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Research Article

Modeling, Simulation and Call Performance Analysis of a TDMA-Based Cognitive Radio Network with Different Slot Allocation Strategies

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ABSTRACT

Since the wireless spectrum is limited, the use of licensed channels for secondary purposes is seen as an important solution to the spectrum scarcity problem. The objective of the work presented in this paper is to model, develop and analyze a cognitive radio network in which secondary users (SUs) utilize opportunistically available spectrum holes of the primary network. In the proposed network model, it is assumed that primary users (PUs) are licensed users and have a higher priority in access to the channel than secondary users and thereby are unaffected by the SUs' channel utilization. PUs employ Time Division Multiple Access as a channel access mechanism and secondary users use the time slots unoccupied by the PUs. Three slot allocation strategies for Cognitive Radio (CR) networks: non-slot-handoff strategy, slot-handoff strategy, and slot-reservation strategy are developed, modeled, and simulated by using Riverbed Modeler simulation software. Moreover, channel access performances of these three strategies in terms of call block, call drop and call handoff probabilities are analyzed. According to the extensive simulation results, the non-slot-handoff strategy gives the lowest call block probability while the slot-reservation strategy provides the lowest call drop probability. When the SUs' offered load is 0.05, the slot-reservation strategy gives 1.75 times better call drop probability results than those of the slot-handoff strategy. However, for the same offered load, the non-slot-handoff strategy gives 2.26 times better call block probability results compared to the slot-reservation strategy.

Keywords: *Cognitive radio, medium access control, TDMA, channel allocation*

TDMA Tabanlı Bilişsel Radyo Ağının Farklı Zaman Dilimi Tahsis Stratejileri için Modellenmesi, Simülasyonu ve Çağrı Performans Analizi

ÖZET

Kablosuz spektrum sınırlı olduğundan lisanslı kanalların ikincil amaçlarla kullanılması spektrum kıtlığı sorununa önemli bir çözüm olarak görülmektedir. Bu makalede sunulan çalışmanın amacı, ikincil kullanıcıların birincil ağın mevcut spektrum boşluklarını fırsatçı olarak kullandığı bir bilişsel radyo ağını modellemek, geliştirmek ve analiz etmektir. Önerilen ağ modelinde, birincil kullanıcıların lisanslı kullanıcılar olduğu ve kanala erişimde ikincil kullanıcılara göre daha yüksek önceliğe sahip oldukları ve dolayısıyla ikincil kullanıcıların kanal kullanımından etkilenmedikleri varsayılmaktadır. Birincil

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kullanıcılar kanal erişim mekanizması olarak Zaman Bölmeli Çoklu Erişimi tekniğini, ikincil kullanıcılar ise birincil kullanıcılar tarafından kullanılmayan zaman aralıklarını kullanmaktadır. Bilişsel Radyo ağı için üç slot tahsis stratejisi: spektrum el-değiştirmesiz slot-tahsis stratejisi, spektrum el-değiştirmeli slot-tahsis stratejisi ve slot-rezervasyon stratejisi Riverbed Modeler benzetim yazılımı kullanılarak geliştirilmiş, modellenmiş ve benzetimi gerçekleştirilmiştir. Ayrıca bu üç stratejinin çağrı bloke, çağrı düşme ve çağrı el-değiştirme olasılıkları açısından kanal erişim başarımları analiz edilmiştir. Kapsamlı benzetim sonuçlarına göre, spektrum el-değiştirmesiz slot-tahsis stratejisi en düşük çağrı bloke olasılığı, slot-rezervasyon stratejisi en düşük çağrı düşme olasılığı vermektedir. İkincil kullanıcı yükü 0,05 olduğunda, slot-rezervasyon stratejisi, spektrum el-değiştirmeli slot-tahsis stratejisine göre 1,75 kat daha iyi çağrı düşme olasılığı sonuçları vermiştir. Bununla birlikte, sunulan aynı yük için, spektrum el-değiştirmesiz slot-tahsis stratejisi, slot-rezervasyon stratejisi ile karşılaştırıldığında 2,26 kat daha iyi çağrı bloke olasılığı sonuçları vermektedir.

Anahtar Kelimeler: *Bilişsel radyo, orta erişim kontrolü, TDMA, kanal tahsisi*

I. INTRODUCTION

Over the past few years, as new communication systems and technologies emerge at an exponential rate, wireless communication systems have become more and more prevalent. With this rapid prevalence of wireless devices and systems, the spectrum scarcity problem has been exposed. Since traditional spectrum allocation policies follow a fixed or static allocation approach, a particular wireless communications system is entitled to exclusive use of certain spectrum resources [1]-[4]. Nevertheless, some parts of the spectrum resources allocated to licensed users also known as primary users (PUs) may not be utilized efficiently. Furthermore, the use of the licensed spectrum may also be dependent on place or time [2]-[7]. Accordingly, the spectrum that is limited and not efficiently utilized by PUs requires new management techniques in order to maximize its utilization. Cognitive Radio (CR) has been put forward as a way to exploit the inefficiently used licensed spectrum and is considered as a promising technology to alleviate the spectrum scarcity problem for wireless communications [2]-[8]. CR networks can improve the efficiency of the spectrum significantly by temporarily using licensed spectrum without interfering with PUs. These networks provide CR users also called as SUs the opportunity to exploit the available (vacant) spectrum gaps when the PUs are not in their active transmission mode. The CR users identify and access vacant portions of the spectrum, also known as spectrum holes, while ensuring that they do not interfere with the communications of the PUs. Therefore, the primary goal of CR networks is to increase the efficiency of the existing spectrum by utilizing the gaps in the entire spectrum on a temporary basis [9]-[10].

There are some fundamental concepts that a CR network must follow in order to be managed successfully, which are spectrum sensing, spectrum access, spectrum mobility, and spectrum sharing [11]. Spectrum sensing operation measures, senses, and is aware of some of the wireless environment parameters such as spectrum availability and channel characteristics. This allows CR networks to identify unused portions of the spectrum and dynamically adapt their transmissions to avoid any interference. There are several methods that are commonly used in spectrum sensing, including energy detection, waveform-based, cyclostationary-based, and cooperative sensing [11]. Each of these methods has its own advantages, disadvantages, and specific performance characteristics. In spectrum access, decisions are made as to which channels are utilized taking into account a number of factors, such as the channel quality and interference levels, and CRs can dynamically allocate and employ these available channels [11]. It is important for CR users to be capable of adapting to changing spectrum conditions and user requirements. Spectrum mobility entails the capacity to switch to different channels in accordance with the availability of spectrum resources, or to evade interference caused by PUs. Spectrum management in CR networks requires the establishment of policies and protocols for spectrum sharing. Spectrum-sharing policies may involve cooperation and other mechanisms for allocating spectrum resources between multiple CR users.

In this paper, a wireless network with a more realistic scenario containing two classes of users, namely PUs and CRs, which use a time-slotted based common communication channel is considered. PUs are licensed users of the frequency band and have higher priority over CR users to access the given channel. PUs use TDMA as a channel access mechanism to access the channel, whereas CR users can only utilize idle channels when they are not used by the PUs. Three slot allocation strategies for CR users: non-slot-handoff strategy, slot-handoff strategy and slot-reservation strategy are developed, modeled and simulated by using Riverbed Modeler simulation software. Besides, channel access performances of these three strategies in terms of call block, call drop and call handoff probabilities are also comparatively analyzed and presented.

The remainder of the paper is organized as follows: In Section 2, related works are presented. The proposed network models which contain the primary network model and CR network model are explained in detail in Section 3. Performance analysis are given in Section 4. Simulation results and discussions are presented in Section 5 followed by conclusions in Section 6.

II. RELATED WORKS

There has been a significant amount of research conducted on the performance of CR networks. In [12] and [13], three-dimensional Markov chain models are used to analyze the call block and call drop performance of the CR network. However, in their paper, the numbers of PUs and SUs are all assumed to be infinite in order to make the analysis tractable. In [14], in order to obtain the SU blocking probability, a discrete-time Markov chain model is developed in CR Sensor Network (CRSN). Their model takes into account the effects of PUs and SUs offered loads and service rates in estimating SU blocking probability. Even though this paper discusses the secondary user (SU) call blocking probability, it does not address the call drop probability. In [15], a four-dimensional continuous-time Markov chain model is developed to evaluate the performance of CR networks. Assuming a bursty arrival process for PUs, the proposed model also considers the possibility of sensing errors (false alarms and miss detections). This paper examines the call blocking probabilities for both primary and secondary users and presents the computation of the average delay experienced by SUs by means of numerical examples for clarification. In [16], SU performance in CR networks with reactive decision spectrum handoff is studied. The main performance metrics used in this work are the SU mean delay, the SU interruption probability, the SU discarded probability, and the SU blocking probability. Two continuous-time Markov chain models are developed in order to investigate the effect of parameters such as sensing time and sensing room size on SU performance. According to the results presented by this work, the performance of SUs is primarily determined by the degree of burstiness in each PUs' arrival process. In [17], a multidimensional Markov chain with three state variables is modeled for a dynamic spectrum access scheme to compute the blocking probability and dropping probability of SUs based on the two different classes of SU traffic. In [18], a Dynamic Spectrum Access (DSA) approach is proposed as a means to dynamic channel allocation with priority in CR Sensor Networks (CRSNs) without spectrum handoff capability. The proposed CRSN provisions PUs and two types of SUs, one of which has a higher priority than the other. Performance analysis of the proposed approach in terms of the blocking probability (BP), forced termination probability (FTP), and call completion rate (CCR) for the SUs with and without priority service support in the CRSN are also presented. A three-dimensional (3D) Markov chain model is developed and analyzed in [19] for a spectrum management scheme that works in CR ad hoc networks with heterogeneous licensed bands of two different licensed spectrum pools. The model developed presents the concept of inter-pool and intra-pool spectrum handoff and derives blocking probability, dropping probability, non-completion probability, and throughput to compute the performance of SUs in heterogeneous licensed spectrum environments. The results obtained from the proposed model taking into consideration of heterogeneous environment of different licensed bands exhibit significant improvement in terms of SUs' performance in CR ad hoc networks. Some of the related works are summarized in Table 1 shown below.

Table 1. *Summary of the related literature employing Dynamic Spectrum Access in cognitive radio*

Ref.	Spectrum handover	Channel reservation	SU's priority	Buffering	Multi-channel allocation	Performance metrics
[12]	✗	✓	✗	✗	✗	SU call blocking probability, SU call dropping probability
[13]	✓	✓	✗	✗	✗	SU call blocking probability, SU call dropping probability
[14]	✓	✗	✗	✗	✗	SU blocking loss, throughput
[15]	✗	✗	✗	✗	✗	Collision rate, SU call blocking probability, mean delay of secondary users
[16]	✓	✗	✗	✗	✗	SU call blocking SU discard probability, mean delay of secondary users
[17]	✓	✗	✓	✗	✓	SU call blocking probability, SU call dropping probability
[18]	✗	✗	✓	✗	✓	SU blocking probability, SU forced termination probability, Call completion rate
[19]	✓	✗	✓	✗	✗	SU blocking probability, SU call dropping probability, SU call non-completion probability, and throughput
[23]	✓	✓	✗	✗	✗	Optimal number of reserved channels, Average number of channel-switching
[24]	✓	✓	✓	✗	✗	Service completion rate (SCR), blocking probability (BP), successful service completion probability (SSCP), handoff probability, throughput
[25]	✓	✗	✗	✓	✗	link maintenance probability, link failure probability,

The main contributions of the paper are the following: (1) a more realistic wireless networking scenario containing two classes of users, namely PUs and CRs, which use a time-slotted based common communication channel is considered while most of the above research papers consider infinite CR users. (2) Three slot allocation strategies for CRs: non-slot-handoff strategy, slot-handoff strategy and slot-reservation strategy are developed, modeled and simulated by using Riverbed Modeler simulation software. Besides, channel access performances of these three strategies in terms of call block, call drop, and call handoff probabilities are also comparatively analyzed and presented.

III. PROPOSED NETWORK MODELS

A. 1. Network Model

In this paper, a network environment in which primary & secondary users and their access points coexist in the same communication area is considered as illustrated in Figure 1. The PUs are authorized entities to access the channel and employ Time Division Multiple Access (TDMA) with constant time slots as a channel access mechanism. SUs are time-synchronized with the PUs and exploit the idle time slots not used by PUs. SUs utilize the overlay spectrum sharing with prioritized PUs. Therefore, the time slotted-based single communication channel is shared in an overlay manner with the higher priority of PUs over SUs. A particular time slot in a frame time is defined as active slots if it is used by any PUs, and the time slots not used by any PU are defined as idle slots. There are two access points within the communication area, one for the PUs and one for the SUs. The primary access point (PAP) does not need to keep a record of the channel usage by SUs and randomly allocates any idle time slot to a newly arrived PU demanding a connection. As a result, a time slot already assigned for an SU can be allocated for a newly arrived PU even when there are other available time slots. Secondary access point (SAP) and SUs are responsible for determining channel occupation and have sensing capabilities to find channel holes (unoccupied channels). Perfect spectrum sensing is considered for SUs and SAP. The SAP keeps a record of the channel usage both by PUs and SUs and assigns an idle time slot to a newly arrived SU if there is any available. It uses a slot allocation table (SAT) in order to keep the slot usage information [20]-[21]. When a time slot is idle, it provides an opportunity for the SU to take advantage of it. There are some distinct conditions in terms of primary and SUs' channel occupation, which are explained in detail in the following sections according to the channel allocation strategies adopted.

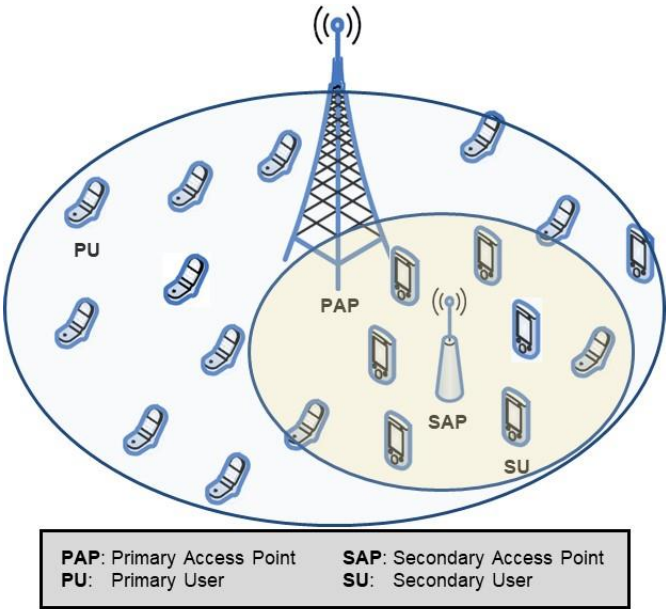

Figure 1. *The proposed cognitive radio network model*

A. 2. Frame Structure of the Proposed CRN Model

The frame structure of the proposed CR network model is shown in Figure 2. Frame time is composed of N equal-size time slots and a time slot in a frame can be utilized by a primary or a secondary user, or can be idle, i.e. not used by any of them. PUs have authorized users to access the licensed channel and they can be allocated any of the N time slots. Whereas, SUs have to sense the channel for idle slots and they are randomly assigned one of the unoccupied idle time slots. In Figure 2, the time slots used by the PUs are shown in yellow color, the time slots filled in a pattern are utilized by the SU and the time slots which are empty are used to depict the idle slots. Sensing time (τ) is used by SAP and SUs to determine whether the following time slot is idle or not. Control slots at the beginning of each time slot following the sensing time slots are used for transmitting control packets to access points both primary and SUs.

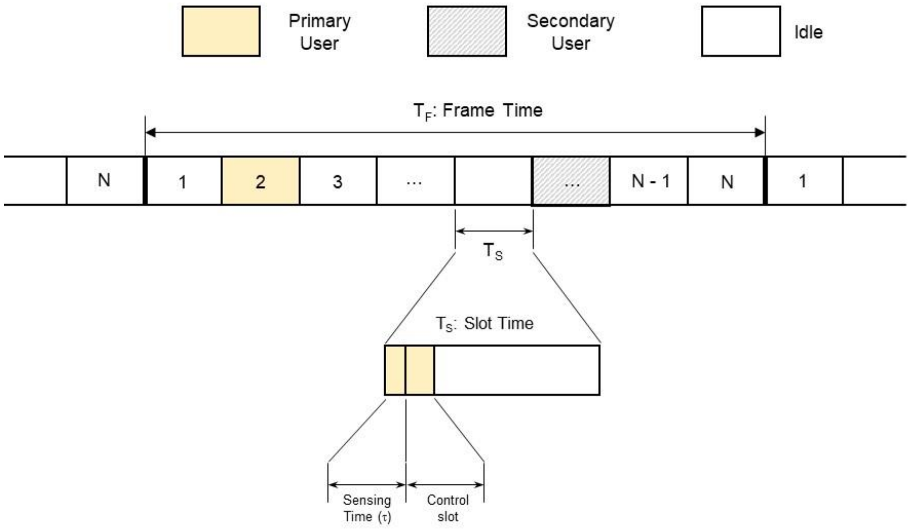

Figure 2. *The Frame structure of the proposed cognitive radio network model*

A. 3. Slot Allocation Strategies

In this presented work, three classical channel allocation strategies, namely, non-slot-handoff, slot-handoff and slot-reservation strategies in a CR network environment are modeled, simulated and analyzed according to their call block, call drop and call handoff probabilities. In order to model the proposed CR network with these channel allocation strategies, Riverbed Modeler discrete event simulation tool was utilized. In the following subsections, these time slot allocation strategies are explained in detail.

A.1.1. Non-Slot-Handoff Strategy

In the proposed non-slot-handoff model, there are total *N* time slots in a frame time and each time slot has an equal time length as shown in Figure 3.a. Since sensing time slots and control slots are very small compared to time slot length, they are not illustrated in the figure. In a frame time, shown in Figure 3.b, there are 6 time-slots used by PUs, one time slot used by an SU and an idle time slot not used by any of them. When one of the PUs wants a connection request from the PAP, PAP may allocate this PU a time slot already used by an SU. In this case, shown in Figure 3.c, incoming PU overlay the SU’s time slot and the SU utilizing this time slot is dropped. If all the time is occupied either by PUs or by SUs, and an SU wants a connection request from the SAP, its connection request (call) is blocked (Figure 3.d).

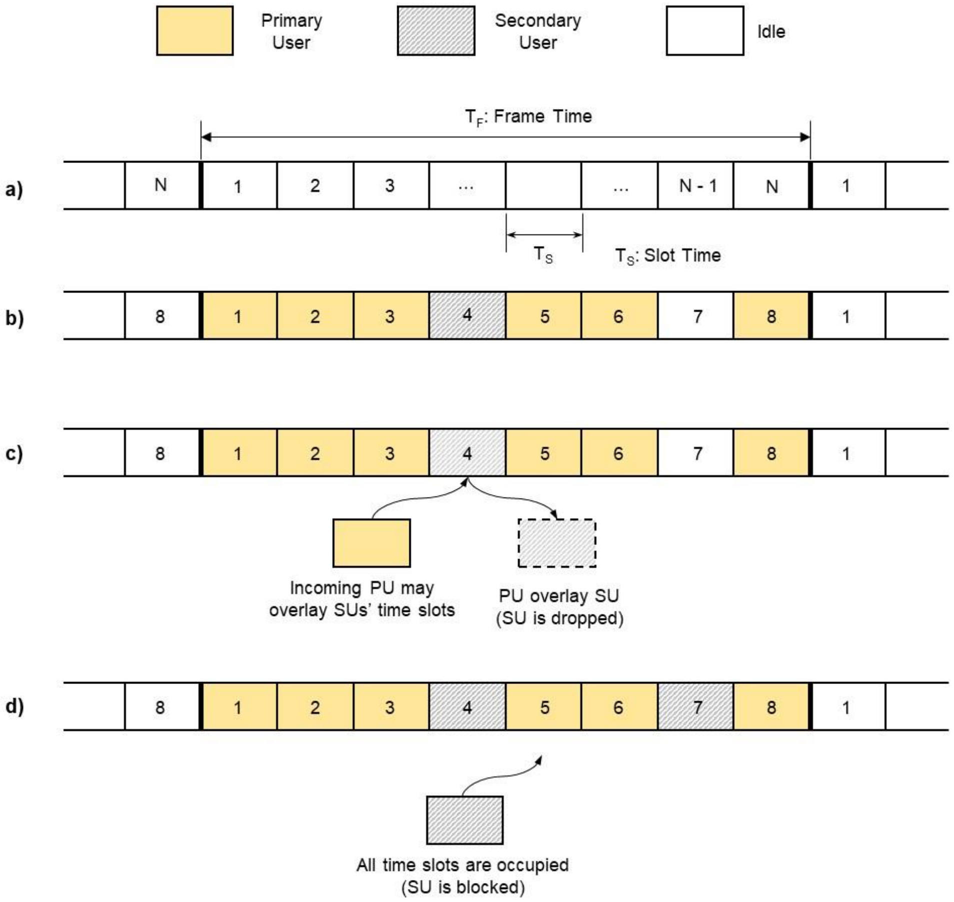

***Figure 3**. Non-Slot-Handoff strategy with (c) SU call drop and (d) call block cases*

A.1.2. Slot-Handoff Strategy

The frame structure of the proposed slot-handoff model with a total of *N* time slots each of which has an equal length is shown in Figure 4.a. In a frame time shown in Figure 4.b, six of the time slots are used by PUs and two of the time slots are idle. When one of the PUs wants a connection request from the PAP, PAP may allocate this PU an idle time slot shown in Figure 4.b or a time slot already utilized by an SU shown in Figure 4.c. If a time slot already utilized by a SU is allocated for the PU requesting connection, SAP may handoff the SU to any idle time slot if there is any available (Figure 4.c). When a PU overlays an SU's time slot, the SAP searches for an idle time slot for the SU to handover, if it cannot find any idle time slot then the SU connection is dropped. This case is shown in Figure 4.d. If all the time slots are occupied either by PUs or by SUs when an SU wants a connection request from the SAP, its call is blocked (Figure 4.e).

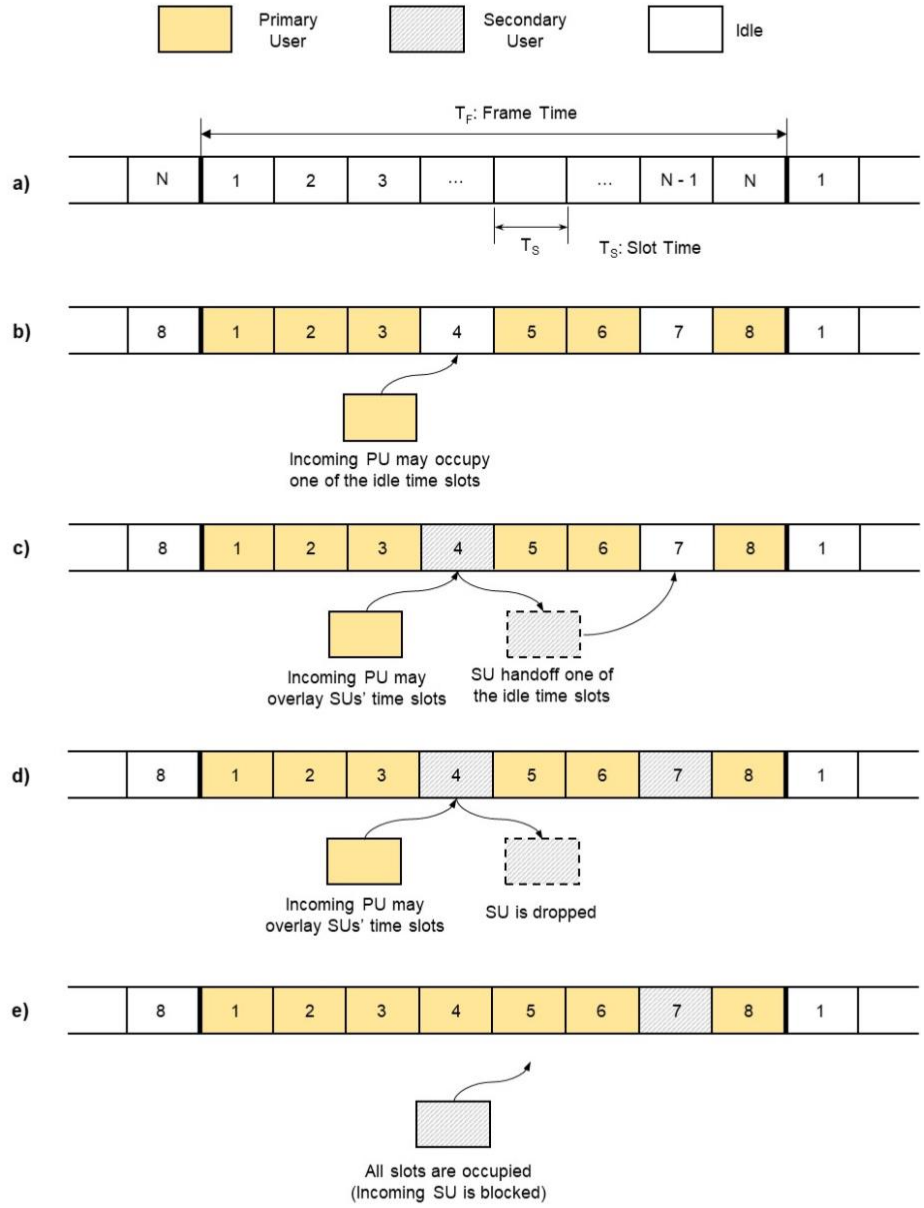

Figure 4. *Slot-Handoff strategy with (c) SU handoff, (d) call drop and (e) call block cases*

A.1.3. Slot-Reservation strategy

In the proposed slot-reservation strategy, a few of the time slots (N_R) in a frame time are reserved for only PUs' usage (Figure 5.a). Therefore, there are totally at most $N - N_R$ time slots for SUs' utilization. If a PU requests a time slot from a PAP and there is an idle time slot in the reserved slots, firstly any idle time slot from the reserved slots is allocated for PU (Figure 5.b). If there is not any idle slot in the reserved slot, then PAP searches for an idle time slot in the remaining $N - N_R$ time slots. When one of the PUs wants a connection request from the PAP, the PAP may allocate this PU an idle time slot or a time slot already utilized by an SU (Figure 5.c). If a time slot already utilized by an SU is allocated for the PU, the SAP may handoff the SU to any idle time slot if there is any available (Figure 5.c). When a PU overlay an SU's time slot, the SAP searches for an idle time slot for the SU to handover, if it cannot find any idle time slot than the SU connection is dropped (Figure 5.d). If all the time slots are occupied either by PUs or by SUs when an SU wants a connection request from the SAP, its call is blocked (Figure 5.e).

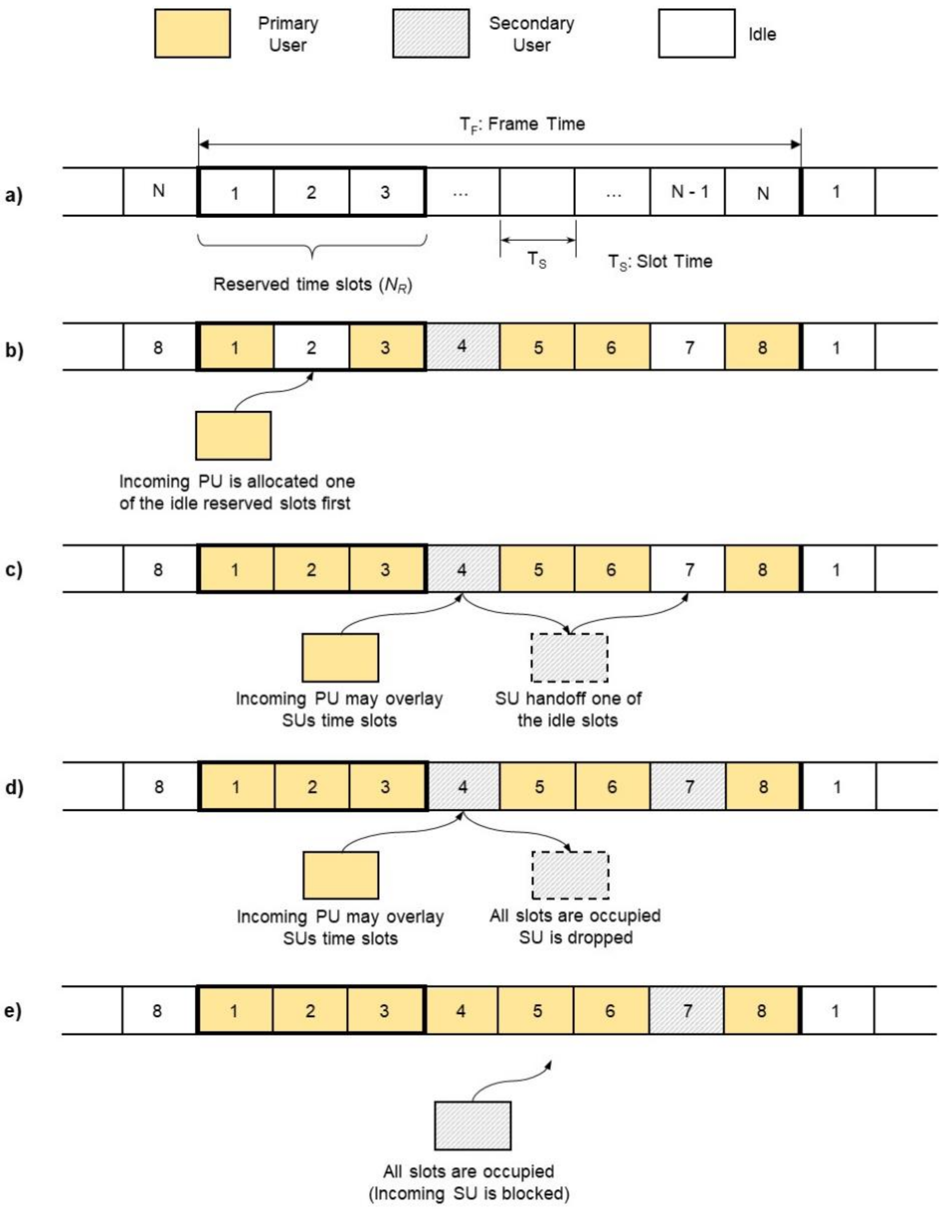

Figure 5. *Slot-Reservation strategy with SU (c) handoff, (d) call drop and (e) call block cases*

IV. PERFORMANCE ANALYSIS

The performance of the CRN model in the proposed networking scenario is analyzed in terms of call block, call drop and call handoff probabilities. These probabilities are explained from the point of SUs since the CRN call admission control performances are of the main interest for this presented work. Call block is defined as a situation where an incoming call is unable to be successfully serviced due to the unavailability of time slots. It occurs when all the time slots are already occupied by either PUs or SUs. SU call block probability is calculated as follows:

$$P_{block} = \frac{\text{Total number of SU call block}}{\text{Total number of SU call arrival}} \tag{1}$$

When a PU wants to use a time slot that is already occupied by an SU, the SU is forced to vacate its current time slot and shift to another idle time slot if there is any available. This case is defined as call handoff, and it is computed as follows:

$$P_{handoff} = \frac{\text{Total number of SU call handoff}}{\text{Total number of SU call arrival}} \tag{2}$$

When a PU wants to utilize a time slot and if there is not any available, then it can utilize a time slot already allocated to one of the SUs. In this case, since there is no other idle time slot for the SU, the SU call is dropped. This situation is referred to as call drop. Call drop probability for the SUs is calculated as follows:

$$P_{drop} = \frac{\text{Total number of SU call drop}}{\text{Total number of SU call arrival}} \tag{3}$$

In the proposed model, the call arrivals of PUs and SUs are assumed to be independent and follow a Poisson process with mean rate λ_p and λ_s respectively. In terms of service times, PUs and SUs have exponential service time distribution with mean rate $1/\mu_p$ and $1/\mu_s$, respectively. Other primary and CR network simulation parameters used are given in Table 1.

Table 2. *Simulation parameters of the proposed CRN model*

Frame time (sec)	$T_F = N_p \cdot T_s$
Time slot length (sec)	$T_s = 10 \cdot 10^{-6}$
Number time slot	$N = 3,5,8$
PU arrival rate	λ_p
SU arrival rate	λ_s
PU service rate	μ_p
SU service rate	μ_s
Number of PUs	$N_p = 10$
Number of SUs	$N_s = 10$

PU call block probability results of the proposed network model are obtained by using Riverbed Modeler simulation software, and they are also confirmed with the analytical results computed by using the standard Engset Loss formula [22] given as follows

$$P_b = \frac{\binom{N_p-1}{N}\left(\frac{\lambda_p}{\mu_p}\right)^N}{\sum_{i=0}^{N}\binom{N_p-1}{i}\left(\frac{\lambda_p}{\mu_p}\right)^i} \tag{4}$$

where N_p and N represent the number of PUs and the number of time slots respectively.

V. RESULTS AND DISCUSSIONS

PUs call block probabilities for varying PUs' offered loads with two different N ($N = 5$ and $N = 8$) values are given in Figure 6 with the parameters $\lambda_s = 0.4$, $\mu_p = 0.4$, $\mu_s = 0.5$. As seen from the graphs, when the PUs' arrival rate is increased from 0.1 to 1.0 while other parameters fixed, call block probabilities for PUs are also increase. Call block probabilities for $N = 8$ are relatively smaller than those of the $N = 5$ for the same PU's offered loads. The differences between call block probabilities for $N = 8$ and for $N = 8$ get widen with the increasing PUs' offered load. When the PUs' offered load is 1.0, call block probability is 0.655 for $N = 5$ and is 0.183 for $N = 8$. Simulation results of the PUs call block probabilities are confirmed by the analytical results obtained by using the standard the Engset Loss model [22].

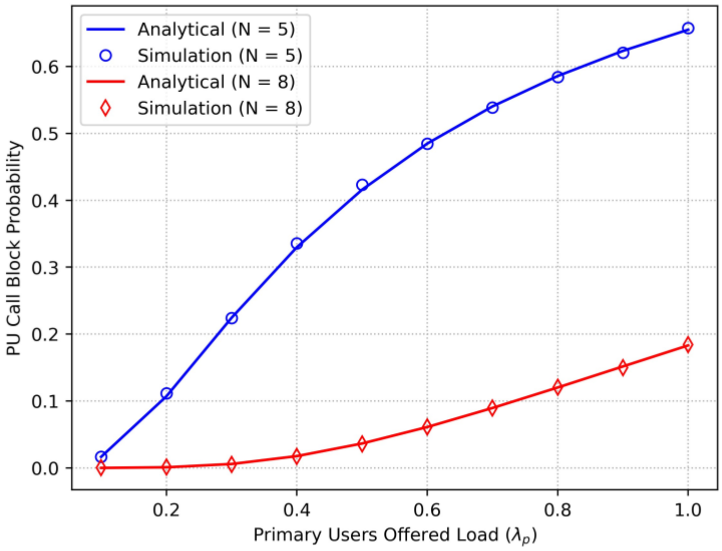

Figure 6. *PU's CBP for varying PU's offered loads*

SUs call block probabilities for varying PUs' offered loads are given in Figure 7, with the parameters $N = 5$, $N_r = 2$, $\lambda_p = 0.05$, $\mu_p = 0.4$, $\mu_s = 0.5$. As seen from the graphs, when the PUs' offered loads are increased from 0 to 1 with fixed SUs' offered loads and service rates, both call block probability for SUs increases and the differences between block probabilities for slot-handoff strategy and non-slot-handoff strategy get larger while increasing the PU's offered loads. Slot-reservation strategy gives the highest SU call block probability. This is due to the fact that in slot-reservation strategy, a certain number of time slots are initially reserved only for PUs, so with the remaining less time slots for SUs, the call block probability for SUs increases.

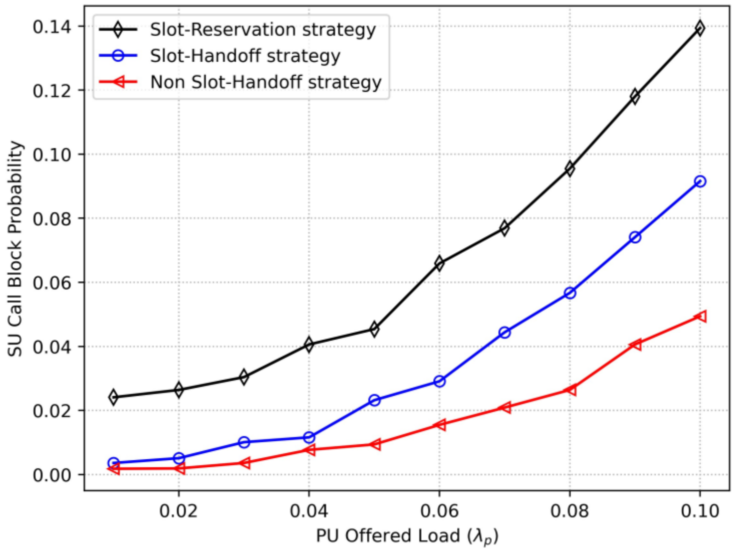

Figure 7. *SU's CBP for varying PU's offered loads*

SUs call drop probabilities for varying the PUs offered loads are given in Figure 8 with the parameters $N = 5,\ N_r = 2,\ \lambda_p = 0.05,\ \mu_p = 0.4,\ \mu_s = 0.5$ for all non-slot-handoff, slot-handoff and slot-reservation strategies. As seen from the graphs, when the PUs' offered loads are increased from 0.1 to 1, call drop probability for non-slot-handoff strategy increases very sharply whereas increasing slightly for both slot-handoff and slot-reservation strategies. There is a great call drop probability improvement with the use of the slot-handoff and slot-reservation strategies. It is clear that the lowest SU call drop probability is obtained by utilizing slot-reservation strategy. This is due to the fact that when slot-reservation-based strategy is utilized, the PUs access the reserved channels first, thereby reducing the possibility of SUs being dropped.

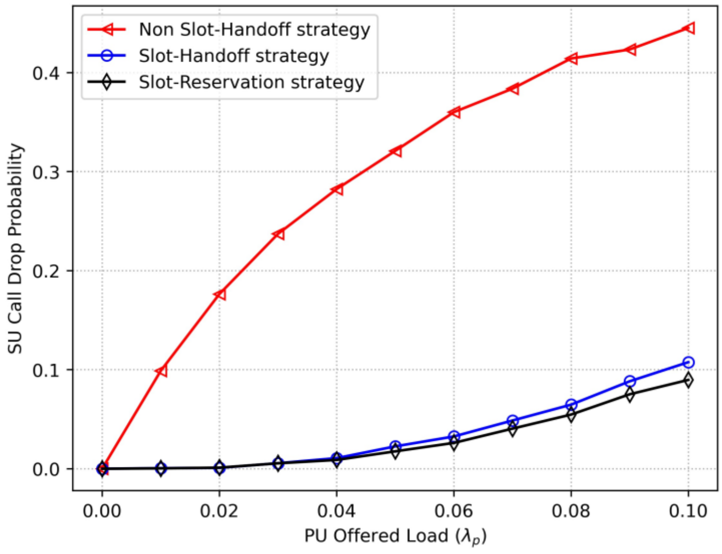

Figure 8. *SU's CDP for varying PU's offered loads*

SUs call block probabilities for varying the SUs offered loads are given in Figure 9, with the parameters $N = 5,\ N_r = 2,\ \lambda_p = 0.05,\ \mu_p = 0.4,\ \mu_s = 0.5$ and for different SU slot allocation strategies. As seen from the graphs, when the SUs' offered loads are increased from 0.01 to 0.1, call block probability for the SUs in all strategies also increases. However, the lowest SU call block probability is obtained when the non-slot-handoff strategy is used. The reason for this is that in slot-reservation strategy a number of time slots are initially reserved just for the PUs, thus with the remaining less time slots, call block probability for the SU increases. In the slot-handoff strategy, while PU overlap the time slot that the SU utilizes, the SU handoff the another vacant time slot, and this increases the total time slot occupation and hence, the SU call block probability.

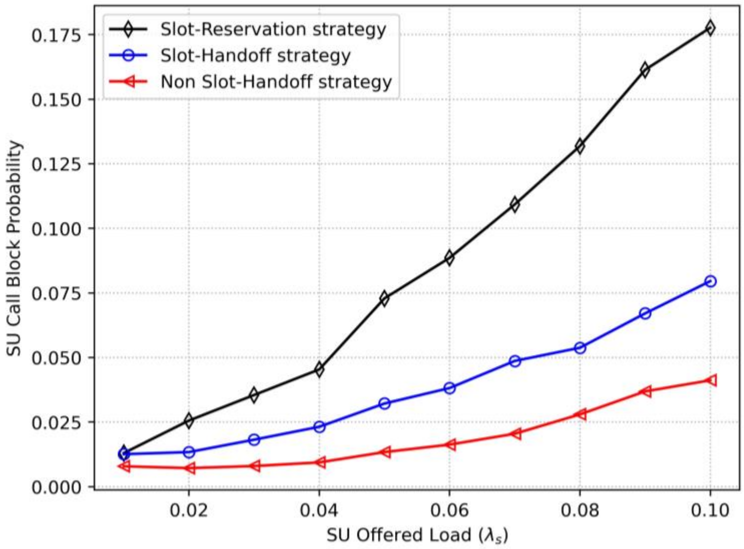

Figure 9. *SU's CBP for varying SU's offered loads*

SUs' call drop probabilities for varying the SUs' offered loads are given in Figure 10 with the parameters $N = 5$, $N_r = 2$, $\lambda_p = 0.05$, $\mu_p = 0.4$, $\mu_s = 0.5$ for all non-slot-handoff, slot-handoff and slot-reservation strategies. As seen from the graphs, when the SUs' offered loads are increased from 0.1 to 1, while call drop probability for non-slot-handoff strategy decreases, it increases slightly for both slot-handoff strategy and slot-reservation strategy. There is a great call drop probability improvement with the use of the slot-handoff and slot-reservation strategies. But the lowest SU call drop probability is obtained from slot-reservation strategy. This is due to the fact that when slot-reservation-based strategy is utilized, the PUs access the reserved channels first, thereby reducing the possibility of the SUs being dropped. When the SUs offered load is 0.05, slot-reservation strategy gives 16.82 and 1.75 times better call drop probability results than those of the non-slot-handoff and slot-handoff strategies respectively.

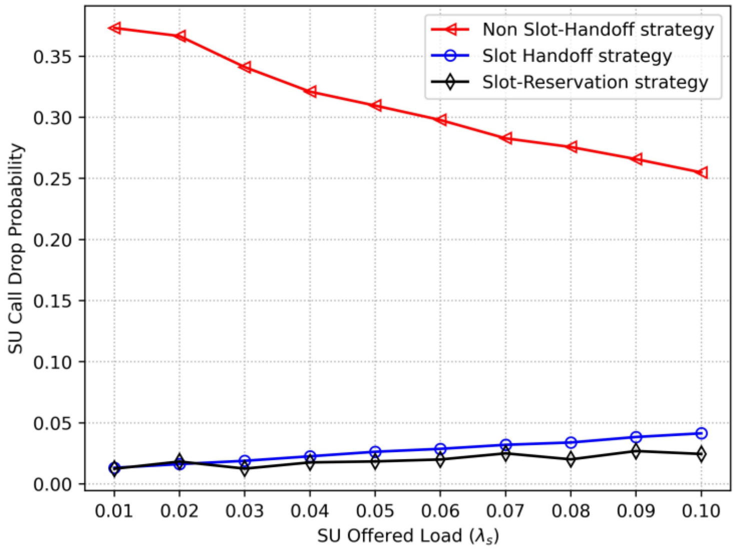

Figure 10. *SU's CDP for varying primary and SUs' offered loads.*

SUs' slot-handoff probabilities for varying the SUs offered loads are given in Figure 11 with the parameters $N = 5,\ N_r = 2,\ \lambda_p = 0.05,\ \mu_p = 0.4,\ \mu_s = 0.5$ for both slot-handoff and slot-reservation strategies. As seen from the graphs, slot-reservation strategy greatly reduces the SU slot-handoff probability. The reason for this is that when slot-reservation-based strategy is utilized, the PUs first access the reserved channels, therefore the possibility of the SUs being dropped decreases. When the offered load of the SU is 0.01, the difference between slot-handoff probabilities and slot-reservation strategies is 0.411 with its maximum value.

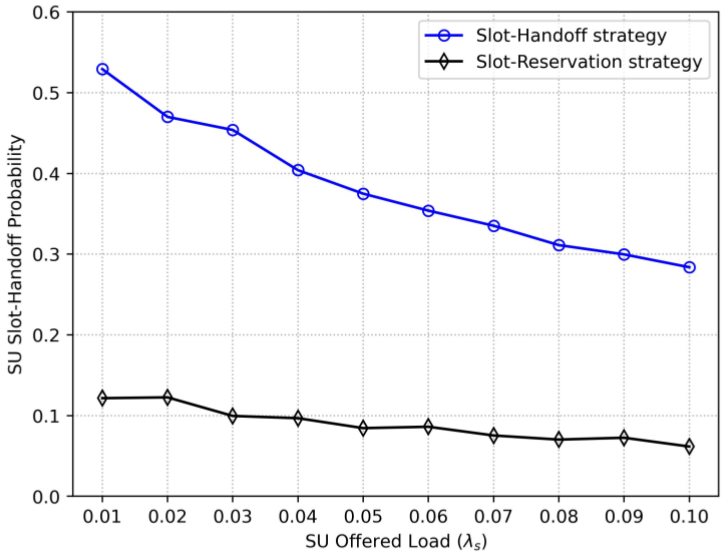

Figure 11. *SU slot handoff probability for varying SUs' offered loads.*

VI. RESULTS AND DISCUSSIONS

In this paper, a TDMA-based CR network is developed, modeled, simulated, and analyzed by using Riverbed Modeler discrete event simulation software. In the proposed network model, the PUs are considered licensed users and have a higher priority in access to the channel than the SUs and thereby are unaffected by the SUs' channel utilization at all. The PUs utilize TDMA as a channel access mechanism and the SUs use the time slots unoccupied by the PUs. Three slot allocation strategies for CRs: non-slot-handoff strategy, slot-handoff strategy, and slot-reservation strategy are developed, modeled, and simulated in this presented work, and their channel access performances in terms of call block, call drop, and call handoff probabilities are analyzed. According to the extensive simulation results, the non-slot-handoff strategy gives the lowest call block probability while the slot-reservation strategy provides the lowest call drop probability. Therefore, in scenarios where low call block probability is desired, non-slot-handoff strategy can be employed, whereas in scenarios where low drop probability is desired, slot-handoff or slot reservation strategy can be adopted. When the SU's offered load is 0.05, the slot-reservation strategy offers 1.75 times better call drop probability results than those of the slot-handoff strategy. However, for the same offered load, the non-slot-handoff strategy gives 2.26 times better call block probability results than those of the slot-reservation strategy. In a future study, it is planned to prioritize the second users according to the data traffic types they use to make channel allocation according to priorities and thus improve the call block and call drop probabilities.

Declarations

Conflict of interest

The authors declare that there is no actual or potential conflict of interest in relation to this article.

Data availability

The authors do not have permission to share data.

VII. REFERENCES

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