evolution of 5G [1]. Hence, CR channels availability and reliability are crucial for their effective function within upcoming 5G wireless networks. Currently, the cellular system is only permitted to use the licensed spectrum with restricted and fixed bandwidth under current bandwidth regulation policy [2]. Despite the common belief that current cellular spectrum

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmed Almradi.

resources are consistently fully utilized; recent evaluations have shown that a substantial portion of licensed frequency bands remain underutilized by incumbent users who do not effectively exploit these resources. In essence, CR represents a form of wireless communication involving a smart transmitter-receiver unit discerns busy and idle communication channels, rapidly transitioning to unoccupied channels while actively avoiding those that are already in use. This strategy optimizes the effective utilization of the available radiofrequency (RF) spectrum while minimizing interference with other users [2], [3]. In CRNs, certain channels may be unavailable to both primary users (PUs) and secondary users (SUs) for two primary causes. Firstly, many PUs and SUs may already be using licensed channels within the frame network. Secondly, these channels may experience failures due to different causes like equipment failure, channel fading and shadowing [2], [4]. CR introduces a technique known as dynamic spectrum access (DSA) to overcome this. This approach allows unlicensed secondary users (SUs) to allocate unoccupied licensed spectrum bands without causing any interference with the services of primary licensed users (PUs) [5]. DSA is employed to detect and utilize these unoccupied licensed bands, often referred to as "spectrum holes." This approach overcomes the challenges related to spectrum scarcity and ineffective use of spectrum resources [5], [6]. However, SUs need to vacant the spectrum gap and switch to another idle channel if a PU suddenly arrives at its assigned frequency band, as in [5]. Underlay and overlay techniques are two methods for controlling the interactions between primary and cognitive networks as in DSA [7]. In this study we focus on examining the overlay utilization technique, for spectrum. It involves granting users higher access privileges while allowing SU users to utilize the unoccupied frequency bands that are available. Additionally, to enhance the performance of overlay systems, an approach known as a "win/win" scenario is employed, as explained in [7]. This approach allows a PU has the option to lease out its spectrum and receive compensation in return with the aim of maximizing its financial gains. To improve the effectiveness of the system, the channel reservation approach is widely used to reserve certain channels for specific users [8], [9]. In studies these reserved channels were allocated solely by SUs, as in [10], or PU allocation, as in [8] and [11]. Furthermore, in our proposed method, we compute the expenses incurred by PUs and SUs while considering variations in the arrival, failure rates, and number of reserved channels. The main objective is to enhance both bandwidth efficiency and the total capacity of the system and quality of service (QoS). To analyze this situation, we employ a Markov chain methodology that considers discrete states and continuous time. The transition rates between these states play a role in determining the arrival and service rates for PUs and SUs across various scenarios [12]. The evaluation of channel occupancy is carried out using a continuous-time Markov chain (CTMC) approach. In this CTMC framework, each state within the model represents the count of PUs and SUs, as in [13]. Additionally, we compute metrics based on the steady-state probabilities obtained from the CTMC as blocking, handover probabilities, and forced termination probability. It is worth noting that previous research efforts have predominantly concentrated on fulfilling the requirements of PUs, often neglecting the QoS experienced by SUs, especially in terms of service interruptions caused by the sudden arrival of PUs, as discussed in [14]. Consequently, various channel reservation strategies were recently proposed in wireless CRNs to significantly enhance the system's QoS. These strategies involve the allocation of a specific number of channels for the benefit of PUs, as detailed in [8] or SUs, as outlined in [15], or even both PUs and SUs, as in [4]. Research outcomes discussed in [16] show that dedicating the reserve channels to SU traffic leads to performance enhancement by lowering the forced termination probability of SUs. However, it may cause a higher blocking probability, compared to a situation when there is no channel reservation. In addition, as in [16], the cost function devised for the implementation of this strategy primarily focused on assessing the performance of SUs. In the study presented in [17], where channel reservation is coupled with a fixed arrival rate for PUs, the utility of SUs increases corresponding to the increased traffic generated by SUs. Conversely, the number of reserved channels is determined by considering a balance between performance metrics, specifically, the blocking and forced termination rates affecting SUs, in addition to the blocking probability for PUs, as in [17]. The main contribution of this paper is to evaluate the performance of the whole system in the presence of different failure rates either in R-CRN or R-CRN and its effect on cost function and compare it to each other.

Moreover, we propose different scenarios for the handover for SUs under the influence of channel reservation, illustrating the potential of SUs to recommence the services depending on the number of reserved channels that are available and different failure rates. When compared to previously published research, these results show the improvement in the SUs's QoS through the implementation of the proposed scheme.

As for the second issue, conducting a comprehensive reliability assessment necessitates accounting for performance variations linked to channel failures. Therefore, the aim of this study is examining how well DSA and DCR work in conjunction within CRNs, emphasizing the influence of channel failures, including those occurring in reserved and non-reserved channels.

This paper's sections are organized as follows:

- Section II elucidates the network scenario, includes the DSA scheme integrated with the DCR algorithm.
- Section III formulates the CTMC model and formulates expressions related to diverse performance metrics.
- Section IV delivers the numerical performance outcomes, with varying number of reserved channels.
- Finally, in Section V, we present the conclusion drawn from this paper.

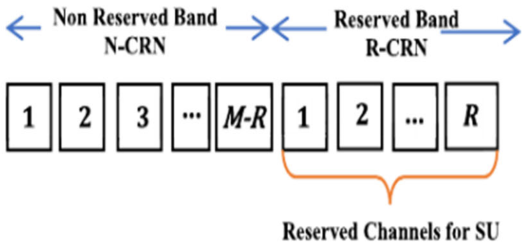


FIGURE 1. **Channel distribution between R-CRN and N-CRN channels [12].**

II. SYSTEM MODEL

In this part, the suggested plan is introduced for offering a comprehensive explanation of the CRN mechanism. Additionally, we delved into the examination of CTMC models and the analysis of state transitions. Furthermore, we compare expressions for performance metrics.

A. NETWORK SCENARIO AND ASSUMPTIONS

Consider the scenario in which the licensed spectrum of the CRN consists of M channels, with M being a positive integer represented as $M \in Z+$, and $Z+$ is a group of numbers greater than zero, excluding fractions or decimals with equal capacity as in [12] and [18]. In the suggested method, the spectrum is divided non reserved channels (N-CRN) and reserved channels (R-CRN). As discussed earlier, N-CRN and R-CRN are susceptible to a variety of potential failures that could disrupt ongoing communication sessions. These failures could be at either N-CRN or R-CRN or both. N-CRN is accessible primarily to higher-privileged PUs, with lower access priority granted to SUs. Conversely, R-CRN is exclusively dedicated to new SU transmissions or pre-empted SUs transitioning from N-CRN because of sudden PU arrivals or have been exposed to failure, as represented in Fig. 1. The number of reserved channels, introduced as R, is dynamically adjusted in response to the current state of channel occupancy. A total of $R \in Z+$ channels, out of the M available channels, are dedicated for this purpose.

Nonetheless, whenever channels suffer from disrupted ongoing services, it leads to a growing in the probability of blockage or forced termination and consequently deterioration in overall capacity due to the inefficient utilization of channels. To improve this decreasing in capacity and ensure the availability of channels for new user, a higher bound of R is specified with $R \leq [\frac{M}{A}]$, where A represents a single-value parameter greater than 1, dictating the extent of spectrum reservation [12]. For example, above twenty-five percent of the system cannot allot over twenty-five percent of its available system's available spectrum cannot be allotted to disrupted users if $A = 4$ as in [12]. This paper employs a service-level methodology to model traffic, capturing the fluctuations of data flows. Each PU /SU is assigned to a specific CRN channel. We also build a set of fundamental assumptions that will serve as the core for the structure of the model of analysis, which will be further explained expounded in Section III.

- Each PU and SU service arrivals per channel follow Poisson distributions with rates of λ_p and λ_s, respectively as [18] and [19]. Additionally, the service durations for PU and SU services have exponential distributions, and their associated service rates for each channel, μ_p and μ_s, in order.

  The uninterrupted duration of a channel, which is the time it functions correctly before a failure happens, follows an exponential distribution with a failure rate of λ_f in either N-CRN or R-CRN. Additionally, we consider the failures can occur in both idle and occupied channels. The duration of sensing and any required spectrum hand-off delay is negligible when contrasted with the time between two consecutive service events.

B. THE PROPOSED SCHEME FOR DYNAMIC SPECTRUM ACCESS AND ALGORITHMS FOR DYNAMIC CHANNEL RESERVATION

This paragraph explains our proposed approach to dynamic channel access, the channel reservation system, and the channel allocation process, all of which are influenced by the arrivals and departures of PUs and SUs. In our analytical model, we employ a CTMC with continuous-time states to evaluate a range of performance metrics. As in [12], A centralized cognitive manager (CCM) manages the used DSA system, a strategy widely implemented in CRNs to coordinate the allocation of users within their transmission range. In this approach, the centralized controller, functioning like the base station, determines the utilization of vacant channels by depending on the data collected from SUs through monitoring and environmental observations. Subsequently, the centralized controller evaluates spectrum availability, new requests from PUs and SUs before allocating the spectrum's resources in accordance with the allocation schemes. Furthermore, our proposed design encompasses J=M-R channels within N-CRN and R reserved channels in R-CRN, specifically dedicated to unlicensed users (SUs) to improve their QoS.

Channels are allocated by PUs and SUs in N-CRN as in [12]. In N-CRN, idle channels are used right away by authorized PUs and arriving unauthorized cognitive users (SUs), however PUs are unable to use reserved channels. While SUs must first determine whether a channel is idle before using it, PUs are able to access at random any available J channel in the N-CRN. If all N-CRN channels have been utilized, they can replace an SU-occupied channel, interrupting its service. To complete its service, the SU then hops to an idle channel in the R-CRN. Additionally, to reduce forced terminations, the SU interrupted service, which was terminated owing to the failure can be assigned to R-CRN if there is no vacant channel in the N-CRN. This is an essential requirement since one key QoS need is to ensure an enhanced level of retainability for services currently in place.

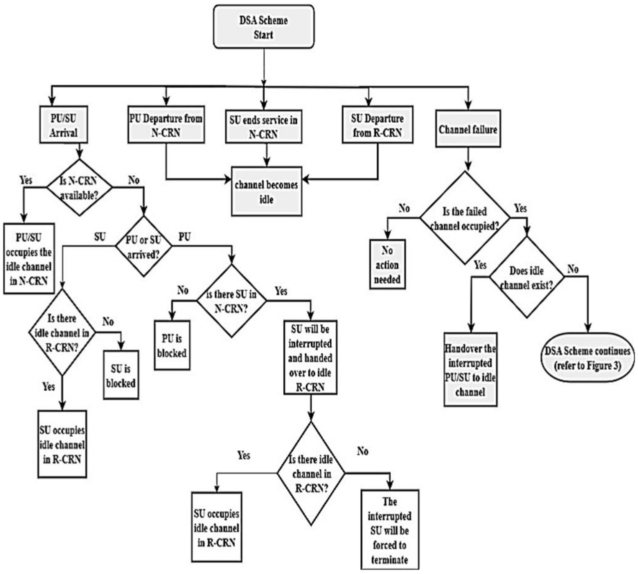


FIGURE 2. A diagram of the suggested DSA method.

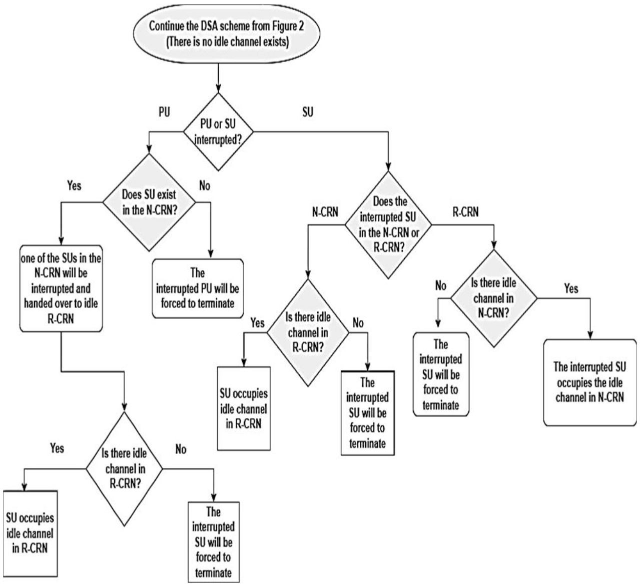


FIGURE 3. A diagram explaining the suggested DSA method in the event of failure channel.

Fig. 2 shows a flowchart for five possible events that can occur.

1) PU Arrival: The DCR scheme assigns the number of reserved channels R as will be shown later in subsection III-A. Upon the arrival of a new PU, it will occupy randomly any vacant channel in N-CRN. However, when all channels in N-CRN are occupied, it will replace randomly a SU occupying a channel in N-CRN. If no available such channels exist, the new PU request will be blocked. In the case of the interrupted SU, it will assign a vacant channel in R-CRN. If no channel is available, it will detect a vacant channel in N-CRN again.
2) SU Arrival: If there is an idle channel in the N-CRN upon the arrival of an SU, the system will assign it to the new SU. If every channel in the N-CRN is occupied by either PUs or SUs, a new SU will be designated to an available channel in the R-CRN if there is one. However, if all channels in each the N-CRN and R-CRN are already in use, an incoming SU will be blocked.
3) Departure of PU or SU from N-CRN: When a PU or SU finishes its service in the N-CRN, the channel that it was utilizing becomes available for allocation to any new PU or SU requests that arrive.
4) SU Departure from R-CRN: The framework retains continuous services within the R-CRN, allowing them to finalize their services within the allocated bandwidth without necessitating spectrum handovers to the N-CRN.
5) Channel Failure: The network's available channels are reduced by one in the case that a failure occurs on an empty channel in the N-CRN or R-CRN. However, In the event of a failure on a channel that is already occupied within the N-CRN or R-CRN, a spectrum handed over process might be necessary, as shown in Fig. 3. The handover process for PU and SU services in both the N-CRN and R-CRN follows a priority level assignment in the event of a failure on a filled channel. The current PU services within the N-CRN are given the priority classification in this initially execution of the DSA scheme, while the SU services within the N-CRN are given the second-most priority classification. In the R-CRN, we establish the third priority classifications for SU services, respectively. The level of priority for any user service, denoted as $PL(s)$ reflects these assignments. So, the priority can be expressed as follows: $PL\left(PU_{N-CRN}\right) > PL\left(SU_{N-CRN}\right) > PL\left(SU_{R-CRN}\right)$.

In Section III, the statistical analysis of the CTMC model, the CRN's QoS will be implemented via the DSA and DCR techniques. In these modified schemes, PUs receive higher priority in the N-CRN and SUs receive the second priority in both the R-CRN and N-CRN.

III. CTMC MODEL AND METRICS OF PERFORMANCE

Using a CTMC, we create the proposed DSA analytical model based on the proposed channel reservation mechanism.

A. CTMC MODEL

in our proposed model, for PUs and SUs services, the traffic arrival rates for each channel, λ_p and λ_s, follow a Poisson distribution. Additionally, exponential distributions are used to represent the service rates per channel for PUs and SUs, respectively, at μ_p and μ_s [12], [18], and [19]. The number of channels in the stated CTMC model is taken to be M in CRN. Non-reserved channels, determined by $J = (M - R)$ in the N-CRN, and reserved channels, represented by (R) in the

R-CRN. The state of the channel is represented as x where $x = (i_n, j_n, i_r, \text{f})$, while the service number of PUs and SUs in the N-CRN is represented by i_n and j_n, respectively, the number of ongoing SUs in the R-CRN is represented by j_r and f is the total number of failing channels in the proposed system. The terms $B_n(x)$ and $B_r(x)$ which are defined as $B_n(x) = i_n + j_n$ and $B_r(x) = j_r$, respectively [18], represent the number of utilized channels in the N-CRN and the R-CRN for a given state x. Additionally, $B(x)$ represents the number of filled and failing channels in the CRN, where $B(x) = B_n(x) + B_r(x) + \text{f}$.

As a result, $M -$ B(x) can be used to calculate how many idle channels there are in state x.

Let $\pi(x)$ represent the probability of steady state x in a steady state z. The normalization equation Q of every state steady state probability can be determined using the following formula [18], [19]:

$$\pi Q = 0, \quad \sum\nolimits_{z} \pi(x) = 1, \tag{1}$$

where 0 is a row vector containing all zeros and π is the steady-state probability vector. The performance results are analyzed using mathematical formulas in the next section.

B. METRICS OF PERFORMANCE

Based on the statistical analysis of the CTMC model, the CRN's QoS based on the DSA strategy and DCR may be designed and computed. SU retainability, PU and SU channel availability, and SU cost function are some of the performance metrics that are established.

1) CHANNEL AVAILABILITY

A new user will be blocked in CRN because every channel is instantly allocated to users. Therefore, the network can no longer handle requests from users. As a result, the important channel availability statistic illustrates the possibility of channel availability for each PUs and SUs in the CRN like in [20]. In this paper, "channel availability for PU or SU requests" is described as a probability that channels in the CRN will be set available for new arrivals of PUs or SUs without causing the services to be blocked. If the current channels in the N-CRN are filled by the services of other PUs, PU requests are blocked. On the other hand, as in [18], the channel availability of PU indicated by A_p is determined as follows:

$$A_p = 1 - \sum\nolimits_{\forall z, B_n(x)=M-R(x) \ \ , j_n=0,)} \pi(x) \tag{2}$$

Additionally, if PUs or/and SUs are using all N-CRN channels and SUs are using all R-CRN channels, an SU request for service will be blocked. Consequently, as in [19], it is possible to determine the SU services' channel availability by

$$A_s = 1 - \sum\nolimits_{\forall z, B_n(x)=M-R(x) \ , B_r(x)=R(x)} \pi(x). \tag{3}$$

As a result, P_{PU}^{B} and P_{SU}^{B}, which stand for the blocking probability of PU and SU services, respectively [19], are represented as:

$$P_{PU}^{B} = 1 - A_p \ \ , P_{SU}^{B} = 1 - A_s \, . \tag{4}$$

2) RETAINABILITY (θ)

Reliability is one of the important measures referring to the QoS dependability of the CRN. It is the chance of successfully performing the designated service throughout the time interval [19]. The user's retainability, is mathematically stated as:

$$\theta = 1 - P^{ft} \tag{5}$$

here P^{ft} is the probability of service's forced termination. The probability of forced termination measures the probability that a current SU service is going to be force terminated before it has completed all its transmissions [19]. An SU's service must end every time a PU arrives when there is not a vacant channel in the N-CRN or R-CRN. It should be noted that probabilities of forced termination of both SU and PU services occurs when considering random channel failures. $Rate_{SU}$ stands for the rate of SUs forced termination as:

$$Rate_{SU} = \lambda_p \sum\nolimits_{\forall z, B_n(\infty)=M \ , j_n>0} \pi(x). \tag{6}$$

Additionally, when every other channel in the CRN is in use, SU services may also be interrupted in the event of a channel failure [18]. f_n are the channels suffered from failure in N-CRN, f_r are the channels suffered from failure in R-CRN and F'_{SU} stands for the rate of SUs that must be terminated for channel failures, it can be acquired by:

$$Rate'_{SU} = \sum\nolimits_{\forall z, B_n(\infty)=M \ , j_n+j_r>0} (M - f_n - f_r)\lambda_f \pi(x). \tag{7}$$

The proportion of the average forced termination rate for (SU) services to the efficient rate when a channel is assigned to an incoming SU service, $\text{A}_S = (1 - P_{SU}^{B}) \ \lambda_s$ [12], can be used to define the forced termination probability of SUs, or P_{SU}^{f}. The blocking probabilities of SU and PU services are denoted by P_{SU}^{B} and P_{PU}^{B}, respectively. As a result, A_S previously mentioned, retainability calculates the probability of service that won't be discontinued before it has finished. The retainability of SU services [18], used by the symbol SU, can be represented as:

$$\theta_{SU} = 1 - \left(\frac{R_{SU} + R'_{SU}}{\text{A}_S} \right). \tag{8}$$

The PU services retainability, θ_{PU}, is determined similarly by:

$$\theta_{PU} = 1 - \left(\frac{R'_{PU}}{\text{A}_p} \right). \tag{9}$$

The PU forced termination because of channel failures, R'_{PU} [18], is also represented as:

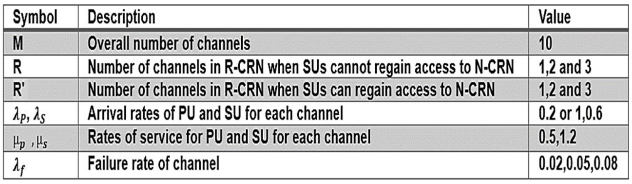
$$R'_{PU} = \sum\nolimits_{\forall z, B_n(\infty)=M \ , j_n=j_r=0} (i_n + i_r)\lambda_f \pi(x). \tag{10}$$

and A_p is given by:

$$A_p = \left(1 - P_{PU}^{B}\right) \, . \tag{11}$$

It should be noted that R_{PU}, which stands for the forced termination rate of PUs owing to new user arriving, is constantly equal to zero because no active PUs can be terminated because of the entry of new users.

TABLE 1. **Characteristics of the CTMC and configuration values.**



Symbol	Description	Value
M	Overall number of channels	10
R	Number of channels in R-CRN when SUs cannot regain access to N-CRN	1,2 and 3
R'	Number of channels in R-CRN when SUs can regain access to N-CRN	1,2 and 3
λ_P, λ_S	Arrival rates of PU and SU for each channel	0.2 or 1,0.6
μ_p , μ_s	Rates of service for PU and SU for each channel	0.5,1.2
λ_f	Failure rate of channel	0.02,0.05,0.08

3) COST FUNCTION

This part evaluates the impact of PU and SU channel availability, service retainability, and probability of handover on the overall system efficiency and the enhancement of Quality of Service (QoS) achieved through the implementation of dynamic channel reservation within the CRN [12], [16].

a: COST FUNCTION FOR PUs

This function calculates the impacts of PU blocking and forced termination probabilities. The PU cost function in the presence of failure is represented as follows:

$$C_{PU} = \alpha_P P^{B}_{PU} + \beta_P P^{ft}_{PU} + \gamma_P P_{int}. \tag{12}$$

b: COST FUNCTION FOR SUs

It quantifies the influence of SU blocking and forced termination probabilities. The cost function of SU in the presence of failure is represented as:

$$C_{SU} = \alpha_S P^{B}_{PU} + \beta_S P^{ft}_{PU} + \gamma_S P_{hdvr}. \tag{13}$$

where α, β and γ are key indicators of their respective importance.

IV. ANALYSIS AND DISCUSSION OF MATHEMATICAL RESULTS

The simulation results are shown in this part. The mathematical results are obtained using MATLAB Simulink modelling from the MATLAB software platform. The MATLAB Simulink is used to code the CTMC model created in Section III on a variation of the traffic flow parameters. The suggested research is designed regarding the DSA mechanism and depending on the DCR system, which corresponds to the CTMC model that was mentioned before. Assume the following parameters as in table 1 for our centralized CRN: The overall channels number is M = 10, and R = 0, 1,2, 3 are the reserved channels. R is limited by this parameter A = 3. Furthermore, since channel failures do not happen frequently, it is important to configure λ_f to lowest possible levels in proportion to arrival and service rates.

We set the channel failure rate for homogeneous channels to be 0.02, 0.05, and 0.08 per unit time. A minimal failure rate is sought in contrast to the arrival rates of PU and SU, with $\lambda_f = 0.02$, 0.05, and 0.08. Because of the acceptable configuration, it rarely happens for a service to be terminated due to a channel failure.

Additionally, the trade-off between performance is considered as shown in [6]. Due to the licensed PU's considered privilege and the higher cost of its service not being completed, the cost weights for primary user $\alpha_P, \beta_P, \gamma_P$ are chosen to be 20, 200, and 4 correspondingly. But the cost weights for secondary user $\alpha_S, \beta_S, \gamma_S$ are 10, 100, and 2.

A. RELIABILITY

For various values of λ_f (0.02, 0.05, and 0.08), where λ_P is set at a lower rate of 0.2 and a higher rate of 1, Fig. 4 illustrates the service retainability for SU services that cannot regain access to the N-CRN concerning different values of R and service retainability for SU services that can regain access to the N-CRN with respect to various values of R'. This Retainability is demonstrated given that the PU arrival rate λ_P is set at a lower rate of 0.2. Notably, service continuity for SUs is greatly improved by an increase in the number of reserved channels R. When the results are examined more closely, the benefits of channel reservation are more pronounced when the channel failure rates are larger. For example, when the failure rate is $\lambda_f = 0.08$. and the system Also in case of SU services that can regain access to the N-CRN, the forced termination decreases approximately 2% reserves R = 3 out of M = 10 channels, the improvement in SU service continuity is approximately 2% compared to a network with R = 1. However, this improvement increases to 3.5% in the case of SU services that can regain access to the N-CRN. when R = 3 and R' = 3 when the failure rate is $\lambda_f = 0.08$.

In Fig. 5, when the failure rate is $\lambda_f = 0.08$, at higher PU arrival rate of 1, it is observed that for R' = 3 out of M = 10 channels leads to an approximate 0.2% improvement in SU service continuity compared to the case of R = 3 reservation.

From Fig. 4 and Fig. 5, it is found that the service retainability for SU services that can regain access to the N-CRN is better than service retainability for SU services that cannot regain access to the N-CRN especially at PU low arrival rate.

For PUs services, the service retainability decreases when number of R or R' increases, and the PUs forced termination probability occurs only in the event of channel failure. The service Retainability of PU services in N-CRN doesn't change whether SUs regain access the N-CRN or not. Fig. 6 presents the service retainability for PUs for different λ_P.

B. CHANNEL AVAILABILITY

In the case of voice and data communication services, when extended service outages are considered undesirable, preserving a high level of service retainability is necessary. Thus, it is advisable to implement channel reservation up to a specific limit, even though it results in a high blocking probability for new users. For SUs services, the numerical outcomes presented in Fig. 7 demonstrate that SU services with different values of R' experience a decrease in

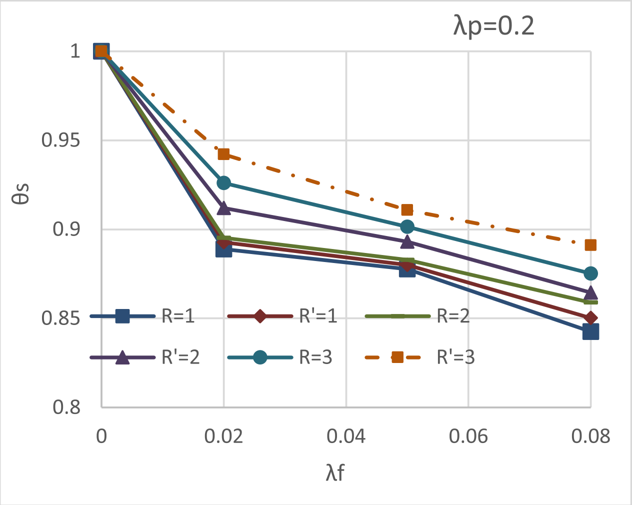


FIGURE 4. Retainability of SUs services due to varying channel failure rates and low PU arrival rates.

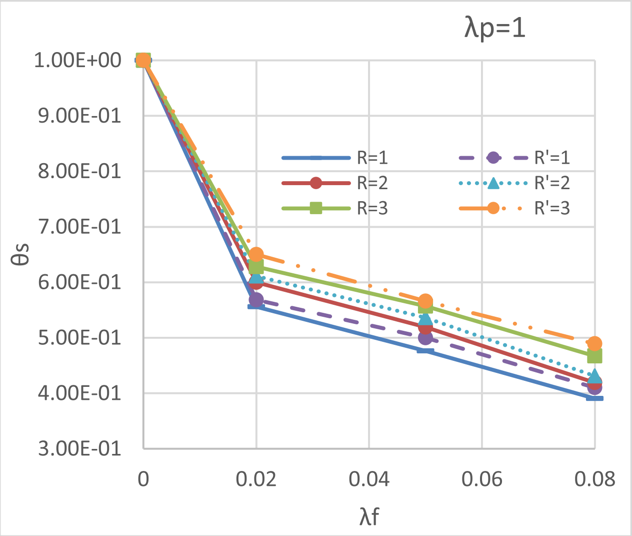


FIGURE 5. Retainability of SU services due to varying channel failure rates and high PU arrival rates.

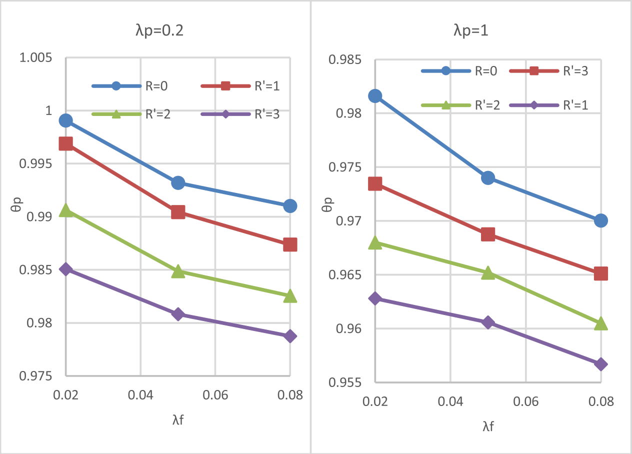


FIGURE 6. Retainability of PUs services in relation to both low and high PU arrival rates, considering various channel failure rates.

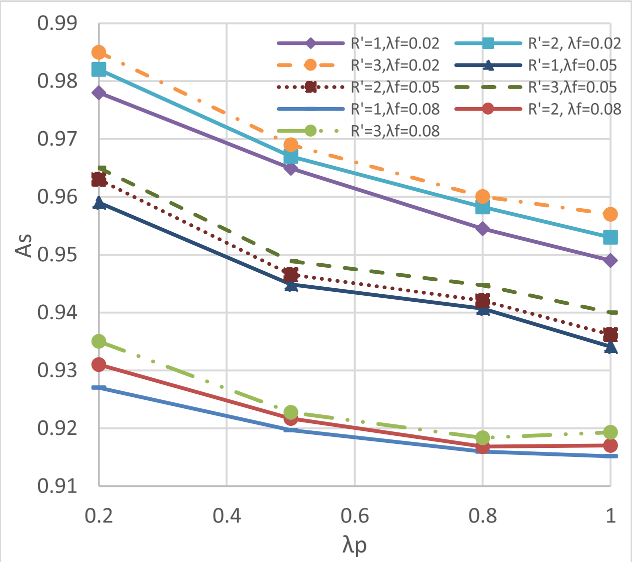


FIGURE 7. Channel availability of SU services in case of the low and high PU arrival rate and different channel failure rates.

channel availability due to increasing rate of PU arrival rate and channel reservations. While the channel availability of SUs increases when a decrease in channel failure rate.

In Fig. 8, the blocking probability of PU services is depicted for different values of R'. Like the previous case, it is observed that increasing the arrival rate of PUs results in an increase in the blocking opportunity for PU services, number of channel reservation and channel failure in case of no idle channel in N-CRN. At lower rate λ_P of 0.2 with reserving R' $= 3$ out of M $= 10$ channels, it leads to an approximate 0.04% improvement in PU blocking probability compared to a network with high rate λ_P of 1 when the failure rate is $\lambda_f = 0.08$. Similarly, this improvement rises to 0.06% when the failure rate is $\lambda_f = 0.05$.

C. COST FUNCTION FOR PUs AND SUs

As shown in Eq. (12), the SU and PU cost function C are calculated regarding λ_P only considers solely the detrimental effects of SU blocking, handover, and forced termination probabilities. and (13). Therefore, for SUs services, in Fig. 9 and Fig. 10, When λ_P increases in a manner same as [6], the cost function of SU raises also. Conversely, as the three negative factors decrease, more reserved channels can lower the cost of SU. It is noted that, in Fig. 9, when $\lambda_P = 0.2$ and the failure with $\lambda_f = 0.02$ occurs in N-CRN, The cost function of the scheme models with R $= 1$, R $= 2$, and R $= 3$ is 7.3, 7, and 6.19, respectively, while the related model in case of the failure in R-CRN and $\lambda_f = 0.02$ has the highest values of about 8.94, 8.5 and 8.1. As a result, adding the reserved channels lowers the SU cost significantly, increasing SU performance. The channel failure causes a higher SU cost

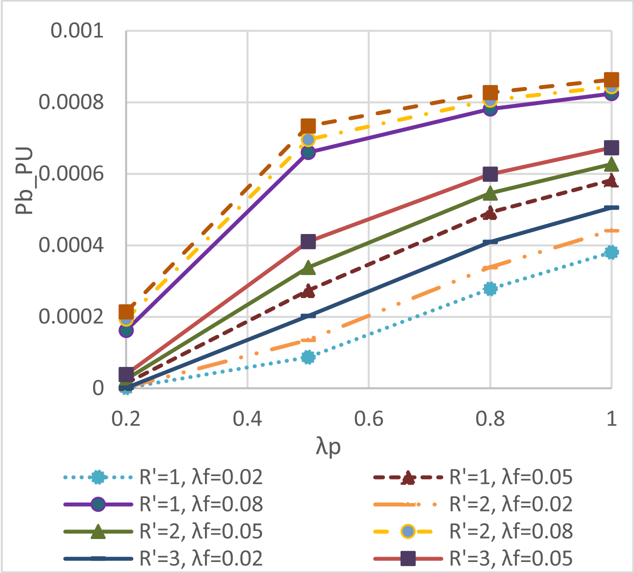


FIGURE 8. Blocking probability of PU services in case of the low and high PU arrival rate and different channel failure rates.

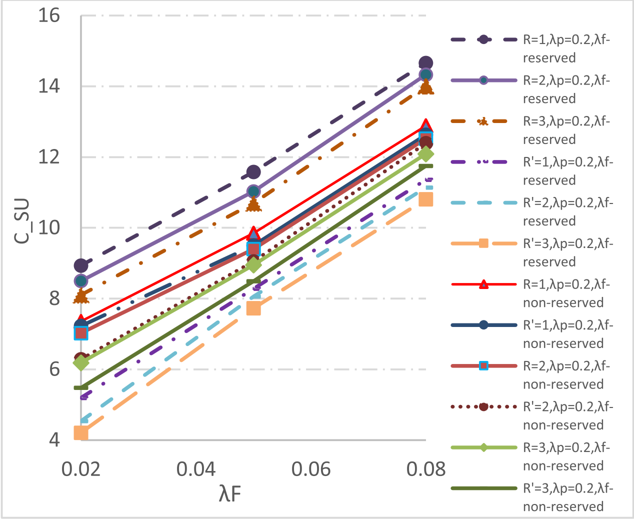


FIGURE 9. Cost function for SUs when the different failure rates occurred at either N-CRN or R-CRN with low arrival rate of PUs.

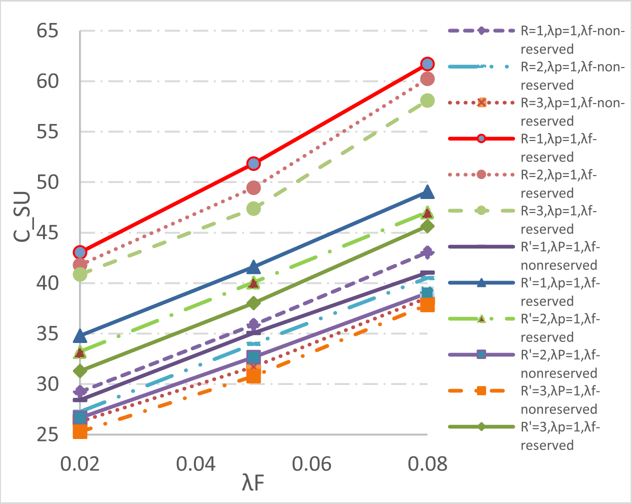


FIGURE 10. Cost function for SUs when the failure occurred at either N-CRN or R-CRN with high arrival rate of PUs.

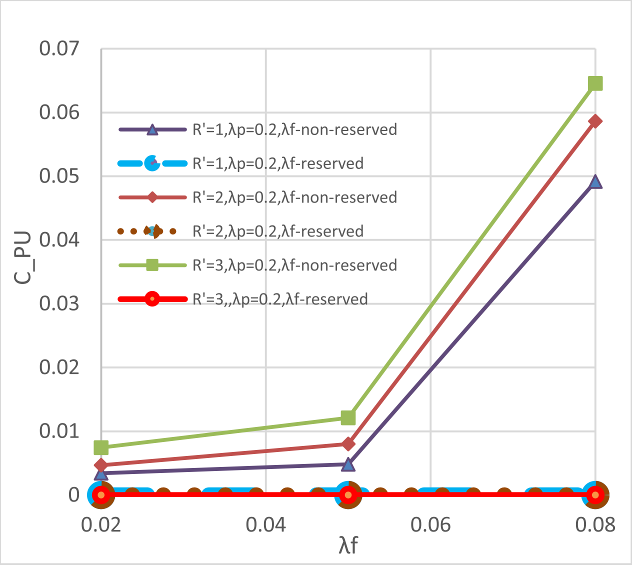


FIGURE 11. Cost function for PUs when the failure occurred at either N-CRN or R-CRN with low arrival rate of PUs.

function when it occurs at R-CRN compared than N-CRN. When SU services can regain access to N-CRN and the failure with $\lambda_f = 0.02$ occurs in N-CRN, the cost function decreases to 7.22, 6.2 and 5.48, but when the same failure occurs in R-CRN, the cost function becomes 5.19, 4.54 and 4.21. Consequently, we conclude that when SU services can regain access to N-CRN, the cost function is decreased compared to SU services cannot regain access to N-CRN and failure that can be happened in N-CRN because of low arrival rate of PUsso the SUs have a big chance to find vacant channels in N-CRN.

Unlike, in Fig. 10, when the arrival rate of PUs is higher, $\lambda_P = 1$ and $\lambda_f = 0.02$ at R-CRN, the cost function of SUs that can regain access to R-CRN is decreased compared to SU services cannot regain access to R-CRN but increased compared to the case of failure that can be happened in N-CRN because of high arrival rate of PUs so the SUs have a low chance to find vacant channels in N-CRN.

Unlike for PUs services, the cost function of PUs cannot be affected by the failure rate occurring in R-CRN either PUs have a low arrival rate or high arrival rate. And the cost function is increased by increasing the failure rate in N-CRN. In Fig. 11, when $\lambda_P = 0.2$ and the failure with $\lambda_f = 0.05$ occurs in N-CRN, the cost function for PUs is equal 0.0048,0.008 and 0.013 when R' = 1,2 and 3 respectively.

Therefore, when the number of reserved channels is increased, the cost function of PUs is increased. On another hand, when the failure occurs in R-CRN, the cost function

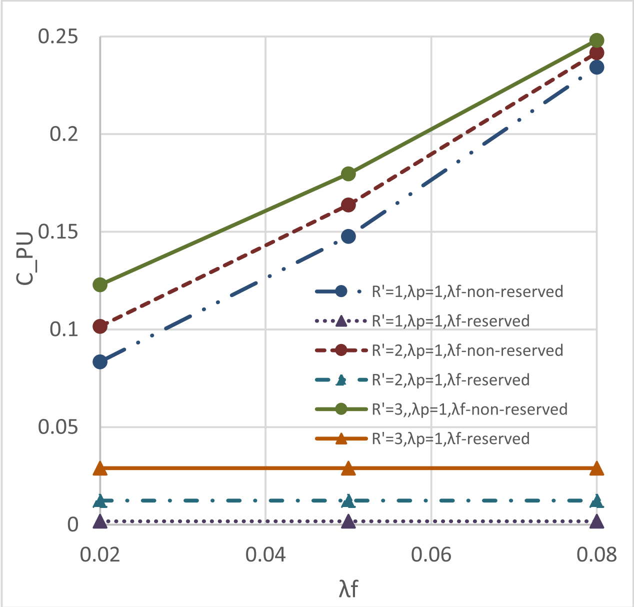


FIGURE 12. Cost function for PUs when the failure occurred at either N-CRN or R-CRN with high arrival rate of PUs.

of PUs doesn’t change because the PUs have only access to N-CRN. When the arrival rate of PUs is low, the cost function is approximately equal to zero.

In the case of high arrival rate of PUs, when increasing failure rates in N-CRN, the cost function of PUs is increased. From Fig. 12 when the arrival rate of PUs is higher ($\lambda_P = 1$) and $\lambda_f = 0.05$ at N-CRN, the cost functions of PUs are 0.148, 0.164 and 0.18 when R’ = 1,2 and 3 respectively. But the cost function of PUs is constant with respect to different rates of failure when it occurs at R-CRN. It is equal to 0.0018, 0.0123 and 0.029 when R’ = 1,2 and 3 respectively. These cost functions are not equal zero due to the higher blocking of PUs with their higher arrival rates.

V. CONCLUSION

This paper delves into the effects of unpredictable channel failures on the efficiency of channel access within CRNs. A dynamic spectrum access strategy is introduced in channel reservation considering the primary aim of enhancing the retainability of ongoing transmission sessions. The numerical results of SUs indicate that channel reservation contributes to a significant increase in retainability levels.

A study is conducted to assess the impact of varying failure rates on PUs and SUs services that may occur in either N-CRN or R-CRN for PUs and SUs services. These outcomes are evaluated under scenarios of low and high PU arrival rates. The simulation results indicate that the cost function of PU is only affected when the failure occurs in N-CRN, while that the cost function of SUs is affected when the failure occurs in either N-CRN or R-CRN, with a higher impact when it occurs in R-CRN. To mitigate the impact of a failure in R-CRN on the SU, it is proposed to reassign the SU from a failed channel back to N-CRN if a vacant channel is available. This reallocation aims to improve the QoS for SUs without affecting on the PUs’s QoS. The improvement is more significant in the scenarios of low PU arrival rates. However, for high PU arrival rates, the improvement decreases due to reduced probability of the presence of available vacant channels in N-CRN.

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