Spectrum Efficiency in CRNs using Hybrid Dynamic Channel Reservation and Enhanced Dynamic Spectrum Access

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***Abstract*—Blocking of new arriving services and dropping of ongoing services are inherent problems in Cognitive Radio Networks (CRNs), which need to be addressed to enhance spectrum efficiency. In particular, Secondary Users (SUs) undergo service degradation in the face of Primary Users (PUs)' arrivals. In this paper, we present a scheme called Efficient Spectrum Utilization (ESU) that reduces the dropping and blocking probabilities of existing and new services, respectively, to make efficient use of the available spectrum. The scheme divides the available spectrum into reserved and non-reserved bands. The reserved band is dynamically allocated a number of channels from the non-reserved band in order to accommodate those services which face interruptions while operating in the non-reserved band. The scheme renders dynamic access to the available spectrum and facilitates priority-based channel allocation and termination. SUs are divided into low and high priority levels depending on their Quality of Service (QoS) requirements. SUs with low priority level are granted direct access to both the bands to enhance channel utilization. SUs operating in the reserved band with high priority levels are granted uninterruptible status to ensure a certain level of service provisioning to SUs. The proposed ESU scheme is modeled using Continuous Time Markov Chain (CTMC) and mathematical expressions are derived for several QoS parameters. Performance of the proposed scheme is evaluated under various network conditions. Results demonstrate that ESU reasonably improves spectrum efficiency under channel failure in CRNs.**

***Keywords*—Blocking probability, Cognitive radio networks, Continuous Time Markov Chain, Dynamic channel reservation, Dynamic spectrum access, Spectrum efficiency.**

I. Introduction

A. Motivation

The rapid growth of wireless technologies and the proliferation of the Internet of Things (IoT) pose numerous challenges to the current wireless industry [1], [2]. Spectrum scarcity is one of the major challenges due to which communicating entities cannot find any vacant channels [3]–[5]. Since IoT enables a large number of autonomous devices to share information via the Internet, it complicates spectrum allocation and leads to spectrum scarcity [6]–[9]. Further, a limited amount of spectrum is reserved and standardized by regulatory bodies, such as Federal Communications Commission (FCC), for wireless communications [10]–[12]. Moreover, the spectrum is assigned statically, which leads to spectrum inefficiency, as a major part of the spectrum remains mostly unused [13]–[16]. The unused spectrum thus created is termed as spectrum holes or white spaces [16]–[18].

Cognitive Radio Networks (CRNs) is an emerging paradigm that ensures efficient utilization of spectrum to address the problem of spectrum scarcity. There are two kinds of users in a CRN: Primary Users (PUs) and Secondary Users (SUs). PUs are licensed and legitimate users that formally own the assigned spectrum. SUs are unlicensed users who can search the spectrum assigned to PUs and access only the unused portion of the spectrum. An SU vacates its occupied channel as soon the channel is required by a PU. In this way, spectrum utilization is enhanced [19]. Channel access can be classified into static and dynamic access. In static spectrum access, certain frequency bands are reserved for SUs, which means SUs cannot access all the channels in the network [20]. This scheme has several drawbacks, such as it is rigid and inelastic and leads to spectrum inefficiency. In response to these limitations, Dynamic Spectrum Access (DSA) scheme [21] has been introduced. In DSA, channels can be dynamically assigned to SUs, which can sense the channels assigned to PUs and select the idle ones. This enables spectrum efficiency. In order to reduce the blocking probability of new entrants and enhance ongoing service completion rate in CRNs, Dynamic Channel Reservation (DCR) is used [22], [23]. The basic mechanism of DCR is to reserve certain channels for accommodating interrupted services. The number of reserved channels may decrease or increase with traffic conditions in the network.

B. Novelty and Contributions

In this paper, a novel scheme, called Efficient Spectrum Utilization (ESU), is proposed to efficiently utilize the available spectrum and enhance the network throughput.

The scheme comprises two algorithms, namely, Hybrid DCR (HDCR) and Enhanced DSA (EDSA). HDCR maintains a balance in channel assignment between reserved and non-reserved bands, whereas EDSA enables spectrum access to the available spectrum dynamically under the concept of Licensed Shared Access (LSA) [24]. The proposed ESU scheme is distinct from the previous studies due to the following reasons. ESU considers two types of SUs based on their priority levels in a way that high priority SUs (SU_H) can access the reserved band conditionally, whereas low priority SUs (SU_L) can access the reserved band directly and unconditionally. Determination of users' priority is operator dependent and can be application-based, revenue-based, or QoS requirements-based.

ESU can be considered as a hybrid approach between the schemes that use channel reservation and those using no channel reservation. This hybrid nature of ESU is corroborated by the fact that SU_L view the network without reservation and can occupy idle channels found anywhere in the network, including the reserved band, at the cost of the highest forced termination probability. Conversely, all other users can access channels in the reserved band only in the case of service interruption. If we restrict the usage of the reserved band for accommodating the interrupted services only, as in [23], [26]–[28], [32], [34], it leads to channels underutilization and spectrum inefficiency. We believe that a scheme based solely on channel reservation or solely without channel reservation cannot achieve ideal performance in terms of channel availability for new user arrivals and successful service completion ratio, also known as retainability, for ongoing services. Reservation based schemes enhance retainability at the cost of decreased channel availability. Contrarily, schemes without reservation enhance channel availability for new arrivals at the cost of decreased service retainability. These contradicting factors motivate us to combine the merits of both of the approaches in ESU.

Moreover, granting direct access to SU_L to reserved band is not at the expense of SU_H or PUs' performance degradation. In effect, SU_L in any band are transparent to both SU_H and PUs, such that SU_L occupied channels are readily available to both SU_H and PUs as and when they require. Furthermore, granting SU_L direct access to reserved band in ESU serves two purposes. It not only enhances SUs' performance, but also reduces potential spectrum underutilization.

Furthermore, no other types of users, including PUs, are allowed to access the reserved band directly owing to the fact that the basic purpose of reservation is to protect and provide certain level of performance to ongoing services, such that the ongoing high priority SUs could complete their services in case of channel failure or interruption [23]. If PUs can directly access the reserved band, there is no way to provide any satisfactory level of services to SUs, which is against the basic guidelines of LSA because of PUs' high priority that can terminate ongoing SUs. Therefore, no new arriving service can directly access the reserved band.

Moreover, a criterion is determined for selecting the most suitable lower priority services for termination to accommodate interrupted or newly arriving high priority services. Additionally, the reservation scheme is simple and requires only a few steps to complete, facilitating the network to respond quickly to various events. Furthermore, both channel failure and channel restoration are considered in performance evaluation. To the best of our knowledge, the existing state-of-the-art has overlooked channel failures and restorations in CRNs' performance evaluation. In addition, Quality of Service (QoS) metrics defined by ITU-T [25] are applied on the proposed ESU scheme for performance evaluation. Lastly, closed form expressions are derived for PU, SU_H and SU_L in terms of various QoS parameters. The scheme is modeled using Continuous Time Markov Chain (CTMC).

The contributions of this paper can be summarized as follows.

- A spectrum efficient scheme, termed ESU, is proposed which incorporates two algorithms, namely, Enhanced DSA (EDSA) and Hybrid DCR (HDCR).
- EDSA, following the concept of LSA [24], renders dynamic and efficient spectrum access in CRNs.
- HDCR determines the number of reserved channels dynamically on each arrival and departure of services. Numerical results show that HDCR is time-efficient in terms of spectrum reservation than the baseline scheme, and has a constant time complexity.
- The combined effects of channel failure, channel restoration, channel non-availability, and forced termination probability are considered in the performance evaluation. It is shown that ESU significantly enhances most of the considered parameters and is spectrum efficient. Moreover, it is also shown that ESU is more time-efficient in spectrum utilization.
- Closed form expressions are derived for channel availability, capacity, retainability and network unserviceable probability for services. Moreover, simulations are performed to validate the obtained analytical results.

C. Paper Organization

The remainder of the paper is organized as follows. Section II presents related work. Section III outlines the system model and assumptions. Section IV presents the proposed ESU scheme. Section V presents results and discussion, and Section VI concludes the paper.

II. Related work

Simultaneously maintaining a certain level of service retainability in a good balance with channel availability for new users has been a daunting task in CRNs [36], [37], which requires several tradeoffs. A dynamic channel reservation based approach is proposed in [26] to enhance retainability and reduce blocking probability. Reserved channels are only used for interrupted services. A maximum limit

Table I: Summary of the related literature

Ref. #	Fairness considered?	Effects of channel failure considered?	Reservation type	SUs types	Focused parameters	Notabilities
[26]	No	Yes	Dynamic	1	Retainability, blocking probability, capacity	Channel failure leads to severe degradation for SUs.
[27]	No	No	Static	1	Blocking probability, PDR, transmission probability, channel availability	SUs cannot access the reserved band, which causes spectrum inefficiency.
[28]	No	No	Static	2	Blocking probability, forced termination probability, throughput	Only PUs can access reserved channels, which leads to spectrum inefficiency.
[29]	No	No	Dynamic	2	Blocking probability, dropping probability, throughput	Dropping probability is left unimproved.
[30]	No	No		1	Delay, throughput, energy efficiency	Uses channel aggregation, which adds to complexity and extra hardware and software requirements. Considers ad hoc network which requires strict coordination among nodes for spectrum sensing.
[31]	No	No	Static	1	Optimal no. of reserved channels, no. of channel switching	Considers channel reservation between communicating nodes only. A node has to maintain a list of reserved channels for every other node.
[32]	No	No	Static	2	Blocking probability, dropping probability, hand off probability.	Assumes static channel reservation, which results in spectrum underutilization.
[33]	No	No	Static	1	Stationary state probability	One primary user, and one idle and one reserved channels are considered in system evaluation.
[34]	No	No	Dynamic	1	Blocking probability, dropping probability, hand off probability	SUs can only occupy non-reserved channels, which gives rise to spectrum underutilization.
[35]	No	No	Static	2	blocking probability, forced termination probability	Separate channels are reserved for low and high priority SUs, which is resource intensive.
[23]	No	Yes	Dynamic	1	Channel availability, service retainability, capacity, network unserviceable probability	The scheme is complex and prone to channel underutilization. Further, the scheme follows random channel interruption.
ESU	Yes	Yes	Dynamic	2	Channel availability, service retainability, capacity, network unserviceable probability	Simple and improved with well-defined criteria for channel interruption and spectrum utilization.

on the number of reserved channels is imposed to avoid channel underutilization. The scheme has been analyzed for retainability, blocking probability and capacity. However, the system is not advantageously performing from the Secondary Network (SN) perspective, and channel failure leads to severe degradation for SUs. Chakraborty *et al.* [27] proposed a scheme that reserves channels for PUs. PUs cannot access unreserved band if the reserved band has idle channels. Further, if the reserved band is fully occupied, a PU occupies unreserved band and an ongoing SU is terminated by the PU. SUs cannot access the reserved band, which causes spectrum inefficiency. Krishna *et al.* [28] proposed a DSA-based scheme that employs two kinds of policies, namely, DSA-C1 and DSA-C2. In DSA-C1, a high priority SU, SU_H, can replace a low priority SU, SU_L. In DSA-C2, an SU_H cannot terminate an ongoing SU_L and SU_L cannot access the reserved band. The scheme assumes that only PUs can access reserved channels, which leads to spectrum inefficiency. Deng *et al.* [29] proposed division of SUs into high priority SUs, SU_H, and low priority SUs, SU_L, depending on time-delay sensitivity requirements. The most suitable number of channels for reservation is forecasted based on renewal theory. The scheme lowers blocking probability and enhances throughput of SN as compared to the static reservation. However, dropping probability has not been improved. Kamruzzaman *et al.* [30] presented a channel-slot aggregation diversity-based slot reservation scheme. An SU can simultaneously select multiple empty time slots from different channels to increase throughput, energy and spectrum efficiency. A PU can preempt an ongoing SU. The scheme has been shown to outperform existing approaches. Channel aggregation, however, requires extra hardware and software, which increases cost of the system. Zhang *et al.* [31] proposed a distributed channel selection scheme. In order to balance successful channel selection and minimal average switching time, an optimal number of channels for reservation between neighboring nodes is derived. The scheme outperforms a simple channel selection algorithm in resilience and adaptability to dynamic channel access. The scheme, however, does not consider interference among users resulting from disusing Common Control Channel (CCC). The authors in [9] presented a novel scheme for resource allocation in vehicle-to-vehicle based Internet-of-Vehicle communication. The scheme is targeted at providing ultra-reliable and low latency communication among vehicles. However, the scheme does not utilize cognitive capabilities of end users' devices. Toukhey *et al.* [32] proposed a 3-D Markov chain based scheme to analyze random channel access with respect to dynamic arrival and service rates of PUs and SUs. Channels are reserved solely for PUs in the scheme and SUs cannot access the reserved channels. The scheme enhances performance of CRNs compared to those not considering prioritized SUs. The scheme, however, assumes static channel reservation, which results in spectrum underutilization. Azaly *et al.* [33] proposed a scheme that uses one primary and multiple secondary users with different traffic flow, and one idle and one reserved channel. Simulation results are derived for 0, 3 and 100 SUs. The scheme assumes only one primary user, and one idle and one reserved channel, which is unrealistic in real-world scenarios. Yafeng *et al.* [34] proposed that SUs can only occupy non-reserved channels. The scheme outperforms fixed channel reservation. The scheme, however, does not support dynamic channel access, which brings about channel underutilization. Similarly, the scheme proposed in [35] takes users' heterogeneity and priority into consideration. However, it considers static reservation of channels, instead of dynamic, which gives rise to spectrum underutilization.

Another interesting concept in spectrum sharing domain is LSA [24] in which both licensed and unlicensed users agree on sharing the spectrum under certain agreement followed by both the users. Thus, the licensed users, after granting permission to unlicensed users for utilizing its spectrum under LSA, cannot interfere or interrupt an active unlicensed user till service completion of the unlicensed user occurs or the service time duration stipulated in the initial agreement reaches to an end [23], [38]–[41]. In this way, spectrum assignment is performed without requiring channel auction or bidding. This concept also ensures a predictable level of unlicensed users' performance irrespective of licensed users' arrivals and channel failures. Legacy CRNs lack in provisioning such service or immunity to unlicensed users and lead to unpredictable service level for unlicensed users.

The closest work to our proposed ESU scheme is presented by Balapuwaduge *et al.* [23], referred to as the BLP scheme in this paper, with three variations of PUs' access privileges. A DCR algorithm is integrated with a DSA algorithm to evaluate blocking probability, dropping probability, service capacity, retainability and network unserviceable probability. BLP assumes two modes of operation. Mode 1 is meant to improve service retainability of currently active services by keeping a large number of channels in reserved band in the event of higher traffic load. Mode 2 targets to decrease blocking probability for new arriving services by reserving small number of channels in the case of higher traffic load. The authors demonstrate that several variations of BLP support various objectives, in terms of the QoS parameters, and selecting any one of the variations is operator-dependent. The scheme, however, is complex in the sense that it makes extensive calculations to determine the level of incoming traffic load in order to reserve channels accordingly. Additionally, the BLP scheme is prone to spectrum underutilization in the sense that, under the low level of incoming traffic load, idle channels in the reserved band can face underutilization. Moreover, there is no well-defined criteria as to which ongoing service should be terminated first to accommodate high priority services. Additionally, BLP is insensitive to channel departure, which brings spectrum inefficiency. Apart from these factors, the last two variations, in which two types of secondary users are considered, are not thoroughly elaborated and no closed form expressions are derived for the obtained results.

The work in this paper is inspired by the aforementioned studies and is based on the LSA concept. However, it differs from the previous studies mainly because, in the proposed ESU scheme, SUs are categorized into two classes, i.e., low priority and high priority SUs, denoted by SU_H and SU_L, respectively[*]. SU_L can access both reserved and non-reserved bands. Previous studies have assumed that reserved bands are solely occupied either by PUs or by SUs [27], [29]. ESU is more flexible in this respect and grants unconditional and direct access to SU_L for both the reserved and non-reserved bands. This type of access makes ESU a hybrid of the reservation and non-reservation based approaches. Moreover, ESU can minimize underutilization of the available spectrum by quickly and effectively adjusting the number of reserved channels with every arrival and departure of services. Further, the channel reservation algorithm is simple and completes in a few steps, which paves the way for quick and smart operation of channel reservation. Lastly, selection of channels for termination are conditioned upon certain criteria and blind terminations are avoided.

From the analysis of existing literature, we came to believe that channels' reservation schemes have been in use since the inception of cellular telephony, to the best of our knowledge, where various variations of channels' reservation existed. It has also been utilized by CRN research community, and many variations with various performance efficiency have been proposed in the literature. It is, therefore,

[*]Note that the terms SU_H, SU_L or PU are used interchangeably to represent high priority, low priority and primary services or users, respectively. For instance, PU denotes both primary user or primary user's service. The same holds for SUs.

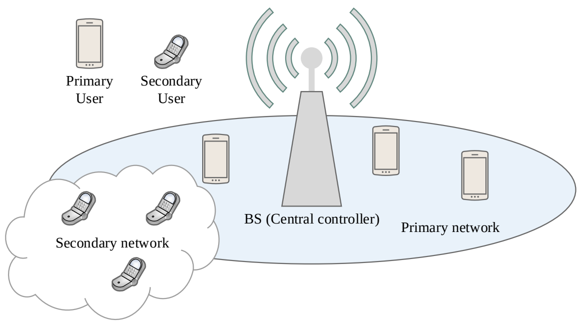


Fig. 1: High-level architecture of a typical CRN.

believed to be valuable if an efficient channel reservation scheme can be proposed, which surpasses previous schemes in this domain in improving certain aspect of the network, and this can be considered a research contribution.

III. System Model

Infrastructure-based CRN architecture with a centralized Base Station (BS) is assumed in this study. The BS controls all users falling within its coverage area, as illustrated in Fig. 1. The Secondary Network (SN) coexists with a Primary Network (PN). The PN consists of multiple PUs, which use their own licensed spectrum under management of BS. In essence, PUs and SUs are managed by their respective BSs in CRNs. In the figure, only the BS of PUs is shown. The rest of the idea is similar to that of the typical CRNs (see, e.g., [42] and [43]). It should be noted that in CRNs, there are two types of networks, PN and SN. PN has licensed spectrum, whereas SN opportunistically uses the idle part of the spectrum. Both PUs and SUs are controlled by their respective BSs when operated under centralized fashion. SUs scan and analyze radio environment and feedback to the BS that decides spectrum availability and allocation. A CCC is used for channel reservation and assignment. The interweave or opportunistic mode of channel access under LSA is assumed, wherein SUs can use a channel only if the channel is not being used by any PU [44]. All the explicable notations and abbreviations used in this paper are listed in Table II.

Assume a PN with T channels of equal capacity, where $T \in Z^+$. The channels are dynamically distributed into Non-Reserved (NR-CRN) and Reserved Bands (R-CRN), as shown in Fig. 2. SUs opportunistically scan, find, occupy and reuse idle channels of the licensed spectrum assigned to PN. Channels can fail under various reasons, which can disrupt ongoing communication sessions. To save the ongoing sessions from termination, several channels are kept reserved, denoted by R, in R-CRN. The size of R dynamically changes depending on the number of occupied channels in the network. Only interrupted SU_H or PU, and newly arrived SU_L that cannot find idle channels in NR-CRN, can access the reserved band. In order to avoid reserving a large number of reserved channels and

Algorithm 1 Hybrid Dynamic Channel Reservation

Input: CH_{idle_N}: Total number of idle or available channels in NR-CRN.
Input: CH_{idle_R}: Total number of idle or available channels in R-CRN.
Input: T: Total number of channels in CRN.
Input: R_{max}: Maximum number of assignable channels to R-CRN.
Input: $O_n(x)$: Total number of occupied channels in NR-CRN.
Input: $threshold$: Threshold level of the number of idle channels in NR-CRN.
Input: N: Total number of channels in NR-CRN.
Output: R: Total number of channels assigned to R-CRN.

1. **Calculate** CH_{idle_N} = $N - O_n(x)$
2. **If** $CH_{idle_N} \leq threshold$ *% Check further for R_{max} and idle channel availability.*
   a) **If** $R = R_{max}$ **OR** $N - O_n(x) = 0$ *% take no action*
   b) **Else** $R = R + 1, N = N - 1$ **End**
3. **Else** keep $R = 0$ **End**
- *For service departure*
4. **If** $CH_{idle_R} \geq threshold/2$
   $R = R - 1, N = N + 1$ **End**

creating large blocking probability for new services' arrivals, a constraint, denoted by R_{max}, is imposed on the number of reserved channels, where $R \leq R_{max} \in Z^+$. The procedure used for adjusting R with changes in the network conditions is explained in the next section. Moreover, the following assumptions are made.

- PU and SU service arrivals are with Poisson distribution with rates λ_P and λ_S, respectively [45], [46]. The service time is exponentially distributed with μ_P and μ_S rates per channel for PU and SU, respectively.
- The activity time, i.e., time in which a channel is available for normal operation, is exponentially distributed with λ_F failure rate per channel. Both idle and occupied channels may fail [23].
- The restoring time of a failed channel is assumed to be exponentially distributed with rate μ_R. Multiple failed channels may be restored simultaneously.
- Latency of spectrum handoff and sensing is assumed to be negligible as compared to the time between two successive service events.

IV. The Proposed Scheme

This section introduces the proposed ESU scheme that consists of two algorithms, namely, HDCR and EDSA. HDCR reserves, adjusts and allocates channels to R-CRN on PUs/SUs' arrivals and departures. EDSA allows users to efficiently and dynamically access idle channels in the network. HDCR is described in Subsection IV-A whereas EDSA is presented in Subsection IV-B. Further, CTMC

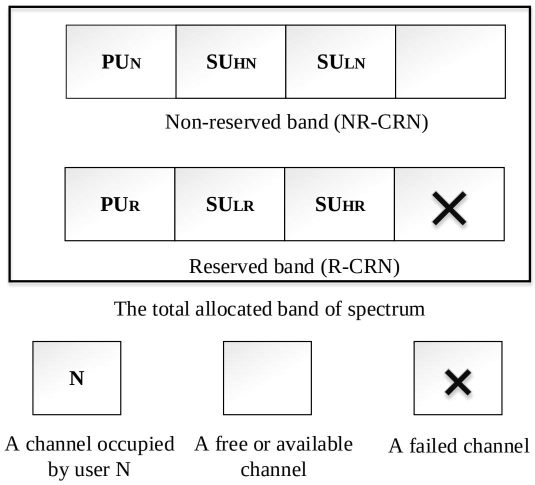


Fig. 2: A High-level description of the reserved and non-reserved bands.

modeling of the system is presented in Subsection IV-C and mathematical formulation for network capacities, channel availabilities, retainabilities and network unserviceable probabilities are derived in Subsections IV-D, IV-E, IV-F and IV-G, respectively.

A. The Hybrid Dynamic Channel Reservation Algorithm

In our proposed HDCR (Algorithm 1), the number of idle channels in NR-CRN is taken as the deciding factor to determine R. The $threshold$ can be adjusted as per operator's requirements. Here, we have assumed it to be half of the total number of channels assigned to the network, such that $threshold = T/2$. Algorithm 1 runs on occurrence of either of the two events: (i) before a channel is allocated to a new service arrival, or (ii) after a channel is released by a service departure.

In the first step of Algorithm 1, CH_{idle_N} is calculated on Line 1. If $threshold$ is greater than CH_{idle_N}, the algorithm further checks if R equals R_{max}, and if there exists any idle channel in NR-CRN. If both the conditions are met, only then it initiates channel allocation to R-CRN. Similarly, with each service departure, the algorithm checks if the number of idle channels in R-CRN is greater than half of $threshold$. If the condition is satisfied, it releases one channel from R-CRN to NR-CRN. Hence, channel utilization can be enhanced by allocating only the required number of channels to R-CRN and retain rest of the channels in NR-CRN to maximize the accommodation of interrupted and new arriving services. Note that a suitable value for $threshold$ depends on QoS requirement of PN and SN, channel failure rates, channel restoration rates and arrival and departure rates of the PUs and SUs. For example, when SUs require minimum forced termination probabilities, a higher value of $threshold$ is preferred.

Table II: List of notations

Notation	Description
AR	Service arrival
bps	Bits per second
CAP_P, CAP_S	PU capacity, SU capacity
CHA_P	Channel availability for PU
CHA_{SH}	Channel availability for SU_H
CHA_{SL}	Channel availability for SU_L
CH_{idle_N}	Total number of idle channels in NR-CRN
CH_{idle_R}	Total number of idle channels in R-CRN
DP	Service departure
f	Total number of failed channels in CRN
λ_F	Channel failure rate
λ_S, λ_P	SUs' arrival rate, PUs' arrival rate
Λ_P	Effective channel assignment rate for PU
Λ_S	Effective channel assignment rate for SU
μ_R	Restoration rate of channel
μ_P, μ_S	PUs' service rates, SUs' service rates
N	Total number of non-reserved channels
NR-CRN	Non-reserved band
NUP_S	Network unserviceable probability for SU
$O_n(x)$	Total number of occupied channels in NR-CRN
$O_r(x)$	Total number of occupied channels in R-CRN
Ω	Probability of successfully finishing an SU service
$\boldsymbol{P}$	Transition rate matrix
P_P^{BL}	Blocking probabilities for PU
P_{SH}^{BL}	Blocking probabilities for SU_H
P_{SL}^{BL}	Blocking probabilities for SU_L
P_P^{FT}	Forced termination probability of PU
P_S^{FT}	Forced termination probability of SU
PU_R, PU_N	PU/PUs in R-CRN, PU/PUs in NR-CRN
p_n, p_r	Total number of PU_N, Total Number of PU_R
$\boldsymbol{\pi}$	Vector of steady state probabilities
R-CRN	Reserved band
R	Total number of reserved channels
RET_S, RET_P	Service retainability of SU, Service retainability of PU
RFT_{SH}	Forced termination rate of SU_H due to PU arrival
RFT_{SL_P}	Forced termination rate of SU_L due to PU arrival
$RFT_{SL_{(SU_H)}}$	Forced termination rate of SU_L because of SU_H arrival
$RFT_{SH}^{'}$	Forced termination rate of SU_H because of channel failure
$RFT_{SL}^{'}$	Forced termination rate of SU_L because of channel failure
$RFT_P^{'}$	Forced termination rate of PU because of channel failure
R_{max}	Maximum number of assignable channels to R-CRN
SN	Secondary Network
γ	Signal to Noise plus Interference Ratio (SNIR)
SU_H, SU_L	High priority SU/SUs, Low priority SU/SUs
SU_{HN}, SU_{LN}	SU_H in NR-CRN, SU_L in NR-CRN
SU_{HR}, SU_{LR}	SU_H in R-CRN, SU_L in R-CRN
s_{nh}, s_{rh}	Total number of SU_{HN}, Total number of SU_{HR}
s_{nl}, s_{rl}	Total number of SU_{LN}, Total number of SU_{LR}
T	Total number of channels assigned to network

Algorithm 2 Service selection for interruption

Input: Currently busy SU_H / SU_L services.
Input: max_s: Service scanning function for the highest SNIR.
Input: max_b: Service scanning function for the highest data rate.
Input: max_t: Service scanning function for the longest busy time duration.
Output: max_{snir}: Set containing services with highest SNIR.
Output: max_{bps}: Set containing services with highest data rate.
Output: max_{time} : Set containing services with longest operation-time duration (seconds).
Output: Max: The service selected for termination.

max_{snir} = max_s (SU_H/SU_L)
If $max_{snir} > 1$
    max_{bps} = max_b (max_{snir})
    If $max_{bps} > 1$
        max_{time} = max_t (max_{bps})
        Max = max_{time}
    Else
        Max = max_{bps}
    End
Else
    Max = max_{snir}
End

B. The Enhanced Dynamic Spectrum Access Algorithm

In this section, our proposed EDSA algorithm is elaborated. The algorithm is employed together with HDCR. The events that trigger EDSA are described below. Moreover, the algorithm along with the events is also illustrated in Fig. 3 and Fig 4.

1) PU arrival: A new PU arrival triggers HDCR algorithm to determine the apposite value of R and allocate channels to R-CRN accordingly. If there is an idle channel in NR-CRN, the new PU will begin transmitting on that channel. However, if the entire NR-CRN is occupied, an SU_L in NR-CRN, selected by Algorithm 2, is forcibly interrupted and replaced by the PU. If there is no SU_L in NR-CRN, an SU_H service in NR-CRN, selected by Algorithm 2, is forcibly interrupted and replaced by the PU. The interrupted SU_H searches an idle channel in R-CRN and performs spectrum handover to that channel, if there is any. Otherwise, one of the SU_L services in R-CRN, determined by Algorithm 2, is interrupted and replaced by the interrupted SU_H. If there is no SU_L service in R-CRN, the interrupted SU_H terminates. The new arriving PU is blocked if no idle or SU_H/SU_L occupied channel exists in NR-CRN. It should be noted that Algorithm 2 is solely used for selecting the most appropriate SU service for termination as per criteria (e.g., channel capacity, SNIR) defined by an operator. This ensures a certain level of regularity and predictability in termination of services. This also provides the operator a choice to apply its own requirements. For instance, some services require reliability and integrity at the expense of delay. Files and data transfer are examples of such services that can tolerate delay but cannot compromise on data integrity. Other services cannot afford delay but can tolerate reliability up to certain extent. Voice and video communication are examples of such services in which losses can be tolerated but delay can lead to incomprehensible communication for the end-users. In this way, the algorithm facilitates operators to configure network parameters to meet the user requirements at particular moments. If multiple services are found with the same value of the considered QoS parameters, the one with the longest time duration is selected for termination.

Table III: Priority levels of services

Priority Level	1	2	3	4	5
service operating in a band	PU in R-CRN	SU_H in R-CRN	PU in NR-CRN	SU_H in NR-CRN	SU_L in any band

2) SU_H arrival: With each SU_H arrival, HDCR is executed and an idle channel is allocated to the new SU_H from NR-CRN if there is any. Otherwise, an SU_L service in NR-CRN, determined by Algorithm 2, is interrupted to serve the new SU_H. If there is no SU_L in NR-CRN, the new SU_H request is blocked without determining the availability of free channels in R-CRN. This is because R-CRN is reserved specifically for interrupted services, not for new arrivals. However, to reduce the channel underutilization and blocking probability, new arriving SU_L can also access R-CRN if it cannot find an idle channel in NR-CRN.

3) SU_L arrival: With each SU_L arrival, HDCR is executed and an idle channel from NR-CRN is allocated to the new SU_L. If idle channel does not exist in NR-CRN, an idle channel from R-CRN is allocated to it. If there is no idle channel in R-CRN either, the SU_L is blocked.

4) PU/SU_H/SU_L service departure: No handover is performed in the network upon a service departure from NR-CRN or R-CRN. However, R is adjusted with each departure by executing HDCR.

5) Channel failure: Failure of an idle channel causes reduction in the number of available channels in CRN. Moreover, no action is taken over such a failure and R does not change. However, failure of occupied channels trigger spectrum handover, as shown in Fig. 4. Handover is performed based on the priority levels of services in both of the bands. Table III shows a hierarchy of the priority levels.

As can be seen in Table III, SU_H in R-CRN has a higher priority than PUs in NR-CRN and cannot be preempted by PU if the PU is interrupted by a channel failure. Note that the priority levels given in Table III do not signify that a service with a higher priority can preempt a service with a lower priority if the former is interrupted. Instead, further

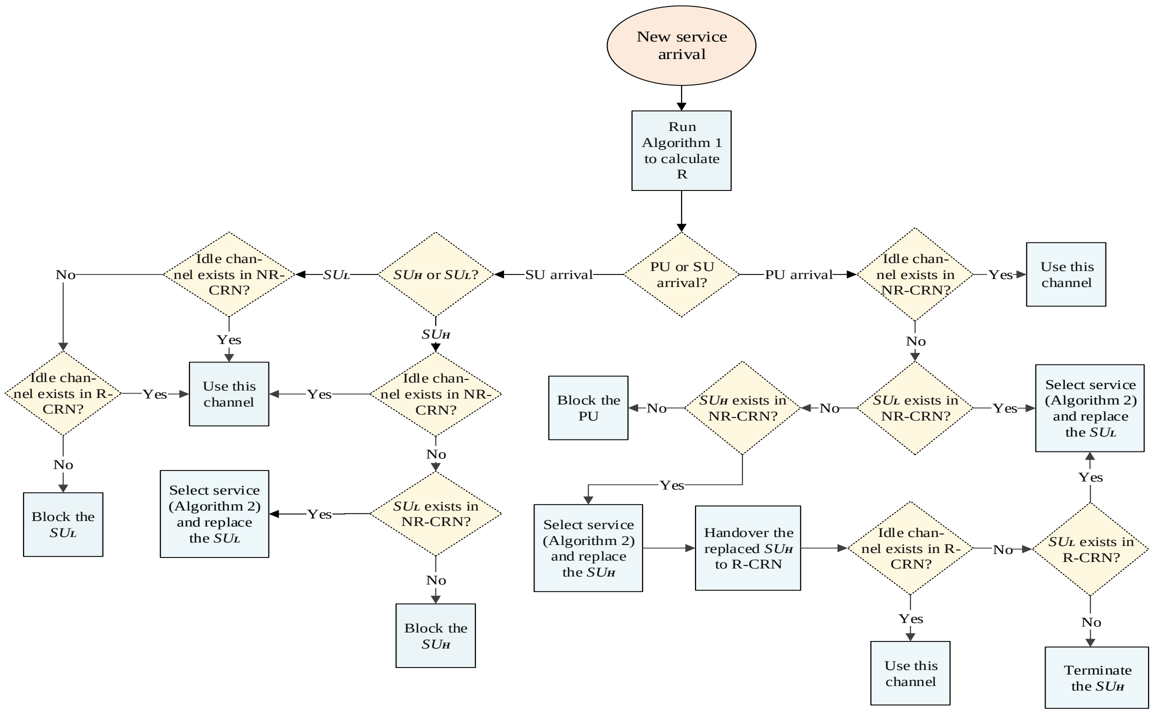


Fig. 3: Procedural flowchart for the arrival of new services in EDSA algorithm.

impositions are set in our proposed ESU scheme, as can be seen in Fig. 4, to determine which services can terminate which ones upon arrivals or failure of certain services.

As shown in Fig. 4, failure of an idle or SU_L occupied channel results in no action except reduction in the number of available or total channels in the network. Failure of a PU occupied channel in NR-CRN is also shown in Fig. 4, wherein the interrupted PU first determines the availability of idle channel in NR-CRN and occupies that channel. Otherwise, PU determines the availability of SU_L in NR-CRN and replaces the most suitable SU_L determined by Algorithm 2. If no SU_L exists in NR-CRN, the PU seeks the most suitable SU_H, determined by Algorithm 2, in NR-CRN and interrupts that SU_H. The interrupted SU_H is handed over to R-CRN where it seeks idle channel for resumption of its services. It subsequently interrupts SU_L for its services resumption if R-CRN does not contain any idle channel. Otherwise, the interrupted SU_H terminates without completing its services. If the interrupted PU does not find any idle, SU_L occupied, or SU_H occupied channel in NR-CRN, it looks for an idle channel in R-CRN and occupies that channel. Otherwise, the SU_L occupied channel in R-CRN is replaced by the PU if there is any. If none of the channels listed above is available, the interrupted PU terminates. In the same fashion, when PU in R-CRN fails, the following list of channels is searched in the given order and the first one found is occupied by the PU: (i) idle channel in R-CRN, (ii) SU_L in R-CRN, (iii) idle channel in NR-CRN, (iv) SU_L in NR-CRN, or (v) SU_H in NR-CRN. If none of the channels mentioned above is available, the PU terminates. Similarly, when an SU_H in NR-CRN fails, it seeks the following channels in the given order and occupies the first one found: (i) idle channel in NR-CRN, (ii) SU_L in NR-CRN, (iii) idle channel in R-CRN, or (iv) SU_L in R-CRN. If none of the channels given above exists, the interrupted SU_H is terminated. When SU_H in R-CRN fails, the following list of channels is searched in the given order and the first one found is occupied: (i) idle channel in R-CRN, (ii) SU_L in R-CRN, (iii) idle channel in NR-CRN, or (iv) SU_L in NR-CRN. If none of the channels listed above exists, the SU_L terminates.

6) Service selection for interruption: Algorithm 2 describes the procedure to determine the most suitable service for interruption, following the given criteria. As can be seen therein, whenever a service of a particular type, such as SU_H or SU_L, requires to be interrupted, all the busy services of that type are analyzed and the one with the highest SNIR is selected. If multiple services exist with the same value of SNIR, such that the set max_{snir} contains multiple services, the algorithm further scans max_{snir} and selects the service with the highest data rate. If more than one services have the same data rate within max_{snir}, which indicates the set max_{bps} having multiple elements, the algorithm further scans max_{bps} and selects the service with the longest duration of busy-time. It is worth noting that the service interruption is performed by the central BS serving the secondary network. Since all the SUs are controlled by the BS, the BS has the statistics of all the channel parameters

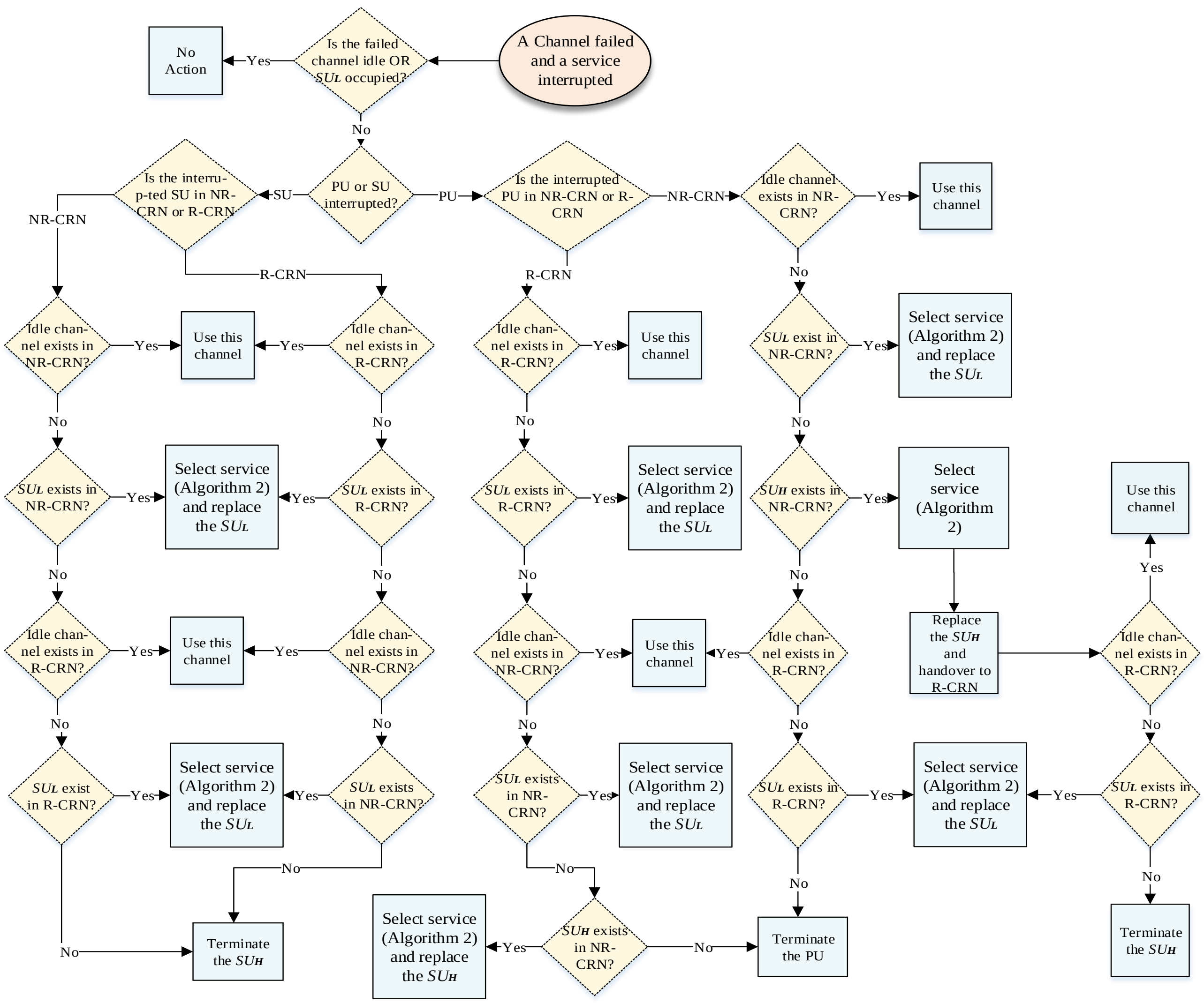


Fig. 4: Procedural flowchart for channel failures in EDSA algorithm.

associated with all the SUs. Moreover, SNIR on a user device can be given as

$$\gamma(dB) = 10\log\frac{\Psi_s\ \delta_{s,u}}{\sum_{j=1}^{M}\Psi_{I_j}\ \delta_{I_{j,u}} + \Theta_n}, \tag{1}$$

where Ψ_s and Ψ_{I_j} denote the transmission power of the BS transmitter antenna and the jth interfering antenna, respectively, $\delta_{s,u}$ and $\delta_{I_{j,u}}$ indicate the channel gain between the user device and both the BS and the jth interfering antenna, respectively, M represents the number of the interfering antennas, and Θ_n denotes the noise power. The SNIR calculated by (1) is shared with the BS by SUs. In this way, the BS can discern among SUs with the respect to their SNIR values.

7) Channel restoration: Channel restoration induces no handover and R remains intact. However, the number of available channels increases.

8) Complexity Analysis: Initially, computational complexity of our proposed ESU scheme can be represented by $O(1)$, in which case there is only one SU operating in the network to be interrupted or terminated and one iteration is required in Algorithm 2. The number of iterations in Algorithm 2 grows to $O(\mathcal{M})$, where $\mathcal{M}$ is the number of active SUs in the network. Thus, computational complexity of ESU is $O(\mathcal{M})$, as determined by Algorithm 2. This implies that the computational complexity increases with increase in the number of currently active SUs. Conversely, the computational complexity experienced by BLP is $O(\mathcal{N})$. This is because the number of iterations in the channel reservation algorithm proposed in BLP grows to $O(\mathcal{N})$ when determining the number of channels to be assigned to the reserved and non-reserved bands, where $\mathcal{N}$ is the number of traffic levels. This implies that the computational complexity of BLP increases with increase in the number of traffic levels selected to determine the number of channels in reserved and non-reserved bands.

C. CTMC modeling

CTMC with discrete states is used to model the proposed ESU scheme. The set of feasible states of the CTMC is represented by S with states $x = (p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f)$, where p_n, s_{nh} and s_{nl} represent the number of PU, SU_H and SU_L services in NR-CRN, respectively, and p_r, s_{rh} and s_{rl} denote the number of PU, SU_H and SU_L services in R-CRN, respectively. The number of failed channels are denoted by f. The notations $O_n(x)$, $O_r(x)$ and $O(x)$ denote the number of occupied channels in NR-CRN, R-CRN and in the whole CRN, respectively, such that $O_n(x) = p_n + s_{nh} + s_{nl}$, $O_r(x) = p_r + s_{rh} + s_{rl}$ and $O(x) = O_n(x) + O_r(x) + f$. Thus, the number of idle channels are represented by $T - O(x)$. The notation $R(x)$ shows the number of reserved channels in state x. In Table IV, transition from the origin state to other states are given with transition rates associated with various events under various conditions.

Transition rate matrix $\boldsymbol{P}$ is obtained from the table to find steady state probabilities $\boldsymbol{\pi}$ for various states. Let $\pi(x)$ denotes the steady state probability of being in state x, the steady state probabilities of each state can be obtained as

$$\boldsymbol{\pi} * \boldsymbol{P} = \boldsymbol{0}, \quad \sum_{x \in S} \pi(x) = 1 \ , \tag{2}$$

where $\boldsymbol{\pi}$ represents steady state probability vector and $\boldsymbol{0}$ is a row vector of all zeros. In the following subsections, mathematical expressions are derived for various performance metrics of the CRN.

D. Service Capacity

In CRN, some services complete their sessions successfully, whereas others get interrupted during their sessions and cannot complete. Herein, capacity denotes the average number of services which complete their sessions per unit time [23]. Let CAP_P and CAP_S denote PU and SU capacities, respectively. We have

$$CAP_P = \sum (p_n + p_r)\mu_P \pi(x), \ x \in S \ , \tag{3}$$

and

$$CAP_S = \sum (s_{nh} + s_{nl} + s_{rh} + s_{rl})\mu_S \pi(x), \ x \in S. \tag{4}$$

Here, CAP_S encompasses capacities achieved by all kinds of SUs, including SU_L and SU_H operating in both the bands. Similarly, CAP_P covers capacities achieved by all PUs operating in both the bands.

E. Channel Availability

When a service enters the network and finds a channel to use, the channel is said to be available for the service. Otherwise, it is unavailable [47]. We denote the probability of a service arrival and acquiring a channel as *channel availability*.

Let CHA_P represents channel availability for PU. We have

$$CHA_P = 1 - \sum_{\substack{O(x)=T \text{ or} \\ O_n(x)=T-R(x);\ s_{nh}=s_{nl}=0}} \pi(x), \quad x \in S. \tag{5}$$

Eq. (5) implies that CHA_P is calculated by selecting those states of the Markov chain where either idle channels are available or any SU, such as s_{nh} or s_{nl}, exists in NR-CRN. Likewise, let CHA_{SH} represents channel availability for SU_H service. We have

$$CHA_{SH} = 1 - \sum_{\substack{O(x)=T \text{ or} \\ O_n(x)=T-R(x);\ s_{nl}=0}} \pi(x), \quad x \in S. \tag{6}$$

Similarly, let CHA_{SL} represents channel availability for SU_L service. We have

$$CHA_{SL} = 1 - \sum_{O(x)=T} \pi(x), \quad x \in S. \tag{7}$$

Therefore, the blocking probabilities of PU, SU_H, and SU_L services are given, respectively, by

$$P_P^{BL} = 1 - CHA_P \ , \tag{8}$$

$$P_{SH}^{BL} = 1 - CHA_{SH} \ , \tag{9}$$

and

$$P_{SL}^{BL} = 1 - CHA_{SL}. \tag{10}$$

F. Service Retainability

Service retainability shows the probability of an established connection to operate for a particular time with a particular QoS provisioning without disruption [25]. This is contrary to the probability of forced termination, wherein a service is likely to be terminated before completion of its established connection. Mathematically, retainability of a service can be defined as

$$RET = 1 - P^{FT}, \tag{11}$$

where RET and P^{FT} represent retainability and forced termination probability of a service, respectively. It is noteworthy that we have two kinds of forced terminations in CRN: (i) forced termination of a service under a higher priority service arrival, and (ii) forced termination of a service under a channel failure. Both of these are described below.

1) Forced termination of services under higher priority service arrivals: As depicted in Fig. 3, new service arrivals can dismiss ongoing services based on the priority levels specified in Table III and described in Subsection IV-B.

The rate of forced termination of SU_H due to PU arrivals is given by [23]

$$RFT_{SH} = \lambda_P \sum_{O(x)=T;\ s_{nl}=s_{rl}=0;\ s_{nh}>0} \pi(x), \quad x \in S. \tag{12}$$

Table IV:
State transition table
Original state is taken to be $x = (p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f)$.

Activity	Dest. state	Trans. rate	Condition
1. PU AR. An idle channel is found in NR-CRN.	$(p_n+1, s_{nh}, s_{nl},\ p_r, s_{rh}, s_{rl}, f)$	λ_P	At least one vacant channel exists in NR-CRN.;$O_n(x) < T - R(x)$
2. PU AR. No idle channel is found in NR-CRN. SU_{LN} terminates.	$(p_n+1, s_{nh}, s_{nl}-1, p_r, s_{rh}, s_{rl}, f)$	λ_P	$O_n(x) = T - R(x); s_{nl} > 0$
3. PU AR. No vacant channel exists in NR-CRN. SU_{HN} performs handover to R-CRN.	$(p_n+1, s_{nh}-1, s_{nl}, p_r, s_{rh}+1, s_{rl}, f)$	λ_P	$O_n(x) = T - R(x);\ s_{nl} = 0;\ s_{nh} > 0; O_r(x) < R(x)$
4. PU AR. An SU_{HN} terminates.	$(p_n+1, s_{nh}-1, s_{nl}, p_r, s_{rh}, s_{rl}, f)$	λ_P	$O_n(x) = T - R(x); s_{nl} = s_{rl} = 0; s_{nh} > 0; O(x) = T$
5. SU_{HN} AR. A vacant channel exists in NR-CRN.	$(p_n, s_{nh}+1, s_{nl}, p_r, s_{rh}, s_{rl}, f)$	λ_S	$O_n(x) < T - R(x); O(x) < T$
6. SU_{HN} AR. No vacant channel exists in NR-CRN. SU_{LN} terminates.	$(p_n, s_{nh}+1, s_{nl}-1, p_r, s_{rh}, s_{rl}, f)$	λ_S	$O_n(x) = T - R(x); s_{nl} > 0$
7. SU_{LN} AR. A vacant channel exists in NR-CRN.	$(p_n, s_{nh}, s_{nl}+1, p_r, s_{rh}, s_{rl}, f)$	λ_S	$O_n(x) < T - R(x)$
8. SU_{LN} AR. No vacant channel exists in NR-CRN. Vacant channel exists in R-CRN.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}+1, f)$	λ_S	$O_n(x) = T - R(x); O_r(x) < R(x)$
9. PU DP from NR-CRN.	$(p_n-1, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f)$	$p_n\ \mu_P$	There is at least one PU service in NR-CRN; $p_n > 0$
10. PU DP from R-CRN.	$(p_n, s_{nh}, s_{nl}, p_r-1, s_{rh}, s_{rl}, f)$	$p_r\ \mu_P$	$p_r > 0$
11. SU_{HN} DP from NR-CRN.	$(p_n, s_{nh}-1, s_{nl}, p_r, s_{rh}, s_{rl}, f)$	$s_{nh}\ \mu_S$	$s_{nh} > 0$
12. SU_{HN} DP from R-CRN.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}-1, s_{rl}, f)$	$s_{rh}\ \mu_S$	$s_{rh} > 0$
13. SU_{LN} DP from NR-CRN.	$(p_n, s_{nh}, s_{nl}-1, p_r, s_{rh}, s_{rl}, f)$	$s_{nl}\ \mu_S$	$s_{nl} > 0$
14. SU_{LN} DP from R-CRN.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}-1, f)$	$s_{rl}\ \mu_S$	$s_{rl} > 0$
15. Idle channel failure.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f+1)$	$(T - O(x))\ \lambda_F$	There is at least one idle channel in the CRN; $O(x) < T$
16. An occupied channel fails. An idle channel exists in the CRN.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f+1)$	$(O(x) - f)\ \lambda_F$	$f < O(x) < T$
17. An occupied channel fails. No idle channels exist in the CRN. An SU_{HN} terminates.	$(p_n, s_{nh}-1, s_{nl}, p_r, s_{rh}, s_{rl}, f+1)$	$(T - f)\ \lambda_F$	$O(x) = T; s_{nh} > 0; s_{nl} = s_{rl} = 0$
18. An occupied channel fails. No idle channels exist in the CRN. An SU_{LN} terminates.	$(p_n, s_{nh}, s_{nl}-1, p_r, s_{rh}, s_{rl}, f+1)$	$(T - f)\ \lambda_F$	$s_{nl} > 0$
19. An occupied channel fails. No idle channels exist in the CRN. A PU_N terminates.	$(p_n-1, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f+1)$	$(T - f)\ \lambda_F$	$O(x) = T; s_{nh} = s_{nl} = s_{rl} = 0; p_n > 0$
20. An occupied channel fails. No idle channels exist in the CRN. An SU_{HR} terminates.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}-1, s_{rl}, f+1)$	$(T - f)\ \lambda_F$	$O(x) = T; s_{nh} = s_{rl} = 0; s_{rh} > 0$
21. An occupied channel fails. No idle channels exist in the CRN. An SU_{LR} terminates.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}-1, f+1)$	$(T - f)\ \lambda_F$	$s_{rl} > 0$
22. An occupied channel fails. No idle channels exist in the CRN. A PU_R terminates.	$(p_n, s_{nh}, s_{nl}, p_r-1, s_{rh}, s_{rl}, f+1)$	$(T - f)\ \lambda_F$	$O(x) = T; s_{nh} = s_{rl} = s_{nl} = 0; p_r > 0$
23. A failed channel is restored.	$(p_n, s_{nh}, s_{nl}, p_r, s_{rh}, s_{rl}, f-1)$	$f\ \mu_R$	$f > 0$

Similarly, for SU_L, the rate of forced termination occurring under PU and SU_H arrivals are given as

$$RFT_{SL\ (P)} = \lambda_P \sum_{O(x)=T;\ s_{nl}>0} \pi(x), \quad x \in S\ , \tag{13}$$

and

$$RFT_{SL\ (SU_H)} = \lambda_S \sum_{O(x)=T;\ s_{nl}>0} \pi(x), \quad x \in S, \tag{14}$$

respectively.

2) Forced terminations under channel failure: When a channel fails, the existing service can terminate if all other channels in the CRN are occupied. Note that unlike the first kind of forced termination described in Subsection IV-F.1, which is exclusively applicable to SUs, this kind of forced termination is common to both PUs and SUs. Thus, the rates of forced termination of SU_H, SU_L and PU due to channel failure are, respectively, given by [23]

$$RFT_{SH}^{'} = \lambda_F \sum_{\substack{O(x)=T \\ (s_{nh}>0;\ s_{nl}=s_{rl}=0)\ \text{or}\ (s_{nl}=s_{rl}=0;\ s_{rh}>0)}} (T-f)\pi(x),\ x \in S\ , \tag{15}$$

$$RFT_{SL}^{'} = \lambda_F \sum_{\substack{O(x)=T \\ (s_{nl}>0\ \text{or}\ s_{rl}>0)}} (T-f)\pi(x), \quad x \in S\ , \tag{16}$$

and

$$RFT_{P}^{'} = \lambda_F \sum_{\substack{O(x)=T \\ (s_{nh}=s_{nl}=s_{rl}=0;\ p_n>0)\ \text{or}\ (s_{nh}=s_{nl}=s_{rl}=0;\ p_r>0)}} (T-f)\pi(x),\ x \in S. \tag{17}$$

3) Retainability of SUs: The effective rate, Λ_S, in which a new SU service is assigned a channel, is given by $\Lambda_S = CHA_S.\lambda_S$ [48]. Hence, the forced termination probability of SUs becomes

$$P_S^{FT} = \frac{(RFT_S + RFT_S^{\prime})}{\Lambda_S}\ , \tag{18}$$

where RFT_S = RFT_{SH} + $RFT_{SL_{(P)}}$ + $RFT_{SL_{(SU_H)}}$ and $RFT_S^{'}$ = $RFT_{SH}^{'}$ + $RFT_{SL}^{'}$. Thus, the retainability of the SU services, RET_S, can be expressed as

$$RET_S = 1 - P_S^{FT}. \tag{19}$$

4) Retainability of PUs: When a PU occupied channel fails and it does not find any legitimate channel for restoration, it is forced to terminate. The forced termination probability of PU services due to channel failure, P_P^{FT}, can be given as

$$P_P^{FT} = \frac{RFT_P^{\prime}}{\Lambda_P}\ , \tag{20}$$

where Λ_P represents the effective rate with which a new PU service is assigned a channel and is given by $\Lambda_P = \lambda_P\ CHA_P$. Consequently, the retainability of PU services is given by

$$RET_P = 1 - P_P^{FT}. \tag{21}$$

It should be noted that RFT_P equals zero in (20) because PUs are interminable by any kind of new service arrivals.

G. Network Unserviceable Probability (NUP)

NUP for a service is the probability that the service cannot complete its transmission successfully because of blockage, channel failure, or high priority service arrivals [23]. NUP for SUs (NUP_S) can be mathematically given as

$$NUP_S = P_S^{BL} + P_S^{FT} - P_S^{BL} P_S^{FT}. \tag{22}$$

V. Results and Discussion

In this section, numerical results are presented to evaluate the proposed ESU scheme under multiple traffic loads and varying rates of channel failure. The results are based on simulation and analytical modeling. The performance of ESU is evaluated in comparison with BLP [23]. Two modes of BLP are used, namely, Mode 1 and Mode 2. The former aims to enhance retainability of ongoing services by reserving channels in a larger number in the event of higher traffic load. The latter is targeted to lower blocking probability for new arriving services by reserving small number of channels in the case of higher traffic load. For further detailed description about BLP, section II should be referred.

The results of our analysis are calculated with MATLAB (R-2018a) running on an Intel(R) Core (TM) i7-6700 CPU 3.4 GHz bearing machine. The nodes are supposed to surround the BS, as shown in Fig. 1, and remain within the coverage zone. All the channels experience Rayleigh fading and simplified path loss. Energy based users' detection is employed with detection threshold of 1.16 dB [49], [50]. It implies that if the energy detected by a user on a channel is greater than the threshold, the channel is deemed to be occupied. Moreover, the nodes are assumed to be randomly spaced in an 1000×1000 m^2 area [51]. A total of 8 licensed channels are assumed with equal capacity [23]. All the SUs can instantly search, select, or switch to another channel in case of interruption [23]. We ran the simulation for time duration ranging from 50 s to 150 s and repeated it for 25 times to obtain average values. Generic file transfer data is considered in the performance evaluation. Several performance metrics including channel availability, network unserviceable probability, service capacity and retainability are used to evaluate the performance. The simulation parameters are listed in Table IV. Unless explicitly stated otherwise, the default values of the parameters listed in Table IV are used for generating the analytical and simulation results. For most results, $\lambda_F = 0.05$ failures per unit time has been assumed as the default value [23]. This assumption means that with $\lambda_P = 5$ services per unit time, a channel failure occurs every 100 PU arrivals on average. We believe that this is a reasonable assumption because a channel failure does not often lead to channel termination. Conversely, μ_R has been assumed to be 1 per unit time, which signifies that channel should be repaired promptly after failure so that higher QoS should be maintained for the end-users.

Table IV: List of parameters with their default configurations

Parameter	Configuration
Simulation area	1000 x 1000
Simulation time	50-150 s
T	8 channels
Threshold detection value	1.16 dB
λ_S, λ_P	5/unit time
μ_R	1/unit time
Transmission power	0.1 W
μ_P, μ_S	2/unit time
Path loss exponent	4
R_{max}	4 channels
λ_F	0.05/unit time

A. Channel Availability

Fig. 5 shows channel availability for SUs and PUs with respect to PUs' arrival rates and channel failure rates. In Fig. 5a and Fig. 5c, Mode 1 of BLP with variations in R_{max} is taken for comparison.

In Fig. 5a, CHA_P is plotted as a function of λ_P. As shown in the figure, CHA_P decreases gradually with increase in λ_P. This is because fewer channels are available for new users when λ_P rises. ESU outperforms BLP under both the variations of R_{max}. The difference in improvement gets more visible with the increase in λ_P, and at $\lambda_P = 15$, ESU achieves $CHA_P = 0.8$ and $CHA_P = 0.7$ for $R_{max} = 2$ and $R_{max} = 3$, respectively. At the same value of λ_P, BLP achieves $CHA_P = 0.66$ and $CHA_P = 0.625$ for $R_{max} = 2$ and $R_{max} = 3$, respectively.

The performance gain of ESU over BLP, in terms of CHA_P, is credited to the flexibility of ESU. ESU makes channels available by allocating idle channels from R-CRN to NR-CRN for direct access to new PU arrivals, if any, by running Algorithm 1 with each arrival and departure of services. Contrarily, BLP does not adjust channel distribution between the two bands with departure of services from R-CRN. This leads to reduced number of channel availability for new PUs since new PUs cannot directly access R-CRN. Moreover, this shortcoming of BLP also leads to channel underutilization.

In Fig. 5b, CHA_S is plotted as a function of λ_F. As can be seen in the figure, CHA_S decreases gradually for all schemes as λ_F increases. This is because the number of available channel decreases as more and more channels face failures. At $\lambda_F = 0.6$, ESU achieves $CHA_S = 0.825$ as compared to $CHA_S = 0.73$ achieved by both the modes of BLP. At $\lambda_F = 0.2$, ESU achieves $CHA_S = 0.945$ as compared to Mode 1 which achieves $CHA_S = 0.795$, and Mode 2 which achieve $CHA_S = 0.84$. Similarly, in Fig. 5c, CHA_S is plotted as a function of λ_P, wherein ESU achieves $CHA_S = 0.89$ and $CHA_S = 0.94$ at $\lambda_P = 15$, as compared to $CHA_S = 0.5$ and $CHA_S = 0.53$ achieved by BLP under $R_{max} = 3$ and $R_{max} = 2$, respectively.

The reasons for the enhancements in the channel availability in ESU are as follows. Firstly, in ESU, SU_L can directly access idle channels in R-CRN if NR-CRN is wholly occupied by other services. This fact ensures channel availability for SUs when an idle channel exists in R-CRN. In BLP, SUs cannot directly access R-CRN even if idle channels exist in R-CRN. Secondly, SU_H access idle channels in R-CRN if they are interrupted by PUs or channel failure in NR-CRN, leading to further enhancement in CHA_S. Thirdly, ESU promptly responds to any change in the number of available channels by running Algorithm 1 with each departure and arrival of services. This property makes ESU more dynamic and ensures channel availability for new arrivals whenever an idle channel is available in the network. All the aforementioned factors make it more likely that, in ESU, an SU will find an idle channel whenever it requires. Since BLP lacks these attributes, it underperforms ESU.

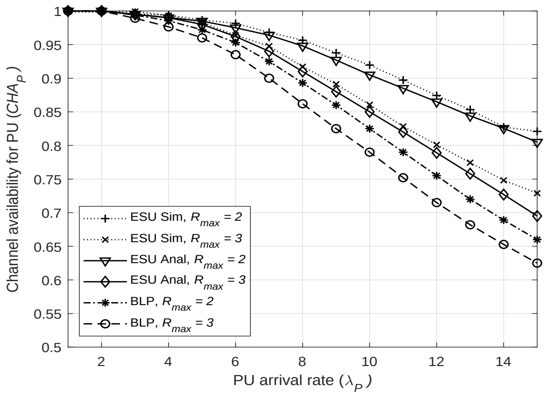
B. Network Unserviceable Probability for SUs (NUP_S)

Fig. 6 illustrates NUP_S as a function of PU arrival rates and channel failure rates. It can be seen that increase in λ_P or λ_F lowers the number of available channels, which eventually leads to low probability for the network to serve the users, as a gradual rise in NUP_S can be observed. In Fig. 6a, NUP_S is plotted as a function of λ_P, wherein ESU is compared with the two modes of BLP. It is found that ESU outperforms both the modes of BLP and lowers NUP_S to 0.52, at $\lambda_P = 15$, as compared to the NUP_S of 0.65 and 0.66 respectively achieved by Mode 1 and Mode 2 of BLP. The reasons for the improvement are as follows. ESU grants direct access to SU_L to occupy an idle channel in R-CRN, whereas BLP does not provide SUs the facility to directly access R-CRN and, consequently, underperforms ESU. Further, SU_H services in R-CRN are interminable by any other service in ESU. This fact reduces forced termination probability and leads to further enhancement in NUP_S.

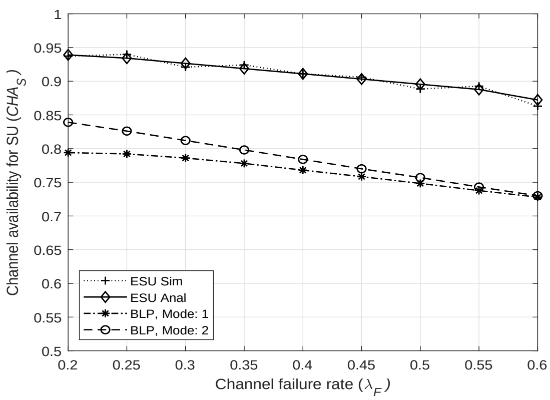
In Fig. 6b, NUP_S is plotted as a function of λ_F. At $\lambda_F = 0.15$, ESU achieves $NUP_S = 0.11$ as compared to Mode 1 which achieves $NUP_S = 0.31$, and Mode 2 which achieves $NUP_S = 0.27$. The reasons for this improvement are as follows. Firstly, SUs can find idle channels in ESU due to existence of an idle channel in R-CRN for it being directly accessible to SU_L. Secondly, SU_H hand over from NR-CRN to R-CRN, in case of interruption, and can avail idle channels in R-CRN.

C. Service Capacity

Fig. 7 depicts capacities of SUs and PUs with respect to λ_P. In Fig. 7a, SUs' capacity is plotted as a function of λ_P. As shown in the figure, SUs' capacity is initially high for both the schemes and decreases with the increase in λ_P. The reason is that, under low λ_P, the number of active PUs are low. This helps SUs to complete their sessions and leads to a



(a)



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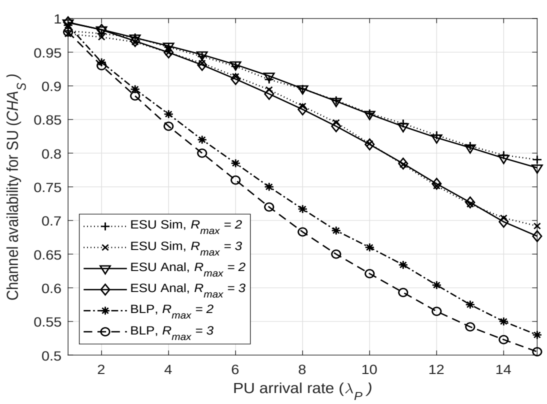
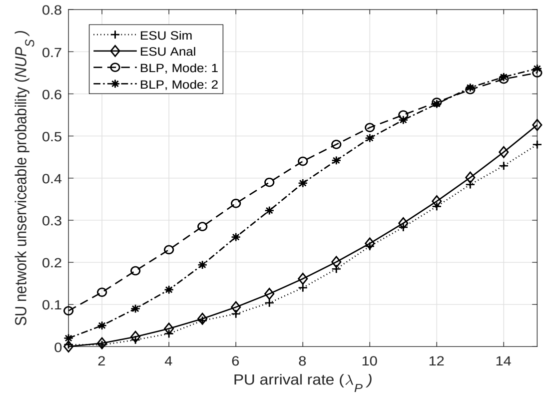
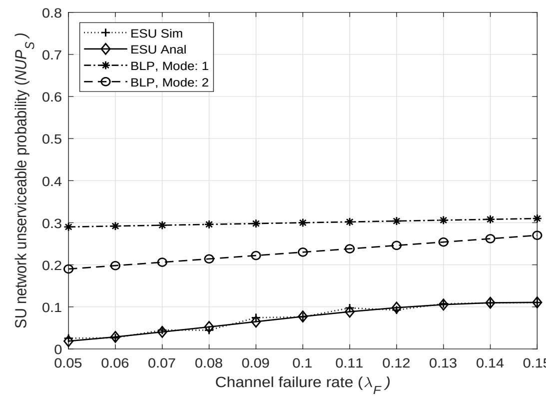


(c)

Fig. 5: Channel availabilities for PU and SU as functions of PU arrival and channel failure rates.



(a)

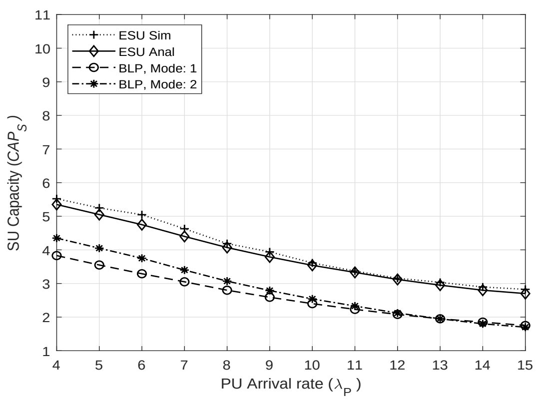


(b)

Fig. 6: Network unserviceable probability for SU as functions of channel failure and PU arrival rates.

high number of SUs' service completion rate per unit time, or capacity. However, with increase in λ_P, since the number of available channel decreases, SUs find it hard to get idle channels and, as a result, their capacity gradually decreases. Moreover, increase in channel switching, which results from high value of λ_P, also gives rise to reduced capacity. In terms of performance, ESU considerably outperforms BLP. At $\lambda_P = 15$, ESU achieves $CAP_S = 2.7$ as compared to BLP that achieves $CAP_S = 1.7$ for both of its modes. At $\lambda_P = 1$, ESU achieves $CAP_S = 5.9$ as compared to BLP that achieves $CAP_S = 4.6$ and $CAP_S = 5.0$ for Mode 1 and Mode 2, respectively. The reason for the enhancement is the privileges our proposed ESU scheme grants to SUs. After $\lambda_P > 10$, the decrease in the SUs' capacity in ESU slows down. The reason is that, since SU_H services in R-CRN are interminable, once an SU_H service enters R-CRN, it completes its service without being interrupted by PU arrivals. BLP lacks this kind of service provisioning to SN and, thus, underperforms ESU.

In Fig. 7b, PUs' capacity is plotted as a function of λ_P. As shown in the figure, there is a gradual hike in CAP_P with increase in λ_P. The reason is that, under low λ_P, the number of PUs are low in the network. This results in low number of service completion per unit time, or capacity. As λ_P increases, more PUs enter the network, and because of PUs' priority, they readily find channels which gives rise to their increased capacity. In terms of performance, PUs' capacity in ESU achieves $CAP_P = 3.7$ at $\lambda_P = 4$, as compared to BLP that achieves $CAP_P = 3.8$ and $CAP_P = 3.9$ for Mode 1 and Mode 2, respectively, for the same value of λ_P. The difference widens as λ_P increases. At $\lambda_P = 15$, ESU achieves $CAP_P = 10.4$, as compared to BLP that achieves $CAP_P = 8.7$ and $CAP_P = 10.6$ for Mode 1 and Mode 2, respectively. The reason is that, since SU_H



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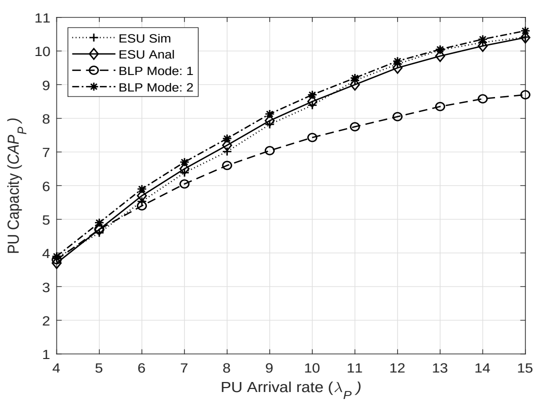

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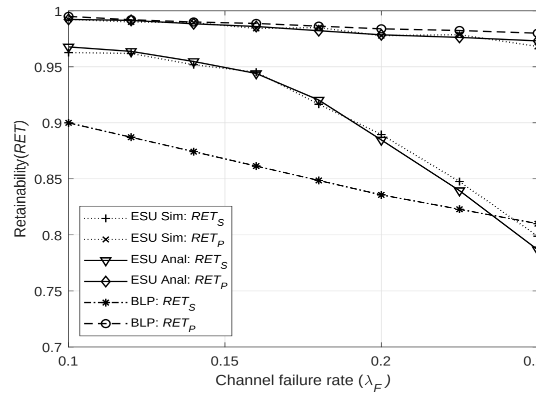
Fig. 7: Capacities for SUs and PUs as functions of PU arrival rates.



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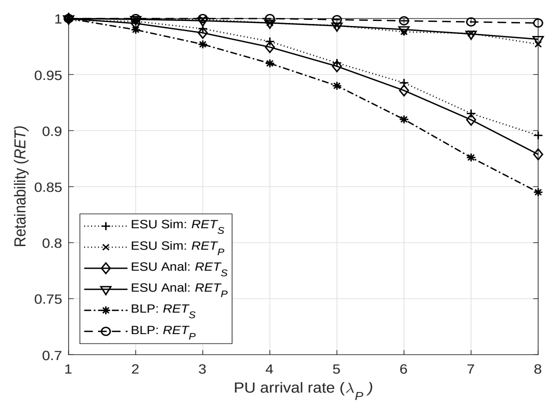

(b)

Fig. 8: Retainability for SU as functions of channel failure and PU arrival rates.

services in R-CRN are interminable by other services in ESU, PUs find it hard to get a channel in R-CRN when there are many SU_H operating in R-CRN. Consequently, the capacity of PUs diminishes as compared to Mode 2 of BLP. However, the reduction is negligible as compared to the enhancements in SU's and PU's capacities achieved by ESU against Mode 1 of BLP, in addition to the significant SUs' capacity enhancement. The improvement in PUs' capacity in our proposed ESU scheme, as compared to BLP, is also logically valid because BLP allows SUs operating in the reserved band to terminate PUs in the non-reserved band. Conversely, ESU does not allow such termination, which leads to a more realistic scenario because PUs are licensed users and should not be terminated by unlicensed users.

D. Service Retainability

Fig. 8 presents retainabilities of PUs and SUs as functions of λ_F and λ_P. It can be seen in the figure that retainabilities of both type of users declines with increase in λ_P or λ_F. However, SUs' retainability declines more rapidly as compared to that of PUs. The reason is that, with increase in λ_P or λ_F, fewer channels become available in the network, which shrinks the probability for interrupted users to find idle channels to resume their transmission. Moreover, the rapid declination in SUs' retainability, as compared to that of PUs, is due to the priority level PUs enjoy.

In terms of performance, in Fig. 8a, retainabilities of PU and SU services are plotted as a function of λ_F. Note that $\lambda_F = 0.5$ is assumed in Fig. 8b and Mode 1 of BLP is considered for comparison. We first discuss SUs' retainability, RET_S. As can be seen in Fig. 8a, ESU achieves higher RET_S before $\lambda_F < 0.23$. At $\lambda_F = 0.1$, ESU achieves $RET_S = 0.97$, as compared to BLP that achieves $RET_S = 0.9$. The reason for this enhancement lies in the fact that ESU allows newly arrived SU_L to enter R-CRN directly if NR-CRN is completely occupied and an idle channel exists in R-CRN. Since retainability is the product of the service admission rate and service completion rate, ESU achieves higher values of retainability before λ_F rises substantially. Moreover, ESU responds quickly to the network dynamics by adjusting R-CRN with each departure, in addition to each arrival. This makes channels available for new SUs' arrivals in case there are idle channels in R-CRN, as described in Algorithm 1.

After $\lambda_F > 0.23$, ESU slightly underperforms BLP in terms of RET_S. At $\lambda_F = 0.25$, $RET_S = 0.79$ is achieved by ESU, as compared to BLP that achieves $RET_S = 0.81$. This reduction in RET_S is attributable to the fact that fewer

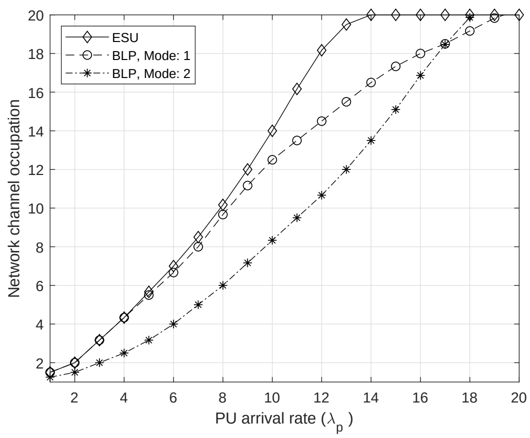

Fig. 9: Networks channel occupancy.

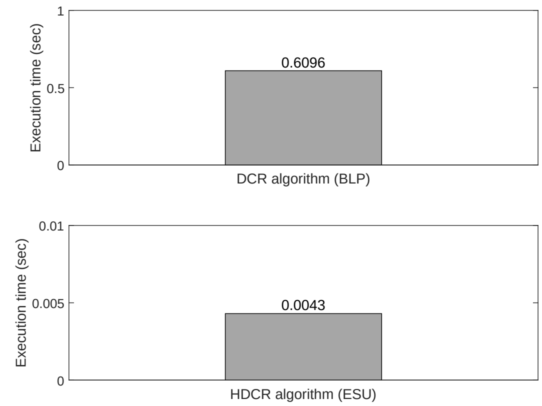

Fig. 10: Execution time comparison of DCR (BLP) and HDCR (ESU).

channels become available in the network as λ_F rises, thus, leading to a reduction in RET_S. Nonetheless, this reduction in RET_S in ESU is of trivial importance because λ_F of such a high magnitude is rarely observable in real-world scenarios [52], [53].

In terms of RET_P, the performance of ESU is comparable to that of BLP initially, as shown in Fig. 8a. However, ESU marginally declines in performance after $\lambda_F > 0.15$. A slight decrease of $RET_P = 0.01$ is observed in ESU as compared to BLP at $\lambda_F = 0.25$. The reason for this decrease is the admission privileges granted by ESU to SUs and the quick adaptability of the two bands with the network changes. However, the decrease is still very low as compared to the overall enhancement achieved by ESU in RET_S.

In Fig. 8b, retainabilities of PUs and SUs are evaluated as a function of λ_P. As shown in the figure, at $\lambda_P = 8$, a slight decrease of almost 0.01 in RET_P can be noticed in ESU, as compared to BLP. Under low PUs traffic, however, ESU performs comparably to BLP in RET_P. Contrarily, in terms of RET_S, ESU achieves $RET_S = 0.88$, as compared to BLP that achieves $RET_S = 0.85$ under $\lambda_P = 8$, as shown in the figure. The improvements are attributable to the flexible nature of ESU wherein SUs enjoy network idle conditions and PUs benefit from their privileges over SUs. For instance, SU_H operating in R-CRN completes its service without having any interruption by other services. Similarly, SU_H can access R-CRN when it faces interruption in NR-CRN. Moreover, SU_L can also access R-CRN. All these factors contribute to the enhanced retainability for SUs in ESU. Similarly, PUs can preempt SU_H operating in NR-CRN. Further, PUs can preempt SU_L operating in any band of the network. Additionally, PUs cannot be preempted by any other services in the network. All these factors lead to the enhancement in PUs' retainability in ESU.

E. Comparison in execution time between HDCR and DCR

After calculation of the execution time for the DCR algorithm proposed in BLP and the HDCR algorithm proposed in ESU, we found that the DCR algorithm takes 0.6096 seconds and the HDCR algorithm takes 0.0043 seconds, as shown in Fig. 10. These values represent 99% enhancement in time efficiency and are averaged over 1000 times running of the respective algorithms under the environment described in Section V and Table IV.

F. Network's Channels Occupancy

ESU can fill all the available channels in the network more swiftly than the two modes of BLP. Fig. 9 shows the comparative performance of ESU with the two modes of BLP. A total of twenty channels are assumed in the network for evaluating this aspect of performance. It is found that under a given PU arrival rate, ESU promptly brings all the available channels into utilization as compared to the two modes of BLP. This is due to the facts that (i) ESU allows SU_L to occupy idle channels anywhere in the network, and (ii) ESU reserves channels only when the threshold number of channels are occupied. Contrarily, both the modes of BLP initiate reservation at every level of network traffic load, which renders the reserved channels unavailable for a new arriving users. Thus, the channel reservation approach of BLP leads to slow utilization of the channels.

G. Critical Discussion

In this section, various performance metrics, including service retainability, channel availability, network unserviceable probability and capacity, are considered for performance evaluation. Results show that the proposed ESU scheme performs robustly to the dynamic nature of CRNs and enhances retainabilities of SUs, capacities of SUs, network unserviceable probabilities of SUs, and channel availabilities for SUs and PUs, when compared with the state-of-the-art.

Looking at the promising results, we believe that ESU is potentially advantageous in IoT-based networks. Since IoT comprises large number of devices that require efficient spectrum access, ESU is efficacious in combating spectrum scarcity in IoT based networking paradigms. Moreover, performance gain of ESU can be magnified many folds in particular scenarios where PUs' traffic is of low or moderate level and SUs' traffic is of high level, as is learnt from the results. Lastly, the application of criterion on channel selection for termination can allow flexibility to operators in terms of network traffic requirement based configuration.

Our proposed ESU scheme can be easily implemented in real networks since it is based on a centralized structure. The scheme can emulate the current cellular and infrastructure based ad hoc networks with additional cognitive capabilities in the end-user devices for its practical deployment. Thus, with cognitive capabilities in end-user devices, the scheme can be seamlessly integrated with other networks.

Apart from the advantages, our proposed ESU scheme has a limitation. For instance, ESU experiences a marginal performance degradation in PUs' retainability under certain conditions, such as higher PU arrivals and channel failure rates. However, this limitation is condition-dependent and the overall improvement brought about by ESU outweighs its limitation.

VI. Conclusions

A novel scheme, named ESU, has been proposed to enhance spectrum efficiency in CRNs. The scheme comprises a hybrid DCR algorithm and an enhanced DSA algorithm while assuming two kinds of SUs with low and high priority levels. The scheme is modeled using continuous time Markov chain and analyzed under multiple loads of network traffic and varying rates of channel failure. Several QoS parameters, including network unserviceable probability, capacity, service retainability, and channel availability, are investigated. Results demonstrate that the scheme improves most of the considered parameters when compared with the state-of-the-art. It is concluded that, although channel reservation might be needless at low traffic level, a requirement based channel reservation scheme can reasonably enhance CRN performance in terms of spectrum efficiency. Moreover, a hybrid approach is more promising and preferable over pure reservation-based or pure non-reservation-based scheme. However, in networks with ultra-criticality or highly dense networks with variable traffic levels, the performance of our scheme needs to be re-evaluated for any possible under-performance. We plan to investigate this aspect of our scheme in the future. In addition to this, we plan to integrate ESU with hybrid underlay-interweave modes of CRNs. Moreover, we also intend to quantify the performance gain achieved by adopting QoS based channel selection for termination. Lastly, we also plan to consider integration of node's mobility in our model and investigate the performance.

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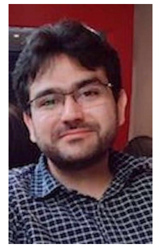

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