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RESEARCH ARTICLE

Toward Spectrum Efficiency and Reliability for Heterogeneous Users in CR-Enabled Social Internet of Things

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ABSTRACT Cognitive radio enabled social internet of things (CR-SIoT) can potentially revolutionize the existing networking paradigm by enabling heterogeneous IoT users to communicate socially like friends using the existing limited spectrum. However, satisfying the varying requirements of heterogeneous users in CR-SIoT remains a key challenge. Therefore, we propose a novel extended scheme, called ES, targeted at CR-SIoT with multi-priority and heterogeneous users. The scheme heuristically utilizes the secondary users' (SUs') heterogeneousness with respect to their priorities, methodically tackles SUs' dropping, and follows efficient approach for channel access. Moreover, the scheme considers the impact of receiver's accessibility for rendering realistic analysis. Aside from this, we propose a spectrum reservation algorithm for increasing spectrum utilization. Leveraging Markov chain, we model the network and derive expressions for capacity, blocking probability (BP), spectrum utilization, and handoff probability (HP). We evaluate the scheme under various users' arrival and service rates, and observe 74% improvement in capacity, 26% in spectrum utilization, 88% in HP, 43% in BP, and significant fairness in service availing among users, compared to the state-of-the-art. Additionally, we gain valuable insights by studying the inherent tradeoff between BP and service retainability resulting from the spectrum reservation.

INDEX TERMS Cognitive radio networks, Internet of Things, resource allocation and management.

I. INTRODUCTION

The social Internet of Things (SIoT) is an emerging networking paradigm wherein IoT nodes can inter-communicate extensively like friends [1], [2]. Therefore, given the massive number of SIoT devices, their extensive communication, and their diversity in terms of resource requirements, a substantial amount of available spectrum is required [3], [4]. However, the existing networks are already in need of more spectrum, and extensive research is being conducted to

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develop new techniques for utilizing the existing spectrum more efficiently. Among these techniques, cognitive radio (CR) has attracted significant interest from the research community [5], [6].

CR integrated with social IoT (CR-SIoT) is envisioned to have a vast number of IoT devices or users with heterogeneous characteristics and diverse quality of service (QoS) requirements [7], [8]. This comes with the following challenges.

- Fulfilling the differing users' requirements in CR-SIoT, particularly of those users that bear low priorities, within the limited spectrum, requires the designing of efficient schemes and algorithms. In particular, users' capacity, users' handoff probability (HP), utilization of the network's spectrum, and users' blocking probability (BP) are some of the core performance metrics associated with modern wireless networks that need to be supported in CR-SIoT as well.
- Although, spectrum reservation is considered an efficacious tool to maintain QoS requirements for all users and, hence, the CR research community has utilized it progressively, its inefficient configuration and design may lead to tradeoffs among specific performance indicators. Notably, a tradeoff between the BP of new users and the service retainability - a core performance indicator defined by International Telecommunication Union-Telecommunication (ITU-T) [9] - of existing users can result from spectrum reservation. This indicates a pressing need for efficient designing and configuration of a spectrum reservation algorithm.
- A credible performance evaluation of any network is closely tied to the consideration of a receiver's accessibility to transmitter. It is often the case that the intended receiver for a user, denoted by Rx, is not accessible to the user because of being inoperable, out of coverage, busy, or because of excessive noise [10], [11], [12]. Therefore, despite the channel provisioning to a user granted by the service provider, the connection remains unsuccessful if the Rx is inaccessible. This consequently renders the channel provisioning futile and leads to imperfect performance assessment of the network.

A. THE MOTIVATION FOR USING SIOT

In this paper, we perform analysis considering SIoT instead of IoT. The reason is that, though, both of them share similarities in their fundamental concept of interconnected devices, they differ in their focus, objectives, and scope [2]. IoT primarily collects and analyzes data to improve operational efficiency, reduce costs, and provide insights for decision-making. SIoT uses data to understand and respond to user behaviors, offering personalized services, adaptive responses, and context-aware interactions. This implies that SIoT needs more spectral resources compared to IoT for its additional intractability with other SIoT devices and users in automated interaction. Therefore, it is more important to investigate spectrum efficiency considering the huge spectrum of SIoT [5].

In what follows, we describe the notable works performed in this direction.

TABLE 1. The list of main notations and abbreviations.

Notation	Meaning
a	The number of active PUs
AC	Aggregated channels
BP	Blocking probability
B_{rp}	The band reserved for PUs
B_1'	The band reserved for SUs-U
B_{r2}	The band reserved for SUs-B
B^{idle}	The total number of idle channels
B_x	The total number of occupied channels
CTMC	Continuous time Markov chain
DSR	Dynamic spectrum reservation
ES	The proposed scheme
HP	Handoff probability
j_0	The number of active SUs-U
j_1	The number of active SUs-A
j_a	The number of active SUs-B with ACs
j_b	The number of active SUs-B without ACs.
J_2	The number of active SUs-B
KPI	Key performance indicators
λ_P	PU arrival rate
λ_S	SU arrival rate
m	the maximum number of ACs.
μ_P	Service rate of PUs
μ_S	Service rate of SUs
n	the minimum number of ACs.
ρ	Current traffic load
RxA	Receiver's accessibility
Rx_S	The intended receiver for a transmitting SU
IoT	Internet of things
SUs-A	High-priority SUs requiring real-time transmission
SUs-B	Low priority SUs
SUs-U	High-priority SUs requiring urgent transmission
TLL	Traffic load level

B. RELATED WORK

Given the applicability of spectrum reservation as an effective tool to enhance CRN performance, the authors in [12] utilize it to reduce users' BP and capacity. Similarly, spectrum reservation is proposed in [10] to increase the call completion probability of users. In the same way, the authors in [13] and [14] have leveraged spectrum reservation to improve users' capacity and BP. Likewise, spectrum reservation is employed in [6], [15], [16], and [17] to improve a number of QoS parameters. Furthermore, the authors in [18] employ spectrum reservation to mitigate the BP of higher-priority SUs while ensuring channel utilization. A priority-based spectrum reservation is proposed in [19], wherein a control channel is solely reserved for SUs. Likewise, a spectrum reservation scheme and cooperative communication are considered in [20]. The authors in [21] present a novel

TABLE 2. The summary of existing relevant literature.

Ref. #	Fairness considered?	Multi level priority considered?	Multi level users' heterogeneity considered?	Channel access mode	Reservation type	Rx accessibility considered?	Reservation Tradeoffs considered?	Performance parameters
[12]	✗	✓	✓	Random	Static	✗	✗	Capacity, BP
[10]	✗	✗	✗	Random	Dynamic	✗	✗	Call completion prob.
[13]	✗	✗	✗	Random	Static	✗	✗	Capacity, BP
[14]	✗	✗	✗	Random	Dynamic	✗	✗	Retainability, channel availability, unserviceable probability
[15]	✗	✓	✓	Random	N/A	✗	✗	Spectrum utilization, collision probability, throughput
[1]	✗	✓	✓	Regulated	Static	✗	✗	Capacity, BP, Spectrum utilization
[16]	✗	✓	✓	Random	Dynamic	✗	✗	Unserviceable probability, channel availability, retainability
[6]	✗	✓	✓	Regulated	Dynamic	✗	✗	Call completion probability, throughput, handoff, serviceability
[17]	✗	✓	✓	Random	Dynamic	✗	✗	Channel availability, capacity, serviceability
[18]	✗	✓	✓	Random	Dynamic	✗	✗	BP, channel utilization, throughput
[19]	✗	✗	✗	Random	Static	✗	✗	Throughput
[20]	✗	✗	✗	Random	Static	✗	✗	Call completion probability, termination probability, BP
[21]	✗	✗	✗	Random	Static	✗	✗	Throughput, serviceability
[22]	✗	✗	✗	Random	Static	✗	✗	Spectrum utilization, serviceability
[23]	✗	✗	✗	Random	Static	✗	✗	Serviceability
[24]	✗	✓	✓	Random	Static	✗	✗	BP, termination probability
[25]	✗			Random	Dynamic	✗	✗	Cost, spectrum utilization
[26]	✗	✗	✗	Random	Static	✗	✗	Delay, spectrum utilization
[27]	✗	✗	✗	Random	Static	✗	✗	Channel availability, delay
[28]	✗			Random	Dynamic	✗	✗	Spectrum utilization
[29]	✗	✗	✗	Random	Dynamic	✗	✗	Spectrum utilization
This paper	✓	✓	✓	Regulated	Dynamic	✓	✓	Serviceability, handoff, capacity, BP, spectrum utilization

medium access control protocol and a reservation scheme for distributed single-channel CRNs. In our work in [22], channel reservation is exploited to comprehensively analyze tradeoffs in various performance indicators. Similarly, in our other work presented in [23], reliability analysis of the work proposed in [12] is carried out. However, the literature mentioned above overlooks the prospective multi-level users' heterogeneousness in QoS requirements and prioritization associated with CR- IoT networks. Additionally, the imperative performance reduction of low-priority users is not taken into account. Similarly, spectrum reservation with multi-types users is considered in [18]. However, the random channel access of high-priority users considerably degrades the performance of low-priority users. In this connection, a spectrum reservation technique is proposed in [1] that takes into account multi-level users' heterogeneity and employs channel aggregation to help low-priority users improve their performance. However, the scheme prioritizes users inefficiently, and performs static spectrum reservation, which leads to spectrum underutilization. Likewise, the authors in [24] proposed allocating resources to users, taking into account the heterogeneity and priority of users. Notwithstanding, the reservation performed is static, rigid, and inflexible, leading to inefficiency in resource allocation. The authors in [25] propose an adaptable spectrum reservation scheme for network virtualization. The scheme considers the events data gathered from various users, and aggregates them for using in user needs estimation. The trend similarity of spectrum allocation is exploited in [26] to present a prediction-based reservation algorithm. The efficiency of the proposed algorithm is validated through simulation against the exponential weighted moving average scheme. In [27], a teaching-learning-based optimization is leveraged to present an adaptive spectrum reservation algorithm. This way, different performance indicators are balanced and optimized. The authors in [28] propose a beam-based channel reservation algorithm for URLLC, wherein the devices can occupy channels in the unlicensed spectrum. As a result of using the reservation algorithm together with beamforming technology, the channel occupancy rate is increased. The authors in [29] analyze advance reservation and on-demand leasing of network resources for a mobile virtual network operator. To this end, the authors jointly optimize the assigned spectrum to maximize the surplus by considering various network parameters. Similarly, machine learning and internet of things based traffic management system is proposed and implemented in [30], the application of IoT based solution is considered in [31], and IoT-based healthcare system is considered in [32]. Aside from this, the authors in [33] and [34] present routing protocols for cognitive radio enabled IoT networks. The authors in [35] investigate energy efficiency in cognitive radio networks under full duplex communication. The authors in [36] present reinforcement-based resource allocation in cognitive radio networks. However, these works don't consider the performance metrics considered in our work.

1) MOTIVATION AND OBJECTIVES

The schemes mentioned above bear certain additional and critical limitations. First, they ignore accessibility of the intended receiver (RxA) in their analyses. For instance, as stated above, it is often the case that Rx is not accessible due to a variety of reasons [10], [11], [12]. Therefore, despite the channel provisioning to a user, the connection remains unsuccessful if the Rx is inaccessible, which renders the channel provisioning futile. This factor advocates for considering the impact of RxA in the CRNs' performance evaluation to realize a realistic and reliable analysis. Second, the schemes utilize spectrum reservation yet do not consider the inherent tradeoff between the BP of new users and the service retainability of existing users resulting from spectrum reservation. Besides, channels are accessed randomly whenever primary users (PUs) require channels' access or when users with high priority need to drop users with low priority, which degrades the performance of users with low priority. Such a random approach of PUs/high-priority users in channel access also gives rise to HPs. Lastly, fairness and balance in service provisioning to SUs have been compromised by following a random and chaotic approach when dealing with SUs' dropping. For instance, when an SU of a specific priority is required to be dropped, it is randomly selected from the set of available SUs of that specific priority.

C. NOVELTY AND CONTRIBUTIONS

To overcome the research gaps identified in the literature, we propose an extended multi-tier spectrum reservation and prioritization scheme, called ES, with the following novel attributes.

- ES heuristically manipulates the secondary users' heterogeneousness with respect to their priorities, in the form of low priority and high priority, to maximize their performance.
- ES methodically tackles the dropping order of SUs to mitigate the divergence in service provisioning to SUs. This is in contrast to the random dropping approach followed by the recorded literature.
- ES ensures that PUs access channels following a band-reservation-based efficient approach for reducing HP. This differs from the random channel access approach employed in the recorded literature.
- ES considers the impact of receiver's accessibility in the performance evaluation of the network for rendering realistic analysis. The recorded literature have ignored to consider the accessibility of receiver for a user in performance evaluation.
- ES is embedded with a dynamic spectrum reservation (DSR) algorithm that is proposed for reserving channels for PUs to enhance spectrum utilization. This way, ES also allows us to analyze the inherent tradeoff between BP and service retainability resulting from the spectrum reservation.

B_{rp}	B'_1	B_{r2}	Unreserved Band

FIGURE 1. The distribution of bands.

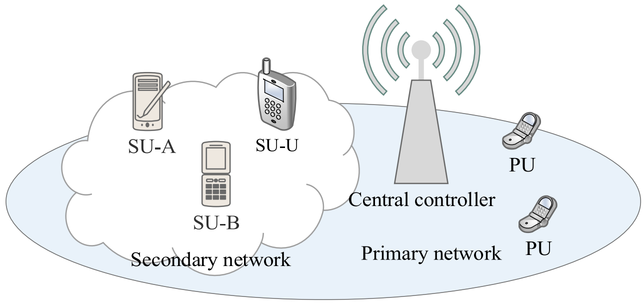

FIGURE 2. The CRN's architecture with PUs' and SUs' IoT devices.

- ES is analytically modeled through continuous-time Markov chain (CTMC). Moreover, several key performance indicators (KPIs), including capacity, spectrum utilization, BP, and HPs, are considered for performance evaluation, and mathematical expressions are derived for them. ES is evaluated under various users' arrival and service rates.

Our contributions are presented briefly in the following.

- As a result of considering RxA in our system model, we present a realistic analysis by quantifying and showing the performance difference when RxA is considered and when it is ignored. Similarly, using the DSR algorithm, we analyze and quantify the tradeoff between BP and service retainability that results from spectrum reservation, which allows us to find conformable configurations of the algorithm's parameters.
- By realizing efficient, logically admissible, and realistic prioritization among SUs, we obtain a considerable decrease in SUs' HP. Likewise, the organized approach proposed for PUs for channel access further reduces the HP of users.
- By using the proposed efficient approach for selecting the appropriate SU for dropping, we mitigate divergence in the performance of SUs. As a collective impact of ES, a large-scale increase in the performance of high-priority SUs and a moderate increase in the performance of low-priority SUs are exhibited.

D. PAPER'S ORGANIZATION

In Section II, we present the system model. Section III presents mathematical derivations for the considered KPIs. In Section IV, we elaborate the numerical results. The paper is concluded in Section V.

II. SYSTEM MODEL

A CR-enabled IoT consisting of k number of PUs' IoT devices and the changeable number of SUs' IoT devices is considered. For the sake of simplicity, they are just termed PUs and SUs. There are multiple classes of SUs with respect to their priorities, which include low-priority SUs (denoted by SUs-B), high-priority SUs requiring real-time transmission

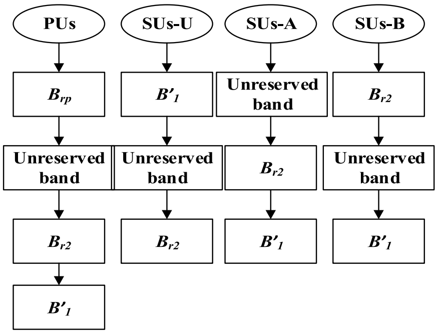

FIGURE 3. The access order of the various spectrum bands.

TABLE 3. The priorities of various users.

Priority-1	Priority-2	Priority-3	Priority-4
PU	SUs-U	SUs-A	SUs-B

(denoted by SUs-A), and high-priority SUs requiring urgent transmission (denoted by SUs-U), as shown in Fig. 2. SUs-U can be those devices or users that are sensitive to delay and can be used in mission-critical applications. Similarly, SUs-A can represent those users or devices that are used in healthcare applications, while SUs-B can represent users with video or file transfer applications. This classification represents the highest level representation of the heterogeneous users in CR-SIoT networks. The CRN has B number of channels with same bandwidth. This assumption corresponds to real-world networks where channels of the same bandwidth are configured. The channels are divided into the following bands – B_{rp}, B'_1, and B_{r2}. Moreover, an unreserved band also exists. The distribution is presented in Fig. 1. The unreserved band can be accessed by all types of users. B_{rp} is reserved for and can be occupied by PUs as their primary band for channel access. Similarly, B'_1 and B_{r2} are reserved for SUs-U and SUs-B as their primary bands for channels. Additionally, the total number of idle channels is denoted by B^{idle} such that $B^{idle} = B - B_x$, where B_x is the total number of occupied channels within the network. Moreover, the total number of available channels to SUs is denoted by B_1, such that $B_1 = B - B_{rp}$. By making spectrum reservations in this way serves two purposes. First, it prevents users from performance degradation and is beneficial, particularly, for low-priority users. Second, it leads to efficient spectrum utilization. SUs-B can make channel aggregation for performance enhancement. The number of aggregated channels (ACs) falls between m and n, where m denotes the maximum and n the minimum number of ACs. It is worth noting that Channel assembling or aggregation is a popular technique that is used in communication networks. Here, in our proposed work, we have used it to enhance the performance of low-priority users and increase the utilization of network resources. To this end, in our scheme, SUs-B can make channel aggregation for performance enhancement. Furthermore, for prioritizing users efficiently, the hierarchically organized model presented in Table 3 is used. Such an organized prioritization is essential for the efficient performance of the network. Moreover, it suits the application's diversity and the variety of requirements mandated by the heterogeneous profiles of users in IoT.

As descriptively presented in Fig. 5, a PU occupies a vacant or idle channel found in B_{rp} in the beginning, followed by an idle channel in the unreserved band, B_{r2}, and B'_1. Subsequently, if the PU cannot find an idle channel, it takes back a channel from an SU obeying this order: SU-B with ACs (aggregated channels) – SU-B – SU-A – SU-U. In a similar fashion, as shown in Fig. 6, new arriving SUs-U occupy idle channels within the given bands with the given order as: B'_1 – the unreserved band – B_{r2}. If no idle channel is available in any of the bands mentioned above, an SU-U takes a channel from an SU-B holding ACs. Alternatively, an SU-U drops an SU-B, or SU-A if SU-B is unavailable.

Additionally, as shown in Fig. 7, an arriving SU-A occupies a channel in the bands with the following order: the unreserved band – B_{r2} – B'_1. If the SU-A fails to find a free channel in the bands given above, it takes a channel from an SU-B holding ACs. Alternatively, an SU-B is dropped in order to make a channel available for the new arriving SU-A. Likewise, as described in Fig. 8, when an SU-B requires a channel, it accesses a vacant channel within the given bands obeying the following order: B_{r2} – the unreserved band – B'_1. Alternatively, a channel is carried back from an SU-B holding ACs in order to make a channel available for the new arriving SU-B.

The channel access privileges and procedure are presented in Fig. 3 and Fig. 4. This way, the number of channels available to SUs is denoted by B_1 and given by $B_1 = B - B_{rp}$ whereas collisions among various users are dealt with by following the procedure given in Table 3 and Fig. 3. This implies that whenever two users of different priorities want to access a channel, the one with higher priority is allowed and the other is denied. Moreover, B_{rp} is dynamic, such that the number of channels it contains changes according to the given traffic level of PUs. Algorithm 1, which is triggered when a new PU arrives, governs on the number of channels B_{rp} can contain.

In Algorithm 1, the number of PUs existing in B_{rp} is divided by the current number of channels in B_{rp} and the ratio is found. The consequent ratio denotes the current traffic load (ρ). Subsequently, ρ is granulated into $c+1$ levels distinguished by c configurable input parameters $\alpha_1, \alpha_2, \ldots, \alpha_{c+1}$. The range of values assumed by the input parameters is given in the algorithm. So, with $c = 2$, ρ is divided into high, medium, and low levels. Consequently, α_1 and α_2 may be configured as $\alpha_1 = 0.70$ and $\alpha_2 = 0.35$. Hence, low, medium, and high traffics are represented by $\rho < 0.35$, $0.35 \leq \rho < 0.70$, and $\rho \geq 0.70$, respectively. After ρ is calculated in this fashion, the consequent traffic-load-level (TLL) is determined. Thereafter, some greater or smaller value, subject to $B_{rp_{max}}$, is assigned to B_{rp_t} when TLL is high or small, respectively, in accordance with the

Algorithm 1 The Spectrum Reservation Algorithm

Input: B_{rp_c}: The number of current channels within B_{rp}
Input: B_{rp_o}: The total number of channels occupied within B_{rp}
Input: $B_{rp_{max}}$: The maximum number of channels maintainable within B_{rp}
Input: α_i: $\alpha_{c+1} < \alpha_c < \ldots < \alpha_i < \ldots < \alpha_1 < \alpha_0$; $0 < \alpha_i < 1, i = 1, \ldots, c : c \in \mathbb{Z}^+$; $\alpha_0 = 1, \alpha_{c+1} = 0$
Output: B_{rp_t}: The total number of revised channels within B_{rp}

1 A new PU arrives
2 $\rho = B_{rp_o} / B_{rp_c}$
3 $N_{avail} = B_{rp_c} - B_{rp_o}$
4 **for** i =1:1:c **do**
5   **if** $\alpha_{i+1} \leq \rho < \alpha_i$ **then**
6   traffic-load-level = i
7   **break;**
8   **end**
9   traffic-load-level = i
10 **end**
11 $R' = B_{rp_{max}} - (c-$traffic-load-level$)$: $R' \in \mathbb{Z}^+$ *is a variable representing the number of channels other than in* B_{rp}.
12 $B_{rp_t} = \max(N_{avail} + B_{rp_o}, R')$

calculation given on Line 11. It is worth noting that when $B_{rp_{max}}$ shrinks by releasing a channel, the channel is assigned to the unreserved band.

Moreover, R' denotes the channels other than those allocated to B_{rp_t}. This way, it can be expressed as $R' = B - B_{rp_t}$. It is used here to calculate how many channels are outside B_{rp_t} that we have left with. This way, B_{rp_t} can be adjusted according to the number of channels that currently exist in the network. Moreover, $B_{rp_{max}}$ is the maximum number of channels that can be allocated to B_{rp}. We need to restrict the number of channels allocatable to B_{rp} for which we need this parameter. If it is not defined, an excessive number of channels can be allocated to B_{rp}, which would undermine the performance of SUs because SUs are not allowed to access B_{rp}. Besides, as stated in Section I, selecting low-priority SUs randomly for the interruption, as used by PUs and high-priority SUs in the current literature, becomes a primary reason for starvation for certain SUs-B in particular. This factor leads to motivation for adopting an organized dropping approach. For this purpose, this paper proposes the following efficient criterion.

$$SU_{opt} = \max_{\forall SU_i \in A} ((SU_i)_t). \quad (1)$$

The notation SU_{opt} denotes the optimal SU to be selected for dropping. Similarly, A denotes the set of N active SUs bearing the same characteristics and priority. Likewise, SU_i denotes a normal SU in set A, whereas the notation $\max(SU)_t$ denotes the function used for selecting the SU bearing the longest active time within set A calculated as $t_2 - t_1$, where t_2 is the ending and t_1 is the starting service time of a particular SU. Thus, services are fairly exploited by SUs of a specific priority without causing network's instability. It is important to note that the service duration of each SU is tracked by the central controller, which enables the controller to identify which SUs to interrupt when required. This way, the SUs' order need not be maintained in the proposed CTMC model, and the model in its present form perfectly captures all the activities and states required for performance analysis. Moreover, PUs and SUs access the channels following the Poisson process with rates λ_P and λ_S, respectively. Furthermore, μ_P and μ_S stand for the service rates of PUs and SUs, respectively. Without loss of generality, it is assumed that users are served following the exponentially distributed.

A. DISCUSSION ON THE SCALABILITY OF THE ALGORITHM 1

How it performs under a large user base and dynamic spectrum conditions. **Algorithm 1 is scalable and performs well under a specified level of traffic conditions, i.e., as long as the number of users matches the total number of channels in the network. However, when these two factors mismatch, such that the number of users considerably exceeds the total number of channels in the network, the network performance gets imbalanced and consequently Algorithm 1 cannot perform as expected.** In Algorithm 1, the number of iterations increases to $\mathcal{O}(\mathcal{N})$, where $\mathcal{N}$ represents the total number of active users in the network. As a result, according to Algorithm 1, the computational complexity of our scheme is $\mathcal{O}(\mathcal{N})$ suggesting that as the number of active users increases, the complexity increases.

B. THE MARKOV CHAIN MODEL

We develop the CTMC model for the system. The generic state of the model is $Z(a, j_0, j_1, j_a, j_b)$, where a, j_0, and j_1 indicate the number of active PUs, SUs-U, and SUs-A, respectively. Likewise, j_a indicates the number of active SUs-B with ACs and j_b indicates the number of active SUs-B without ACs. So, $j_2 = j_a + j_b$. We use j_2 instead of j_a or j_b in Table 4 because it is more appropriate to use j_2 given that the objective is to show that it is a SU-B that is served/interrupted. This way, the complexity involved in the system's understanding and modeling is reduced. Rx_S represents the intended receiver for a transmitting SU, which may either be accessible or inaccessible. When accessible, it is represented by 1, and by 0 when inaccessible, as also shown in Table 4 and Table 5. It is worth noting that Table 4 and Table 5 each represent the state transition rate table (STRT) resulting from the CTMC modeling. Moreover, given that the accessibility or inaccessibility of Rx_S is casual and uncertain, we leverage the probabilistic model to capture its behavior. Among the well-known probabilistic models available, we use Gaussian random variable to compute the accessibility of Rx_S as Gaussian distribution is suitably applicable to this problem [37], [38]

$$P(t,\ t+\Delta t|Rx_S=1)=p(t)\,\Delta t. \tag{2}$$

The probability $P(t,\ t+\Delta t|Rx_S=1)$ indicates that Rx_S can be found, or is available, between t and $t+\Delta t$ time period. Δt indicates a small duration of time such that $p(t)\times\Delta t\leq 1$, and $p(t)$ is the probability density function [37] expressed as

$$p(t)=\frac{1}{\sigma\sqrt{2\pi}}e^{-(t-t_{avg})^2/2\sigma^2}. \tag{3}$$

t_{avg} is the average available time of Rx_S and σ is the standard deviation.

The state transition rates for all the events occurring within the network, and the conditions associated with the events, are represented in our CTMC model by Table 4 and Table 5. Since it is crucial to find steady-state probability (SSP) vector π for the subsequent analysis, the tables enable us to find out it using [39]

$$\pi\times\boldsymbol{Q}=\boldsymbol{0},\qquad\sum_{z\in Z}\pi_z=1. \tag{4}$$

The notations $\boldsymbol{0}$ is a row vector and $\boldsymbol{Q}$ is the transition rate matrix. It is worth noting that Eq. (4) is a standard equation that is used in the literature to calculate the steady-state probability vector (π). The equation implies that: (a) when π is multiplied with the transition rate matrix ($\boldsymbol{Q}$), the result is 0, and (b) the summation of all possible vectors in steady state results in 1. So, with the help of these two equations, we are able to find the probabilistic performance for users in each state of the system. This is a standard approach used by the research community to calculate the steady-state probability vector. References [10], [16], and [40] can be referred for further details.

1) THE INTENDED RECEIVER'S ACCESSIBILITY

RxA is integrated in the CTMC model. To this end, let Pr_{R_1} be the probability denoting that RxA is guaranteed. By formulation,

$$\begin{aligned}Pr_{R_1}&=1-\text{receiver's inaccessibility}\\&=1-\sum_{\substack{z\in Z,\ B^{idle}>0;\\ Rx_S(\boldsymbol{x})=0}}\pi_z,\end{aligned} \tag{5}$$

where $Rx_S(\boldsymbol{x})=0$ shows that Rx_S is inaccessible in state $\boldsymbol{x}$. The value of $Rx_S(\boldsymbol{x})$ is determined by Eqs. (2) and (3). The summation sign with the given states listed in the equation means that all the states where an idle channel is available, but the intended receiver is not accessible are summed up. The consequent probability becomes the receiver's inaccessibility, which is subtracted from 1 to get the receiver's accessibility. This way, we are dealing with the problem very realistically and with logical mathematical modeling.

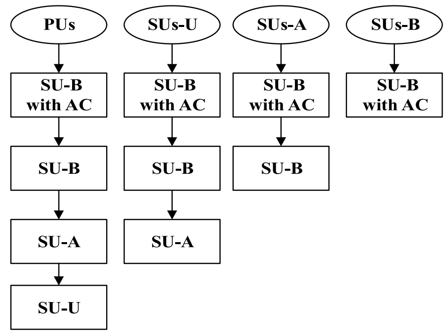

FIGURE 4. The interruption order followed by various users for channel access.

It is worth noting that in Table 5 we are interested only in those cases where Rx_S is inaccessible and have skipped mentioning all other states/activities, which is why the number of transitions listed therein seems small.

III. PERFORMANCE METRICS

The considered KPIs are formulated in the following.

A. USERS' CAPACITY

We use the term capacity to denote the average number of services that complete their sessions per unit time [40]. This way, the capacity of SU-U is expressed as,

$$CAP_{R1}=\sum_{z\in Z,Rx_S=1}j_0\mu_S\pi_z=\sum_{z\in Z}j_0\mu_S\pi_z-\sum_{z\in Z,Rx_S=0}j_0\mu_S\pi_z. \tag{6}$$

In the above equation, the first term, i.e., $\sum_{z\in Z}j_0\mu_S\pi_z$ indicates the summation of all the states where incoming SU-U is served or admitted by assigning it resources. The second term, i.e., $\sum_{z\in Z,\ Rx_S=0}j_0\mu_S\pi_z$ indicates all the states where incoming SU-U is assigned resources but the intended receiver is inaccessible.

Similarly, the capacity of SUs-A is calculated by

$$CAP_1=\sum_{z\in Z,Rx_S=1}j_1\mu_S\pi_z=\sum_{z\in Z}j_1\mu_S\pi_z-\sum_{z\in Z,Rx_S=0}j_1\mu_S\pi_z, \tag{7}$$

In the above equation, the first term, i.e., $\sum_{z\in Z}j_1\mu_S\pi_z$ indicates the summation of all the states where incoming SU-A is served or admitted by assigning it resources. The second term, i.e., $\sum_{z\in Z,\ Rx_S=0}j_1\mu_S\pi_z$ indicates all the states where incoming SU-A is assigned resources but the intended receiver is inaccessible.

In the same way, the capacity of SUs-B is given by

$$\begin{aligned}CAP_2=&\sum_{k=n,z\in Z,Rx_S=1}^{m}kj_k\mu_S\pi_z=\sum_{k=n,z\in Z}^{m}kj_k\mu_S\pi_z\\&-\sum_{k=n,z\in Z,Rx_S=0}^{m}kj_k\mu_S\pi_z.\end{aligned} \tag{8}$$

TABLE 4. The STRT concerning PUs' and SUs' arrivals and departures. $Rx_S = 1$ wherever applicable.

Activity	Condition	Destination state	Transition Rate
1. A PU needs channel. A reserved idle channel is utilized.	$B^{idle} > 0, a < B_{rp}$	$Z'(a+1, j_0, j_1, j_a, j_b)$	c'^*
2. A PU needs channel. An unreserved idle channel is utilized.	$B^{idle} > 0, B_{rp} \le a < B$	$Z'(a+1, j_0, j_1, j_a, j_b)$	a'^*
3. A PU needs channel. No idle channel is available. An SU-B with ACs releases a channel.	$B^{idle} = 0, j_a > 0$	$Z'(a+1, j_0, j_1, j_a-1, j_b+1)$	c'^*
4. A PU needs channel. No idle channel is available. An SU-B is dropped following (1).	$B^{idle} = j_a = 0,\ j_b > 0$	$Z'(a+1, j_0, j_1, j_a, j_b-1)$	c'^*
5. A PU needs channel. No idle channel is available. An SU-A is dropped following (1).	$B^{idle} = j_a = j_b = 0, j_1 > 0$	$Z'(a+1, j_0, j_1-1, j_a, j_b)$	c'^*
6. A PU needs channel. No idle channel is available. An SU-U is dropped following (1).	$B^{idle} = 0, j_a = j_b = j_1 = 0, j_0 > 0$	$Z'(a+1, j_0-1, j_1, j_a, j_b)$	c'^*
7. A PU departs.	$a > 0$	$Z'(a-1, j_0, j_1, j_a, j_b)$	$a\mu_P$
8. An SU-U needs channel. An idle channel is utilized. Rx_S is accessible.	$B^{idle} > 0, j_0 < B_1', Rx_S = 1$	$Z'(a, j_0+1, j_1, j_a, j_b)$	λ_S
9. An SU-U needs channel. No idle channel is available. An SU-B with ACs releases a channel. Rx_S is accessible.	$B^{idle} = 0, j_a > 0, Rx_S = 1$	$Z'(a, j_0+1, j_1, j_a-1, j_b+1)$	λ_S
10. An SU-U needs channel. No idle channel is available. An SU-B is dropped following (1). Rx_S is accessible.	$B^{idle} = j_a = 0, j_0 < B_1', j_b > 0, Rx_S = 1$	$Z'(a, j_0+1, j_1, j_a, j_b-1)$	λ_S
11. An SU-U needs channel. No idle channel is available. An SU-A is dropped following (1). Rx_S is accessible.	$B^{idle} = j_a = j_b = 0, j_0 < B_1', j_1 > 0, Rx_S = 1$	$Z'(a, j_0+1, j_1-1, j_a, j_b)$	λ_S
12. An SU-U departs.	$j_0 > 0, Rx_S = 1$	$Z'(a, j_0-1, j_1, j_a, j_b)$	$j_0\mu_S$
13. An SU-A needs and utilizes an idle channel. Rx_S is accessible.	$B^{idle} > 0, j_1 < B_1, Rx_S = 1$	$Z'(a, j_0, j_1+1, j_a, j_b)$	λ_S
14. An SU-A needs channel. No idle channel is available. An SU-B with ACs loses a channel. Rx_S is accessible.	$B^{idle} = 0, j_1 < B_1, j_a > 0, Rx_S = 1$	$Z'(a, j_0, j_1+1, j_a-1, j_b+1)$	λ_S
15. An SU-A needs channel. No idle channel is available. An SU-B is dropped following (1). Rx_S is accessible.	$B^{idle} = j_a = 0, j_1 < B_1, j_b > 0, Rx_S = 1$	$Z'(a, j_0, j_1+1, j_a, j_b-1)$	λ_S
16. An SU-A departs.	$j_1 > 0, Rx_S = 1$	$Z'(a, j_0, j_1-1, j_a, j_b)$	$j_1\mu_S$
17. An SU-B needs channel. m idle channels are utilized in aggregation. Rx_S is accessible.	$B^{idle} > 0, mj_a + nj_b < B, Rx_S = 1$	$Z'(a, j_0, j_1, j_a+1, j_b)$	λ_S
18. An SU-B needs channel. No idle channel is available. An SU-B with ACs releases a channel. Rx_S is accessible.	$B^{idle} = 0, j_a > 0, Rx_S = 1$	$Z'(a, j_0, j_1, j_a-1, j_b+1)$	λ_S
19. An SU-B with ACs departs.	$j_a > 0$	$Z'(a, j_0, j_1, j_a-1, j_b)$	$j_2\mu_S$
20. An SU-B departs.	$j_b > 0$	$Z'(a, j_0, j_1, j_a, j_b-1)$	$j_2\mu_S$
$*a' = \frac{B-(a+j_0+j_1+j_2)}{(B-a)}(k-a)\lambda_P$		$*c' = (k-a)\lambda_P$	

TABLE 5. The STRT concerning SUs' arrivals and departures. $Rx_S = 0$ for all the events..

Activity	Condition	Destination state	Transition Rate
1. An SU-U needs channel. An occupiable channel exists. Rx_S is inaccessible.	$B^{idle} > 0,\ j_0 < B_1', Rx_S = 0$	$Z'(a, j_0+1, j_1, j_a, j_b)$	λ_S
2. An SU-U needs channel. No occupiable channel is available. An SU-B with ACs releases a channel. Rx_S is inaccessible.	$B^{idle} = 0, j_a > 0, Rx_S = 0$	$Z'(a, j_0+1, j_1, j_a-1, j_b+1)$	λ_S
3. An SU-U needs channel. No occupiable channel is available. An SU-B is dropped following (1). Rx_S is inaccessible.	$B^{idle} = j_a = 0, j_0 < B_1', j_b > 0, Rx_S = 0$	$Z'(a, j_0+1, j_1, j_a, j_b-1)$	λ_S
4. An SU-U needs channel. No occupiable channel is available. An SU-A is dropped following (1). Rx_S is inaccessible.	$B^{idle} = j_a = j_b = 0, j_0 < B_1', j_1 > 0; Rx_S = 0$	$Z'(a, j_0+1, j_1-1, j_a, j_b)$	λ_S
5. An SU-A needs channel. An occupiable channel is available. Rx_S is inaccessible.	$B^{idle} > 0,\ j_1 < B_1, Rx_S = 0$	$Z'(a, j_0, j_1+1, j_a, j_b)$	λ_S
6. An SU-A needs channel. No occupiable channel is available. An SU-B with ACs releases a channel. Rx_S is inaccessible.	$B^{idle} = 0,\ j_1 < B_1,\ j_a > 0, Rx_S = 0$	$Z'(a, j_0, j_1+1, j_a-1, j_b+1)$	λ_S
7. An SU-A needs channel. No occupiable channel is available. an SU-B is dropped following (1). Rx_S is inaccessible.	$B^{idle} = j_a = 0, j_1 < B_1, j_b > 0, Rx_S = 0$	$Z'(a, j_0, j_1+1, j_a, j_b-1)$	λ_S
8. An SU-B needs channel. m idle channels are utilized in aggregation. Rx_S is inaccessible.	$B^{idle} > 0, (mj_a + nj_b) < B_{r2}, Rx_S = 0$ OR $B^{idle} > 0, j_a > 0, j_b > 0, (mj_a + nj_b) < B_{r2}, Rx_S = 0$	$Z'(a, j_0, j_1, j_a+1, j_b)$	λ_S
9. An SU-B needs channel. No occupiable channel is available. An SU-B with ACs releases a channel. Rx_S is inaccessible.	$B^{idle} = 0, j_a > 0, Rx_S = 0$	$Z'(a, j_0, j_1, j_a-1, j_b+1)$	λ_S

In the above equation, the first term, i.e., $\sum_{k=n,\, z\in Z}^{m} kj_k\mu_S\pi_z$ indicates the summation of all the states where incoming SU-B is served or admitted by assigning it resources. The second term, i.e., $\sum_{k=n,\, z\in Z,\, Rx_S=0}^{m} kj_k\mu_S\pi_z$ indicates all the states where incoming SU-B is assigned resources but the intended receiver is inaccessible.

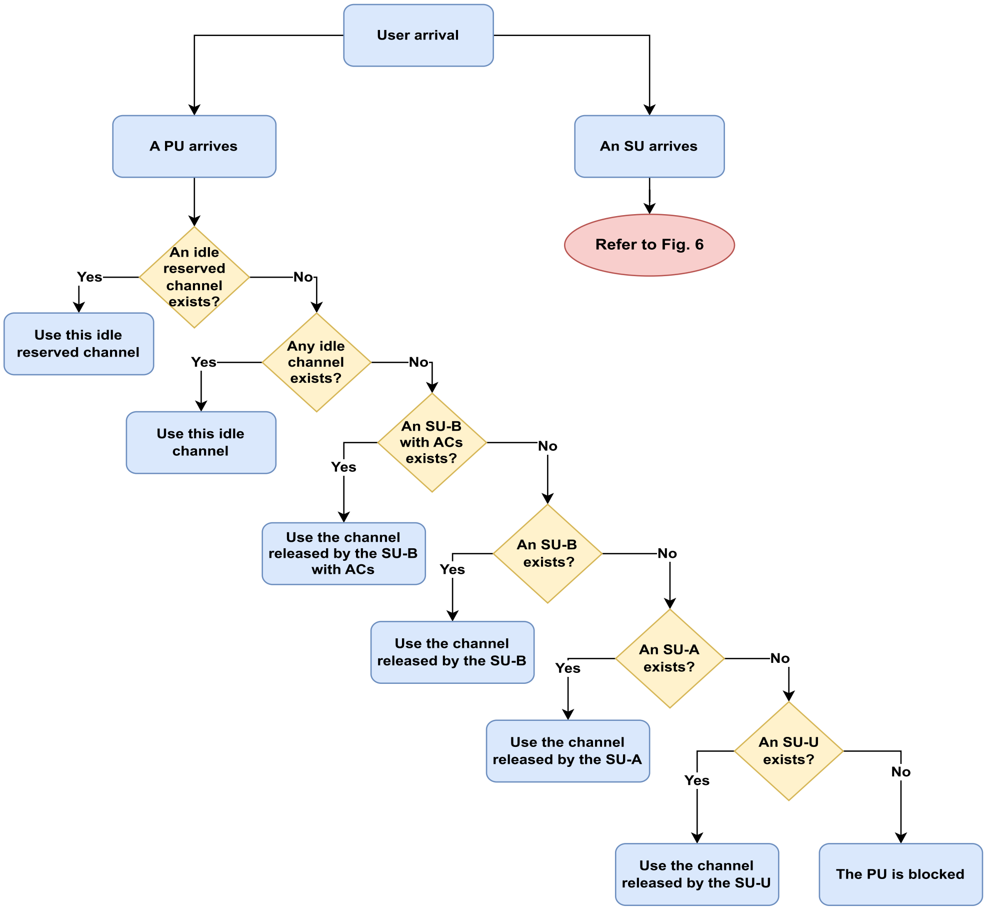

FIGURE 5. The high-level description of the proposed priority-based channel occupation for PUs.

B. SPECTRUM UTILIZATION

Spectrum utilization is defined as the amount of spectrum that is under utilization out of the total allocated spectrum [1]. Spectrum utilization is given by

$$U' = \sum_{z \in Z, Rx_S=1} \frac{B_x}{B}\pi_z = \sum_{z \in Z} \frac{B_x}{B}\pi_z - \sum_{z \in Z, Rx_S=0} \frac{B_x}{B}\pi_z, \quad (9)$$

The equation implies that all the values in the steady-state probability matrix where the ratio B_x/B is non-zero and the intended receiver is accessible are added to calculate U'. B_x and B represent the total number of occupied channels and the total number of assigned channels to the network, respectively.

C. BLOCKING PROBABILITY

The expressions for BPs for SU-U, SU-A, and SU-B are respectively given by Eqs. (10), (11), and (12).

$$P'_{bR1} = \lambda_S \sum_{\substack{a=0,\, z \in Z; \\ B_x=B,\, j_1=j_a=j_b=0}}^{B} \frac{\pi_z}{(k-a)\lambda_P + \lambda_S}. \quad (10)$$

The equation implies that SU-U is blocked on its arrival if all the channels are occupied and there is no SU-A or SU-B exists.

$$P'_{b1} = \lambda_S \sum_{a=0,\, z \in Z}^{B} \sum_{\substack{j_1=0,\, B_x=B-B_{rp}, \\ j_a=j_b=0}}^{B_1} \frac{\pi_z}{(k-a)\lambda_P + \lambda_S}. \quad (11)$$

The equation implies that SU-A is blocked on its arrival if all the channels are occupied and there is no SU-B exists.

$$P'_{b2} = \lambda_S \sum_{a=0,\, z \in Z}^{B} \sum_{\substack{j_1=0,\, B_x=B-B_{rp}, \\ j_a=0}}^{B_1} \frac{\pi_z}{(k-a)\lambda_P + \lambda_S}. \quad (12)$$

The equation implies that SU-B is blocked on its arrival if all the channels are occupied and there is no SU-B with aggregated channels exists.

D. HANDOFF PROBABILITY

We define handoff probability for SUs' services to be the likelihood that, in the event of SUs' services interruptions happened due to channel failures or PUs' arrivals, at least one vacant channel or low priority service is available to be used for channel handoff [11], [16]. By utilizing Table 4 and Table 5, it can be shown that the HPs of SU-U, SU-A, and

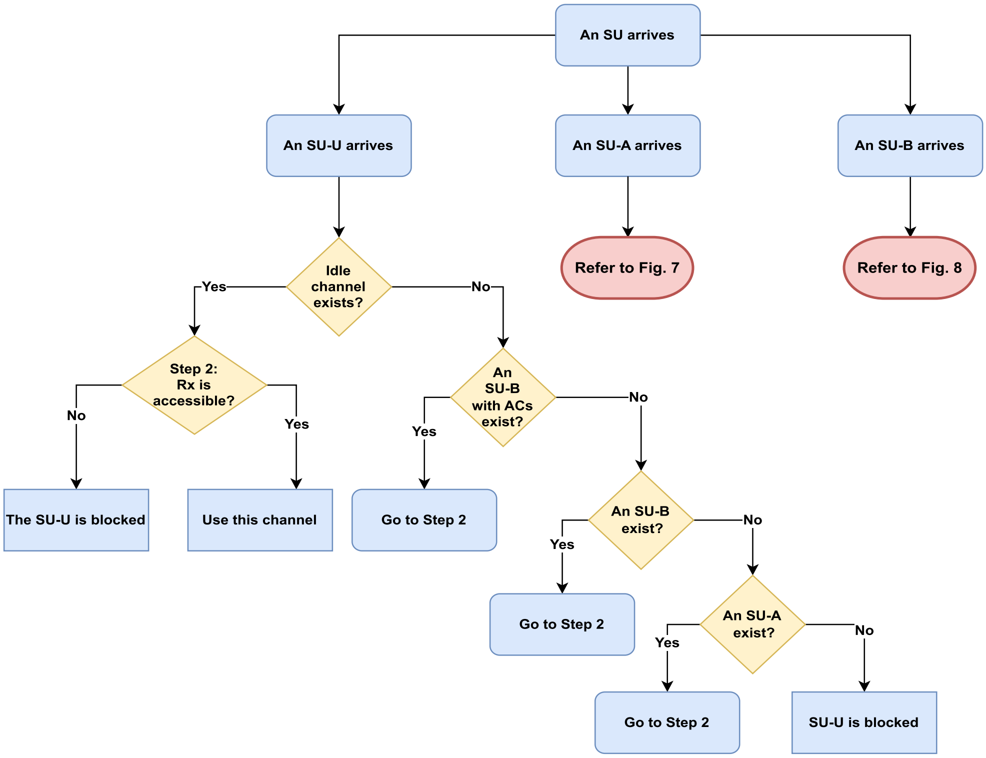

FIGURE 6. The high-level description of the proposed priority-based channel occupation for SU-Us.

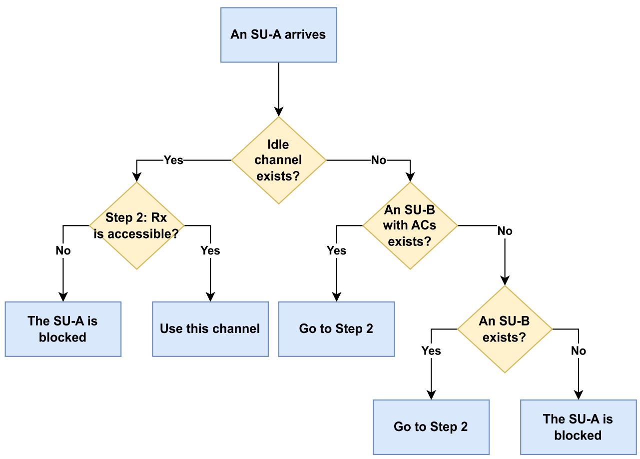

FIGURE 7. The high-level description of the proposed priority-based channel occupation for SU-As.

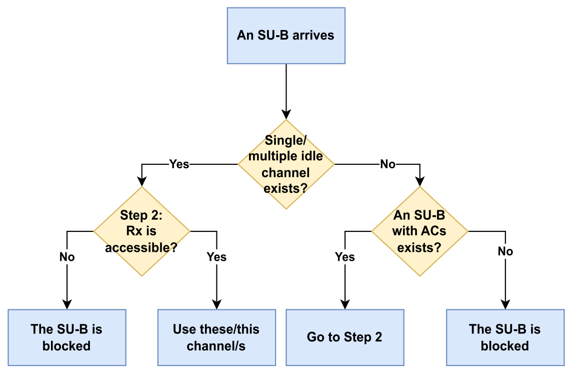

FIGURE 8. The high-level description of the proposed priority-based channel occupation for SU-Bs.

SU-B are respectively expressed in Eqs. (13), (14), and (15).

$$P'_{hR1} = \frac{\lambda_P}{(1-P'_{bR1})}\Bigg\{ \sum_{\substack{a=B_{rp},\ z\in Z;\\ B_x<B;\\ B_x=B,j_a>0;\\ B_x=B,j_a=0j_b>0;Rx_S=1}}^{B} \frac{\frac{j_0}{(B-a)}(k-a)\pi_z}{((k-a)\lambda_P+\lambda_S)} + \sum_{\substack{a=B_{rp},z\in Z;\\ B_x=B,j_a=j_b=0,j_1>0;Rx_S=1}}^{B} \frac{\frac{j_0}{(B-a)}(k-a)\pi_z}{((k-a)\lambda_P+\lambda_S)} \Bigg\}, \quad (13)$$

The equation implies that on the arrival of a PU, a SU-U hands-off when the band reserved for PUs (B_{rp}) is occupied or when the number of occupied channels is less than the total channels or the number of occupied channels is equal to the total channels of the network but a SU-B with aggregated channel exists or no idle channel and SU-B with aggregated channels is available, but a SU-B without aggregated channels exist.

$$P'_{h1} = \frac{\lambda_P}{(1-P'_{b1})} \sum_{\substack{a=B_{rp},\ z\in Z,\\ B_x<B;\\ B_x=B,j_a>0\\ B_x=B,j_a=0,j_b>0;Rx_S=1}}^{B} \frac{\frac{j_1}{(B-a)}(k-a)\pi_z}{((k-a)\lambda_P+\lambda_S)}, \quad (14)$$

The equation implies that on the arrival of a PU, a SU-A hands-off when the band reserved for PUs (B_{rp}) is occupied or when the number of occupied channels is less than the total channels or the number of occupied channels is equal to the total channels of the network but a SU-B with aggregated channel exists or no idle channel and SU-B with aggregated channels is available, but a SU-B without aggregated channels exist.

$$P'_{h2} = \frac{\lambda_P}{(1-P'_{b2})} \sum_{\substack{a=B_{rp},\ z\in Z,\\ B_x<B;\\ B_x=B,\, j_a>0;\ Rx_S=1}}^{B} \frac{\frac{j_2}{(B-a)}(k-a)\pi_z}{((k-a)\lambda_P+\lambda_S)}. \tag{15}$$

The equation implies that on the arrival of a PU, a SU-B hands-off when the band reserved for PUs (B_{rp}) is occupied or when the number of occupied channels is less than the total channels or the number of occupied channels is equal to the total channels of the network but a SU-B with aggregated channel exists.

E. SERVICE RETAINABILITY

Service retainability refers to the probability that a user, once provided with resources, is able to complete its session with the required quality and time. Mathematically,

$$Ret = 1 - \text{forced termination probability (FTP)}. \tag{16}$$

FTP of type 'x' users is calculated as

$$\text{FTP}_x = \frac{FTR_x}{\Lambda_x}, \tag{17}$$

where FTR_x is the forced termination rate (FTR) and Λ_x is the effective channel assignment rate of type 'x' users. FTR of SUs-U, SUs-A, and SUs-B are respectively calculated in Eq. (18), (19), and (20).

$$FTR_R = \lambda_P \sum_{\substack{a=B_{rp},\ z\in Z,\\ B_x=B, j_2=j_1=0, j_0>0}}^{B} (k-a)\pi_z, \tag{18}$$

The equation implies that on the arrival of a PU, a SU-U is interrupted/terminated when the band reserved for PUs (B_{rp}) is occupied or when the number of occupied channels is equal to the total number of channels, there is no active SU-A or SU-B exists but at least one SU-U exists.

$$FTR_{S_1} = \lambda_P \sum_{\substack{a=B_{rp},\ z\in Z,\\ B_x=B, j_2=0, j_1>0}}^{B} (k-a)\pi_z + \lambda_{S_R} \sum_{\substack{z\in Z, B_x=B,\\ j_2=0,\ j_1>0}}^{B} \frac{\pi_z}{(k-a)\lambda_P+\lambda_S}, \tag{19}$$

The equation implies that a SU-A is terminated upon a PU arrival when all the channels are occupied within the band dedicated for PUs, i.e., B_{rp}, or all the channels are occupied in the network and there is no SU-B exists but at least one SU-A exists. In the second term of the equation, the same holds, as that for PU, for SU-U arrival.

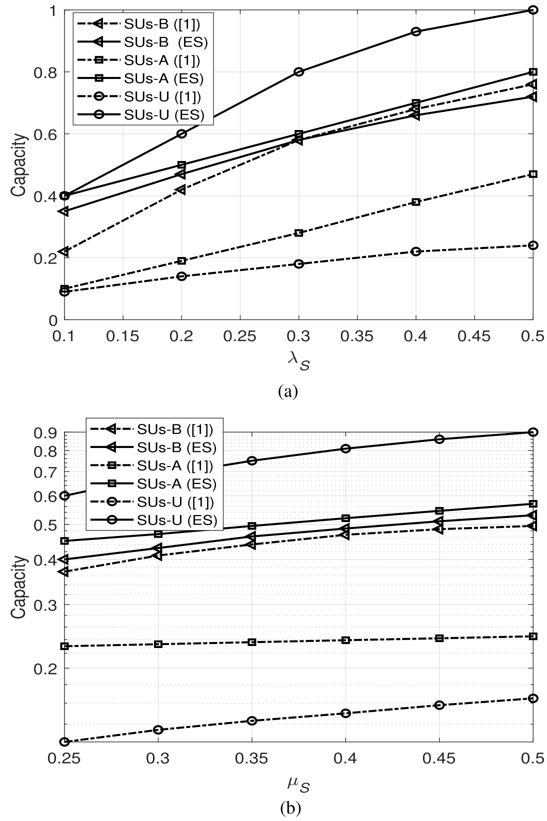

FIGURE 9. Capacity as a function of (a) λ_S and (b) μ_S.

$$FTR_{S_2} = \lambda_P \sum_{\substack{a=B_{rp},\ z\in Z,\\ j_1>0, B_x=B, j_2=0}}^{B} (k-a)\pi_z + \lambda_{S_R} \sum_{\substack{z\in Z, B_x=B\\ j_2>0}}^{B} \frac{\pi_z}{(k-a)\lambda_P+\lambda_S} + \lambda_{S_1} \sum_{z\in Z, B_x=B, j_2>0}^{B} \frac{\pi_z}{(k-a)\lambda_P+\lambda_S}. \tag{20}$$

The equation implies that a SU-B is terminated upon a PU arrival when all the channels are occupied within the band dedicated for PUs, i.e., B_{rp}, or all the channels are occupied in the network and there is no SU-B exists. In the second term of the equation, the same holds, as that for PU, for SU-U arrival. While in the third term, the same holds for SU-A. λ_{S_1} and λ_{S_R} are the arrival rates of SUs-A and SUs-U, respectively. So, service retainabilities for SU-U, SU-A, and SU-B are respectively calculated as

$$Ret_R = 1 - \frac{FTR_R}{\Lambda_{S_R}}, \tag{21}$$

$$Ret_{S_1} = 1 - \frac{FTR_{S_1}}{\Lambda_{S_1}}, \tag{22}$$

$$Ret_{S_2} = 1 - \frac{FTR_{S_2}}{\Lambda_{S_2}}, \tag{23}$$

where Λ_{S_R}, Λ_{S_1}, and Λ_{S_2} are the channel assignment rate for SUs-U, SUs-A, and SUs-B, respectively [11].

TABLE 6. List of parameters with their default configurations.

Parameter	Value	Parameter	Value
B	7	$B_{rp_{max}}$	4
$B_{r2},\ B_1^{'}$	1	n	1
k	10	m	2
λ_P	0.05	μ_P	0.4
μ_S	0.5	λ_S	0.25

IV. NUMERICAL RESULTS

We compare ES with the scheme presented in [1] and [41] through numerical results. To this end, the list of parameters with their configurations given in Table 6 are assumed in most of the results. For performance analysis, capacity, BP, spectrum utilization, and HP are considered. It is worth noting that the baseline scheme proposed in [1] is also considering prioritized access of IoT devices to resources and have leveraged CTMC modeling, which makes it the right choice for comparison with ES. Similarly, the scheme presented in [41] leverages a machine learning algorithm and is suitable for comparison with ES. It is also important to mention that m and n used in the proposed CTMC model are generic that can assume any combination of values with $m < n$. In our analysis, we have used its value as shown in Table 6.

In Fig. 9, the capacities of SUs are given against λ_S and μ_S. Fig. 9a shows that the capacities of SUs-U and SUs-A have drastically increased in ES as compared to [1] when plotted with respect to λ_S. For example, in SUs-U performance, a significant increase of 74% is noticed. Similarly, the capacity of SUs-B has marginally increased compared to [1]. Fig. 9b shows the capacities as a function of μ_S wherein nearly the same trend can be seen as observed in Fig. 9a. Additionally, the minor down performance of SUs-B in ES compared to [1] noticed in 9a is avoided in Fig. 9b.

Fig. 10 shows the spectrum utilization profile of the network. As shown in Fig. 10a, ES substantially enhances the spectrum utilization as compared to [1], and the difference in their performance increases with increasing λ_S. This is because, as more users become active in the network, more channels are utilized, which translates to larger spectrum utilization. Since ES follows the proposed approach for users in channel access, the channels are better utilized compared to other schemes, leading to a maximum of 26% improvement compared to [1]. In the same fashion, Fig. 10b shows that spectrum utilization is considerably enhanced in ES compared to [1] when plotted with respect to μ_S. Spectrum utilization generally decreases as user service rates increase, implying that as more and more users are served at a given rate of user arrivals, more spectrum becomes available or not utilized, resulting in a decreasing value of spectrum utilization. Fig. 10c shows the impact of considering RxA on spectrum utilization. It is observed that when RxA is considered, spectrum utilization yields lower values than when RxA is ignored, and the difference increases with an increase in λ_S and μ_S.

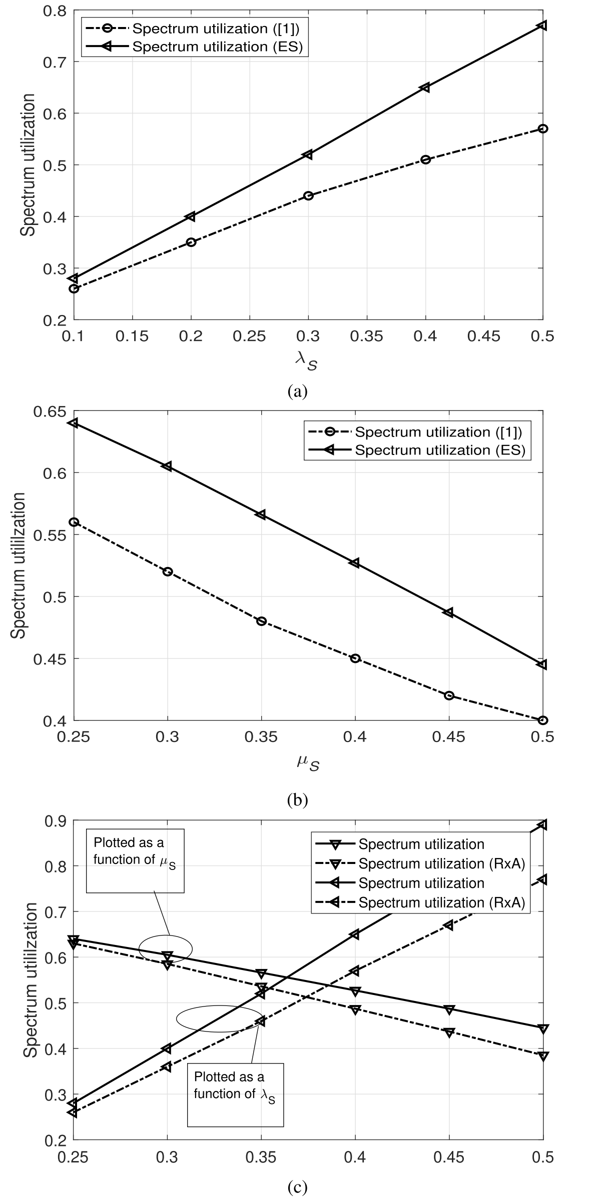

FIGURE 10. Spectrum utilization as a function of (a) λ_S, (b) μ_S, and (c) both λ_S and μ_S with RxA considered.

Fig. 11 shows BPs of SUs plotted as functions of λ_S and μ_S. It is shown in Fig. 11a that, when plotted relative to λ_S, the BP of SUs-U is significant while that of SUs-A is marginally mitigated in ES compared to [1]. For example, in SUs-U performance, a significant improvement of 43% is recorded in ES compared to [1]. For SUs-B, the BP in both the schemes are equal before $\lambda_S < 0.3$. Afterward, a gradual yet at the small level increase in the BP of SUs-B in ES is witnessed compared to [1]. In Fig. 11b, SUs-U attain a substantial, SUs-A a reasonable, and SUs-B a minor enhancement in BP in ES compared to [1].

Fig. 12a shows HPs plotted with respect to λ_S. It can be seen that HPs of all the user types increase with increasing λ_S. However, ES reduces the HPs of all the user types as compared to [1]. This reduction is more pronounced for

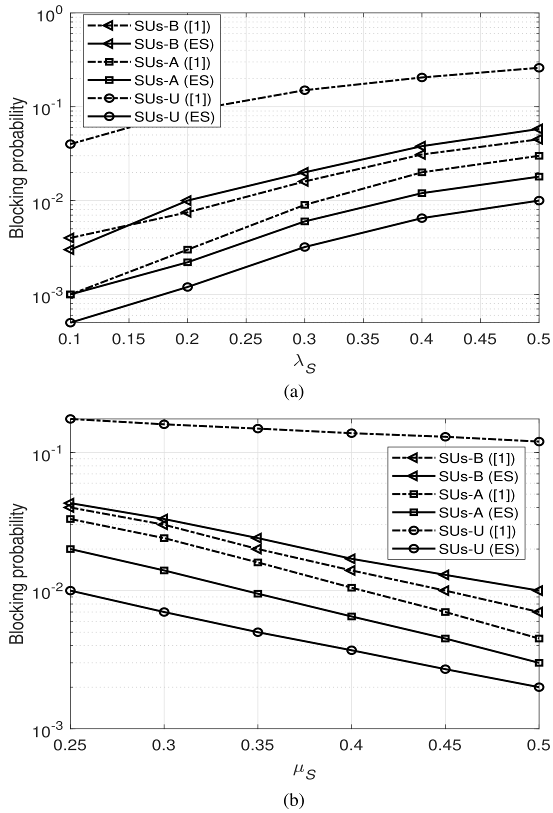

FIGURE 11. BP as a function of (a) λ_S and (b) μ_S.

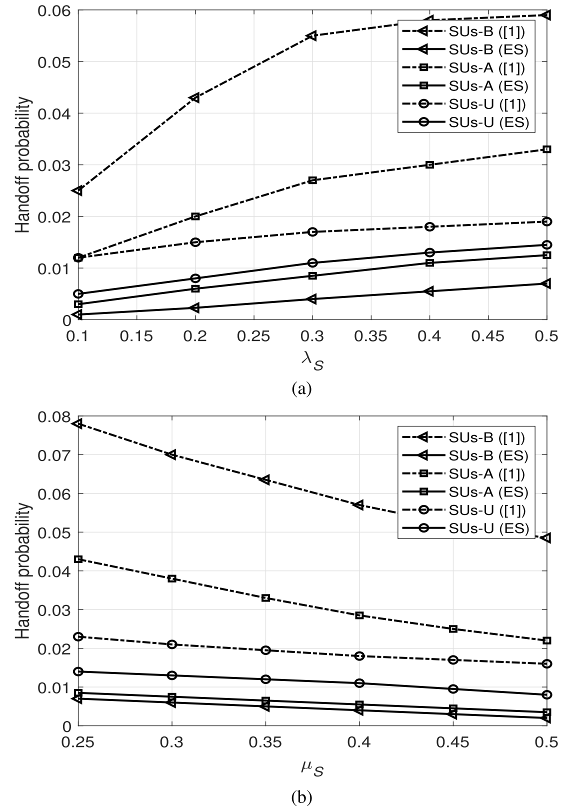

FIGURE 12. HP as a function of (a) λ_S and (b) μ_S.

SUs-B. Interestingly, SUs-B has the highest HPs in [1], whereas in ES, they exhibit the lowest HPs. For example, in SUs-B performance, a significant reduction of up to 88% is observed in ES compared to [1]. Similarly, Fig. 12b indicates that HPs of all types of users decrease with increasing μ_S. Again, ES reduces HPs substantially for all users compared to [1]. This reduction is particularly noticeable for SUs-B, where the impact is more pronounced.

The reasons for the better performance of ES compared to [1] are as follows. The DSR algorithm utilized by ES leads to better utilization of the available channels by reserving only the minimum required number of channels in B_{rp}. Consequently, a larger number of channels become available for SUs to utilize in ES as compared to [1]. Likewise, the efficient prioritization approach adopted by ES leads to better channel access privileges among SUs. Together with this, ES flexibly organizes the bands and manipulates the conditions set for utilizing a specific band by SUs belonging to other bands. Moreover, ES takes advantage of the systematic approach used for users to access channels and to determine the optimal SU for dropping.

Fig. 13a shows the impact of RxA on the users' performance by plotting the SUs' BPs with respect to λ_P. It is shown that BPs increase with various scales for different SUs when RxA is considered. This is because RxA also takes into account the availability of the intended receiver in addition to the resource allocation. In the conventional evaluation, RxA is overlooked, which causes the analysis to reflect improved yet unrealistic values compared to the analysis performed under RxA consideration. Similarly, Fig. 13b shows the impact of RxA on the users' capacity when plotted with respect to λ_S. It is shown that when RxA is considered, the capacities do not increase at the scale; instead, capacities increase when RxA is not taken into account. This is because RxA also takes into account the availability of the intended receiver in addition to the resources allocation. In the conventional evaluation, RxA is overlooked which causes the analysis to reflect improved yet unrealistic values compared to analysis performed under RxA consideration.

Fig. 14a shows the retainability and BP relationship created by the spectrum reservation. It can be seen that BP increases while retainability decreases with an increase in λ_P at the given configurations of the reserved bands. However, when the configurations change, their proportionality of change also varies. For example, when $B_{rp_{max}}$ is increased to 5, as shown in Fig. 14b, service retainability is affected more rapidly than BP. This indicates that spectrum reservation has a significant impact on the users' performance and that it can be used to achieve a conformable and favorable tradeoff between BP and retainability. For instance, at a given value of λ_P and the desirable level of tradeoff between BP and retainability, the optimal value of $B_{rp_{max}}$ can be determined and adjusted.

Fig. 15 shows the divergence observed in SUs' FTP in ES. Four instances of FTP that occurred to the users of each type of SUs are presented in the figure. It can be seen that there is a negligible amount of divergence in the users' FTP belonging

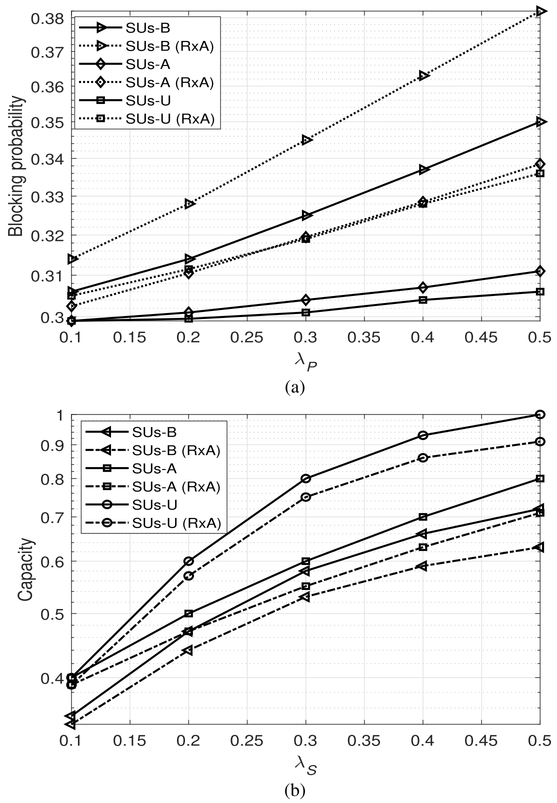

FIGURE 13. BP as a function of λ_P and (b) capacity as a function of λ_S, with and without considering RxA.

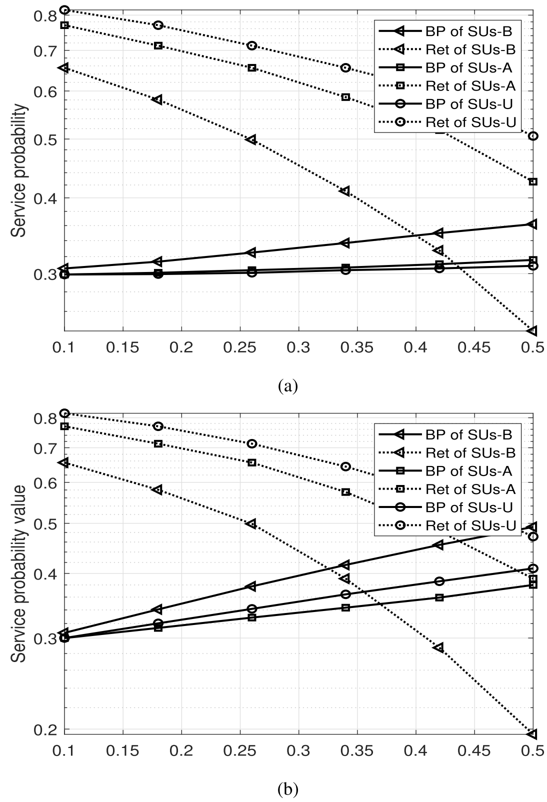

FIGURE 14. *Ret* and BP tradeoff plotted as a function of λ_P. In (a) $B_{rpmax} = 4$ and in (b) $B_{rpmax} = 5$.

to a particular type of SUs. For instance, up to 0.018 standard deviations is noted among SUs-B, up to 0.022 in SUs-A, and up to 0.013 in SUs-U. This indirectly implies that SUs' get fairness in service availment, which leads to reliability, predictability, and better users satisfaction and trust.

Fig. 16 presents a performance comparison between ES and the scheme presented in [41], referred to as competing scheme hereafter, by plotting HP as functions of λ_S. It is worth noting that the competing scheme employs a support vector machine, a machine learning-based algorithm, to assist users in predicting, sensing, and using only those channels that are most suitable for transmission. It can be witnessed that ES performs better than the competing scheme, and all three types of SUs have lower values of HP than SUs in the competing scheme. The reason is that ES assumes perfect spectrum sensing, while the competing scheme is based on imperfect spectrum sensing. Secondly, ES follows a hierarchical and reservation-based approach in channel selection and search, while users in the competing scheme select channels from all over the available band.

A. DISCUSSION

The proposed work provides the basis for fine-grained analyses of multi-tier heterogeneous users in CR-SIoT. Additionally, it provides insights into the efficient tackling of the users' heterogeneity, the efficient utilization of the available spectrum, and the reliable performance analysis of CR-SIoT.

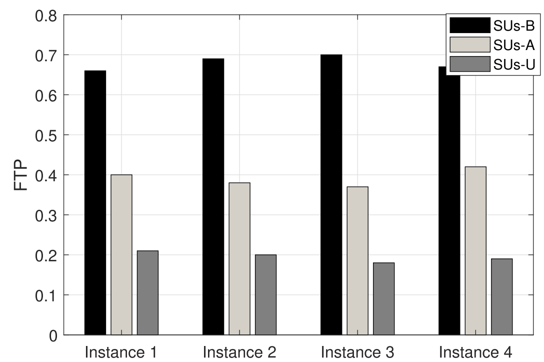

FIGURE 15. The degree of divergence in SUs' FTP.

This work can be used to precisely model the network performance in future CR-SIoT. Additionally, it can be used for extensively connected cities and societies; especially, the internet of drones, industrial internet of things, and vehicular networks can benefit significantly. Moreover, by accommodating more users within the limited spectrum, it can assist in the realization of massive machine-type communication and denser networks, thereby enabling real-time mandating applications like virtual reality, augmented reality, and machine-learning applications.

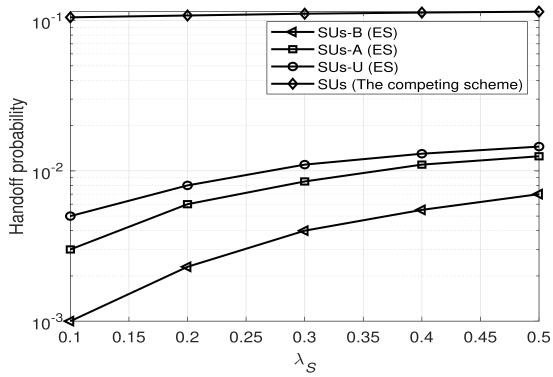

FIGURE 16. **HP comparison between ES and the competing scheme.**

This work has a few limitations. First, the Markov chain model yields probabilistic results that further need to be validated in the real-world environment. Second, the model suits Poisson arrivals of users and cannot be comfortably used with the bursty nature of user arrivals. Third, in the future, a greater variety of users in terms of quality of service demands will be observed, which is nearly impractical to model with Markov model.

V. CONCLUSION

With the aim to enhance spectrum availability for IoT users, in this paper, we have proposed a novel scheme targeting a multi-priority and heterogeneous framework of users and reservation-based spectrum management and allocation regime in CR-enable IoT. The scheme exploits the SUs' heterogeneousness with respect to their priorities to enhance their performance. Besides, the scheme methodically tackles SUs' interruption to reduce differences in their service levels. Additionally, it ensures an organized approach for PUs in accessing channels to mitigate handoff probability. Furthermore, the analysis paves the way for determining a favorable tradeoff between BP and retainability. Moreover, the scheme considers the impact of the receiver's accessibility for rendering realistic analysis. In addition, the scheme is embedded with a DSR algorithm proposed to enhance spectrum utilization. It is found that the scheme renders significant improvement when equated against the existing schemes in terms of several KPIs and provides useful insights on the tradeoff between BP and service retainability and on the impact of considering the receiver's accessibility on the system's performance, which ultimately translates to enhanced spectrum availability for IoT users. In the future, we plan to optimize the configuration of the DSR algorithm for the optimal tradeoff between retainability and BP.

The scheme has certain limitations. First, it increases complexity of the network. Second, communication overheads increase to cope with such a large communication among network nodes. Third, energy efficiency can be hampered by the scheme. Fourth, the DSR configuration has not been optimized, and possible tradeoffs between retainability and BP have not been investigated. All these are the future directions of our work.

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