Markov Modeling and Analysis of an Adaptive Switching Mechanism in Cognitive Radio Networks (Postprint)

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Abstract

To improve the utilization and throughput performance of cognitive radio networks (CRNs), a novel primary-user-priority adaptive spectrum switching mechanism is proposed. Emphasizing the priority status of primary users, and considering the impact of primary user arrival rates on secondary user communications as well as limiting the interference power of secondary users to primary users, secondary users adaptively decide whether to execute a proactive switching mechanism or a reactive switching mechanism. Under this adaptive switching mechanism, a Markov chain between primary and secondary users is established, the corresponding steady-state probabilities are derived, and analytical expressions for system throughput and channel utilization are obtained from the steady-state probabilities and throughput under different states. Additionally, a Markov chain for communication among secondary users is established, and the time for transmitting control information among secondary users is derived. Numerical results demonstrate that the proposed novel adaptive switching mechanism achieves higher system throughput and channel utilization compared to CSMA-based access methods, and the transmission time among secondary users can be calculated.

Full Text

Preamble

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Markov Modeling Analysis of an Adaptive Handoff Strategy in Cognitive Radio Networks

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Abstract: To improve the utilization and throughput performance of cognitive radio networks (CRNs), this paper proposes a new primary-user-prioritized adaptive spectrum handoff mechanism. The mechanism emphasizes the priority status of primary users, considers the impact of primary user arrival rates on secondary user communications, and limits the interference power of secondary users to primary users. Based on these factors, secondary users adaptively decide whether to execute a proactive or reactive handoff scheme. Under this adaptive handoff mechanism, Markov chains are established between primary and secondary users to derive the corresponding steady-state probabilities. From these steady-state probabilities and the throughput under different states, analytical expressions for system throughput and channel utilization are derived. Additionally, a Markov chain is established for communication among secondary users to derive the time required for control information transfer. Numerical results demonstrate that the proposed adaptive handoff mechanism achieves higher system throughput and channel utilization than CSMA-based access methods, and enables calculation of the transfer time between secondary users.

Keywords: CRNs; spectrum handoff; adaptive handoff; Markov; system throughput; channel utilization

0 Introduction

With the rapid development of wireless communication networks, the number of spectrum-using devices has grown exponentially, leading to increased demand for spectrum bandwidth. The mismatch between existing static spectrum allocation approaches and bandwidth demand has created spectrum scarcity issues. In reality, static spectrum allocation results in underutilization of many licensed spectrum bands.

Cognitive radio networks (CRNs) represent an effective solution to spectrum scarcity. CRNs enable secondary users to utilize temporarily unoccupied bandwidth, thereby improving the efficiency of limited spectrum resources. Secondary users can maximize channel utilization without disrupting established spectrum allocation schemes.

CRN management mechanisms consist of three steps: spectrum sensing, spectrum sharing, and spectrum handoff. Spectrum sensing monitors spectrum usage status to detect spectrum holes. Spectrum sharing addresses scenarios where multiple secondary users attempt to access the channel. Spectrum handoff selects appropriate frequency bands based on spectrum characteristics and user requirements. Among these, spectrum handoff is the most critical step, as it enables dynamic utilization of temporarily unused spectrum bandwidth. On any given channel, secondary users sense the surrounding spectrum and determine which handoff mechanism to execute upon primary user arrival. Spectrum handoff seamlessly switches ongoing secondary user transmissions to another idle channel without degrading quality of service. During this process, secondary users must not cause interference to primary users.

Spectrum handoff mechanisms are generally classified into two categories: proactive handoff schemes and reactive handoff schemes. In proactive handoff, the next channel for data transmission is determined before the handoff trigger based on the primary user's communication pattern. This approach avoids time wasted on spectrum sensing and maintains communication continuity effectively, but target channel selection may be inaccurate due to system dynamics. In reactive handoff, the next channel is determined through instantaneous sensing after handoff occurs, offering higher accuracy in target channel selection but potentially causing communication interruptions. In proactive schemes, secondary users must periodically sense the surrounding spectrum, generating frequent sensing operations and substantial interaction overhead. Therefore, selecting appropriate sensing times can reduce unnecessary sensing and improve handoff efficiency. In reactive schemes, secondary users search for spectrum resources through sensing and access available idle channels to resume remaining services. Since sensing occurs after communication interruption, accurate detection of available spectrum information becomes critical to the entire handoff mechanism.

The authors of [?] attempted to combine the advantages of proactive and reactive handoff to avoid unnecessary switching. Reference [?] also combined these approaches and achieved some results, but their research assumed continuous channel switching during handoff events. The mechanism proposed in [?] employed a backup channel, but when the backup channel remained idle, channel utilization became insufficient, leading to resource waste.

References [?, ?] investigated proactive handoff mechanisms. The proactive scheme in [?] minimized secondary user handoff frequency by selecting channels with maximum idle time. When multiple secondary users switched simultaneously, each generated a pseudo-random selection sequence, but this mechanism might inaccurately predict primary user activity. Reference [?] proposed that secondary user switching to a new channel depends on energy consumption during the handoff process. Specifically, this mechanism considered primary user energy status, handoff time, imperfect sensing, handoff energy requirements, and channel idle probability to determine whether to switch.

References [?] studied reactive handoff mechanisms. The authors of [?] proposed a reactive scheme for next target channel selection based on two criteria: the predicted probability of the target channel being idle or busy, and the length of busy periods. Handoff occurred if the channel was idle or had short busy periods. While this mechanism improved target channel selection accuracy, it increased handoff delay. Reference [?] presented a reactive handoff mechanism where secondary users sensed the availability of the next target channel while communicating on the current channel. While providing reliable and timely spectrum sensing, the approach used interruption avoidance to improve system throughput, but increased handoff delay and waiting time. The mechanism in [?] allowed secondary users to hold multiple available channels simultaneously when primary users were present, enabling communication across multiple channels. This approach avoided harmful interference to primary users while meeting secondary user communication requirements.

Hybrid handoff mechanisms combine proactive and reactive approaches. Although [?] proposed such a hybrid mechanism, secondary users continuously switched channels upon primary user arrival, causing substantial unnecessary handoffs. The mechanism in [?] neglected primary user behavior during design, leading to additional delays, insufficient channel utilization, and unnecessary handoffs during secondary user transmission. In [?], secondary users determined which handoff mechanism to implement by detecting primary user behavior, but did not specify the behavioral changes of primary users.

A hybrid handoff mechanism termed "adaptive" makes channel selection and handoff decisions through continuous monitoring of primary user arrival and departure processes. Reference [?] proposed an adaptive handoff mechanism based on primary user arrival rates, where secondary users decided whether to stay on the current channel or switch based on arrival rates. However, it did not address secondary user impact on primary users or cooperative communication among secondary users.

This paper therefore proposes a new adaptive handoff mechanism that unequivocally prioritizes primary users—no secondary user can interrupt primary user data transmission upon channel arrival. By incorporating interference temperature constraints, secondary user power is limited to avoid impacting primary user communications. Secondary users then decide whether to remain on the current channel or switch, and which handoff mechanism to execute, based on primary user arrival rates. Markov chains are established to describe system dynamics, reflecting arrival and departure processes of primary and secondary users, enabling performance analysis of the proposed handoff mechanism.

1 Adaptive Handoff Mechanism Establishment

The primary-user-prioritized adaptive handoff mechanism balances system fairness and efficiency while avoiding insufficient channel utilization. To improve CRN performance, this paper incorporates two new parameters—primary user arrival rate and secondary user interference power—into performance analysis. By characterizing user behaviors and channel transmission states, we propose an algorithm for communication between primary and secondary users, as shown in Figure 1. The figure assumes CRNs operate as a slotted system with two parts per slot. During the first part of each slot, secondary users can monitor primary user behavior. During the second part, secondary users make handoff decisions based on primary user activity: if no primary user arrives on the channel, secondary users can transmit and receive data; if a primary user arrives, secondary users execute appropriate mobility mechanisms to decide whether to stay on the current channel or switch.

The working principle of this handoff mechanism is described as follows:

a) Secondary users sense the surrounding environment. If no primary user arrives, they continue data transmission. Upon primary user arrival, they calculate the interference power caused to the primary user.

b) An interference temperature limit is introduced to constrain interference at the primary user receiver:

$$T_c(f_c, B) = \frac{1}{KB} \cdot \frac{P_t(f_c, B)}{L_c(f_c, B)} \leq T_c^{\text{limit}}$$

where $T_c(f_c, B)$ represents interference temperature within a frequency band centered at f_c with bandwidth B, $P_t(f_c, B)$ denotes the average transmission power of the secondary user transmitter at center frequency f_c with bandwidth B, K is the Boltzmann constant, and constant $L_c(f_c, B)$ is an attenuation factor describing multiplicative noise from fading and path loss between secondary transmitter and primary receiver. Transforming equation (1) yields the maximum transmission power for the secondary user transmitter:

$$P_t^{\max}(f_c, B) = KB \cdot T_c^{\text{limit}} \cdot L_c(f_c, B)$$

c) Let $P_{\max}(f_c, B)$ be the interference threshold. If the secondary user' s transmission power is below the interference threshold $P_{\max}(f_c, B)$, data transmission can continue on the current channel. If transmission power exceeds the threshold, spectrum handoff is executed.

d) Upon entering the spectrum handoff mechanism, secondary users decide whether to execute proactive or reactive handoff based on thresholds set according to previous primary user behavior. Primary user arrival rates are obtained through energy detection. Assuming the received signal is $y(n) = s(n) + \omega(n)$, where $s(n)$ is the signal to be detected, $\omega(n)$ is additive white Gaussian noise samples, and n is the sample index. When the primary user is inactive ($s(n) = 0$), the energy detector decision statistic is:

$$M = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2$$

where N is the measurement vector length.

e) By comparing the decision statistic M with a fixed threshold λ, spectrum handoff decisions are made. This threshold λ is set based on previous primary user arrival rates because when primary users occupy their licensed channel, the energy level sensed by the detector increases. Through multiple measurements of energy levels at different primary user arrival rates, the energy threshold is established. If the primary user arrival rate is less than threshold λ, secondary users execute proactive handoff; if greater than λ, they execute reactive handoff.

2 Markov Model Establishment and Analysis

In the proposed adaptive handoff mechanism, primary user priority is unequivocal. To describe this priority while capturing states among different users, continuous-time Markov chains (CTMC) can model the relationships between users. Figure 2 illustrates the cooperative relationships among different users, where primary users can exchange data information, secondary users can also exchange data information, but only control information can be transferred between primary and secondary users.

In dynamic spectrum access, secondary users opportunistically access unused spectrum. Primary users have high-priority queues while secondary users have low-priority queues. Secondary users cannot share channels simultaneously with primary users. When a primary user appears on a channel, all secondary users on that channel must immediately stop service. Here, each user' s arrival and departure processes follow independent Poisson processes. Therefore, the relationship between primary and secondary users can be modeled as continuous-time Markov chains (CTMCs).

2.1.1 Primary-User-Prioritized Markov Chain Without Queuing

First, assume that when primary user P appears, no waiting queue exists for secondary users. This spectrum access process is modeled as a five-state continuous-time Markov chain (denoted CTMC-5), as shown in Figure 3. State φ represents no user accessing the channel, state S_1 (or S_2) represents user S_1 (or S_2) being served on the channel, and state $S_{1S}2$ represents secondary users S_1 and S_2 sharing the channel.

Assuming the spectrum bandwidth is initially idle, CTMC-5 begins in state φ, where secondary users attempt to access the channel. When secondary user S_1 attempts access, CTMC-5 transitions to state S_1 at rate λ_{S_1}. If S_1 completes service before other users request access, CTMC-5 returns from state S_1 to state φ at rate μ_{S_1}. If S_2' s service request arrives before S_1 completes service, CTMC-5 transitions to state $S_{1S}2$ at rate λ_{S_2}, where both secondary users share the channel. Once S_1 (or S_2) completes service, CTMC-5 transitions from state $S_{1S}2$ to state S_2 (or S_1) at rate μ_{S_1} (or μ_{S_2}). However, if a primary user appears during secondary user communication in states S_1, S_2, or $S_{1S}2$, secondary users suspend incomplete service to avoid collision, and the primary user is served—CTMC-5 transitions to state P at rate λ_P. During primary user service, no secondary user has channel access rights. After the primary user completes service, CTMC-5 transitions from state P to idle state φ at rate μ_P. For computational simplicity, identical arrival and departure rates are assumed across different users.

The infinitesimal generator matrix for CTMC-5 is shown in Table 1. The flow balance equations are:

$$\begin{cases} (\lambda_{S_1} + \lambda_{S_2} + \lambda_P)\pi_\varphi = \mu_{S_1}\pi_{S_1} + \mu_{S_2}\pi_{S_2} + \mu_P\pi_P \\ (\lambda_{S_2} + \lambda_P + \mu_{S_1})\pi_{S_1} = \lambda_{S_1}\pi_\varphi + \mu_{S_2}\pi_{S_{1S}2} \\ (\lambda_{S_1} + \lambda_P + \mu_{S_2})\pi_{S_2} = \lambda_{S_2}\pi_\varphi + \mu_{S_1}\pi_{S_{1S}2} \\ (\lambda_P + \mu_{S_1} + \mu_{S_2})\pi_{S_{1S}2} = \lambda_{S_2}\pi_{S_1} + \lambda_{S_1}\pi_{S_2} \\ \mu_P\pi_P = \lambda_P(\pi_{S_1} + \pi_{S_2} + \pi_{S_{1S}2}) \\ \pi_\varphi + \pi_{S_1} + \pi_{S_2} + \pi_{S_{1S}2} + \pi_P = 1 \end{cases}$$

where π_i is the steady-state probability of state i. For convenient calculation, let $\lambda_{S_1} = \lambda_{S_2} = \lambda_S$ and $\mu_{S_1} = \mu_{S_2} = \mu_S$. Solving these equations yields the steady-state probabilities for each user occupying the channel:

$$\begin{cases} \pi_\varphi = \frac{2\mu_S^2\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P} \\ \pi_{S_1} = \pi_{S_2} = \frac{2\lambda_S\mu_S\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P} \\ \pi_{S_{1S}2} = \frac{2\lambda_S^2\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P} \\ \pi_P = \frac{2\lambda_S\lambda_P\mu_S+\lambda_P\mu_S^2}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P} \end{cases}$$

2.1.2 Primary-User-Prioritized Markov Chain With Queuing

In the non-queuing model, secondary users are forced to terminate service when a primary user appears on the spectrum bandwidth. After primary user completion, CTMC-5 transitions to the idle state, but time intervals may be wasted between system idleness and the next secondary user access. To improve spectrum utilization, we consider queuing secondary user service requests due to primary user presence. When the spectrum is occupied by secondary users and a primary user appears, secondary users interrupt service and cache the interrupted service in a buffer. By detecting primary user arrival rates and secondary user interference power, decisions are made regarding whether to execute handoff and which mechanism to use. If the primary user occupies the channel, new secondary user service requests are queued. A two-channel example illustrates this queuing approach, as shown in Figure 4, where each channel has a high-priority queue for primary users and a low-priority queue for secondary users. When interruption occurs (primary user arrival), secondary users have two choices: remain on the current channel or transfer service to another available channel. If remaining, the remaining service of a secondary user is placed at the head of the low-priority queue; if changing channels, it is placed at the tail. This head-tail arrangement ensures first-come-first-served (FCFS) among secondary users. Secondary users that vacate the channel upon primary user arrival have higher priority than waiting secondary users, thus occupying the head of the low-priority queue. Once the primary user leaves, the secondary user at the head immediately accesses the channel. Following [?], the S-lock mechanism maintains uninterrupted communication.

Considering these factors, we model the spectrum access process with queuing as an eight-state CTMC, denoted CTMC-8. The rate transition diagram for CTMC-8 is shown in Figure 5. Like CTMC-5, state φ represents no user accessing the channel, state S_1 (or S_2) represents user S_1 (or S_2) being served, and state $S_{1S}2$ represents S_1 and S_2 sharing the channel. CTMC-8 includes three additional states: state $(P, 0)$ represents primary user P being served while S_1 waits; state $(0, P)$ represents P being served while S_2 waits; and state $(P, S_{1S}2)$ represents P being served while both S_1 and S_2 wait.

State $(P, 0)$ (or $(0, P)$) indicates primary user P is being served while secondary user S_1 (or S_2) waits. If secondary user S_1 (or S_2) transmits at power below the interference threshold $P_{\max}(f_c, B)$, it can continue data transmission on the current channel, placing the system in state S_1 (or S_2). If transmission power exceeds the interference threshold, secondary users execute spectrum handoff, transitioning the system to state $(P, 0)$ (or $(0, P)$). When CTMC-8 is in state $(P, 0)$ and secondary user S_2 accesses the channel, if S_2' s transmission power is below the threshold, it can wait on the current channel, transitioning CTMC-8 to state $(P, S_{1S}2)$ at rate λ_{S_2}. Once the primary user leaves, CTMC-8 transitions from state $(P, S_{1S}2)$ to state $S_{1S}2$ at rate μ_P, where S_1 and S_2 share the spectrum bandwidth. When CTMC-8 is in state $S_{1S}2$ and secondary user S_1 (or S_2) attempts spectrum access, if S_1 (or S_2) transmits below the threshold, it can wait, transitioning CTMC-8 to state $(P, S_{1S}2)$ at rate λ_P (or from $S_{1S}2$ to $(P, S_{1S}2)$). If transmission power exceeds the threshold, spectrum handoff is executed.

The infinitesimal generator matrix for CTMC-8 is shown in Table 2. The flow balance equations are:

$$\begin{cases}
(\lambda_{S_1} + \lambda_{S_2} + \lambda_P)\pi_\varphi = \mu_{S_1}\pi_{S_1} + \mu_{S_2}\pi_{S_2} + \mu_P\pi_{(P,0)} + \mu_P\pi_{(0,P)} \\
(\lambda_{S_2} + \lambda_P + \mu_{S_1})\pi_{S_1} = \lambda_{S_1}\pi_\varphi + \mu_{S_2}\pi_{S_{1S}2} + \mu_P\pi_{(P,S_{1S}2)} \\
(\lambda_{S_1} + \lambda_P + \mu_{S_2})\pi_{S_2} = \lambda_{S_2}\pi_\varphi + \mu_{S_1}\pi_{S_{1S}2} + \mu_P\pi_{(P,S_{1S}2)} \\
(\lambda_P + \mu_{S_1} + \mu_{S_2})\pi_{S_{1S}2} = \lambda_{S_2}\pi_{S_1} + \lambda_{S_1}\pi_{S_2} \\
\mu_P\pi_{(P,0)} = \lambda_P\pi_{S_1} \\
\mu_P\pi_{(0,P)} = \lambda_P\pi_{S_2} \\
\mu_P\pi_{(P,S_{1S}2)} = \lambda_P\pi_{S_{1S}2} \\
\pi_\varphi + \pi_{S_1} + \pi_{S_2} + \pi_{S_{1S}2} + \pi_{(P,0)} + \pi_{(0,P)} + \pi_{(P,S_{1S}2)} = 1
\end{cases}$$

Assuming the first state is φ, if secondary user S_1 (or S_2) accesses the channel, CTMC-8 transitions to state S_1 (or S_2) at rate λ_{S_1} (or λ_{S_2}). If primary user P appears, CTMC-8 transitions to state $(P, 0)$ (or $(0, P)$) at rate λ_P.

To solve for steady-state probabilities, let $\lambda_{S_1} = \lambda_{S_2} = \lambda_S$ and $\mu_{S_1} = \mu_{S_2} = \mu_S$. Solving the equation system yields the steady-state probabilities for each state:

$$\begin{cases} \pi_\varphi = \frac{2\mu_S^2\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P+2\lambda_P\mu_S^2} \\ \pi_{S_1} = \pi_{S_2} = \frac{2\lambda_S\mu_S\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P+2\lambda_P\mu_S^2} \\ \pi_{S_{1S}2} = \frac{2\lambda_S^2\mu_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P+2\lambda_P\mu_S^2} \\ \pi_{(P,0)} = \pi_{(0,P)} = \frac{2\lambda_S\lambda_P\mu_S}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P+2\lambda_P\mu_S^2} \\ \pi_{(P,S_{1S}2)} = \frac{2\lambda_S^2\lambda_P}{2\lambda_S^2\mu_P+2\lambda_S\lambda_P\mu_S+2\lambda_S\mu_S\mu_P+\lambda_P\mu_S^2+2\mu_S^2\mu_P+2\lambda_P\mu_S^2} \end{cases}$$

2.2 Markov Model Among Secondary Users

Figure 6 illustrates that secondary users can improve channel utilization by exchanging control information. This paper does not consider competition among secondary users, and the following Markov model can be established for their cooperative states.

Let m be the number of secondary users, with one user having obtained control information at time 0 and $m - 1$ users not having obtained it. Each secondary user that obtains control information from others remains in this state permanently. Assume that at any time, any secondary user with control information sends it to any specified user without control information at rate a. Let $X(t)$ denote the number of secondary users that have obtained control information at time t. Then $\{X(t), t \geq 0\}$ is a pure birth process with parameters:

$$\lambda_n = \begin{cases} (m-n)na, & n = 1, 2, \dots, m-1 \\ 0, & \text{otherwise} \end{cases}$$

Let T_i be the time from i informed secondary users to $i+1$ informed users. Since T_i are independent exponential random variables with parameter $(m-i)ia$, the expected value and variance of the total time T for all m secondary users to obtain control information are:

$$E[T] = \sum_{i=1}^{m-1} E[T_i] = \sum_{i=1}^{m-1} \frac{1}{(m-i)ia}$$

$$\text{Var}[T] = \sum_{i=1}^{m-1} \text{Var}[T_i] = \sum_{i=1}^{m-1} \frac{1}{[(m-i)ia]^2}$$

For reasonably large m, $E[T]$ asymptotically approaches $\frac{1}{a}\ln(m)$.

3 System Performance Analysis

1) System Throughput

From the models above, we have derived solutions for steady-state probabilities. Since π_i represents the steady-state probability of the system being in state i, it can be considered as the expected long-run fraction of time CTMC spends in state i:

$$\pi_i = \lim_{T\to\infty} \frac{1}{T} \int_0^T \mathbb{I}\{S(t) = i\} dt$$

where $S(t)$ is the CTMC state at time t. Assuming R is the long-term average throughput and $R(i)$ is the throughput in state i, we have:

$$R = \lim_{T\to\infty} \frac{1}{T} \int_0^T R(S(t))dt = \sum_{i\in\{S\}} \pi_i R(i)$$

For any primary user P and secondary user S operating alone on the channel, let the maximum transmission rates be C_P and C_S respectively:

$$C_P = B\log_2\left(1 + \frac{P_P G_{PP}}{N_0 B}\right)$$

$$C_S = B\log_2\left(1 + \frac{P_S G_{SS}}{N_0 B}\right)$$

When two secondary users share the channel, the maximum transmission rate $C_{S_{1S}2}$ is:

$$C_{S_{1S}2} = B\log_2\left(1 + \frac{P_{S_1} G_{S_{1S}2}}{N_0 B + P_{S_2} G_{S_{2S}2}}\right) + B\log_2\left(1 + \frac{P_{S_2} G_{S_{2S}1}}{N_0 B + P_{S_1} G_{S_{1S}1}}\right)$$

where B is communication bandwidth, N_0 is additive white Gaussian noise power, P_P and P_S are transmission powers of primary and secondary users, G_{PP} and G_{SS} are channel gains for primary and secondary users, and $G_{S_{1S}2}$ is the channel gain from secondary user S_1 transmitter to secondary user S_2.

Thus, for CTMC-5 and CTMC-8, the average system throughputs S_5 and S_8 can be expressed as:

$$S_5 = \pi_{S_1} C_S + \pi_{S_2} C_S + \pi_{S_{1S}2} C_{S_{1S}2} + \pi_P C_P$$

$$S_8 = \pi_{S_1} C_S + \pi_{S_2} C_S + \pi_{S_{1S}2} C_{S_{1S}2} + \pi_{(P,0)} C_P + \pi_{(0,P)} C_P + \pi_{(P,S_{1S}2)} C_P$$

2) Channel Utilization

Let η_5 and η_8 denote channel utilization for CTMC-5 and CTMC-8 respectively:

$$\eta_5 = 1 - \pi_\varphi$$

$$\eta_8 = 1 - \pi_\varphi$$

4 Numerical Results and Analysis

This section presents numerical analysis of the proposed scheme using Matlab simulations, focusing on two parameters: system throughput and channel utilization. We first compare the performance metrics of the proposed adaptive handoff mechanism with CSMA to verify its superiority. Simulation parameters are listed in Table 3.

When multiple secondary users attempt to access idle channels using CSMA, collisions occur if service requests arrive simultaneously. In the proposed adaptive handoff mechanism, CRNs are assumed to be a slotted system where user service cycles begin in different slots, effectively avoiding collisions and improving system performance. The CTMC-8 approach further improves upon CTMC-5 by queuing secondary user services, thereby enhancing channel utilization. Therefore, CTMC-8 outperforms CTMC-5.

Figure 7 shows the relationship between system throughput and secondary user arrival rate. The dashed curve represents CSMA, while the other two curves represent CTMC-5 and CTMC-8. In CSMA, system throughput initially increases with secondary user arrival rate but eventually decreases because secondary users cannot simultaneously utilize the spectrum and collisions occur, reducing throughput. In contrast, both CTMC-5 and CTMC-8 curves show increasing system throughput with secondary user arrival rate, with CTMC-8 consistently achieving higher throughput than CTMC-5. This demonstrates that CTMC-8 outperforms CTMC-5.

Figure 8 compares channel utilization versus secondary user arrival rate. The dashed curve shows CSMA, while the other curves represent the proposed mechanism. As arrival rate increases, channel utilization improves for both CSMA and the adaptive handoff mechanism. However, CTMC-5 and CTMC-8 achieve better performance than CSMA because CSMA prevents simultaneous spectrum utilization, leaving spectrum idle and resulting in low utilization. Although interference exists when secondary users share channels in the adaptive mechanism, allowing spectrum sharing and optimizing arrival rates yields good performance. Figure 8 also shows CTMC-8 outperforming CTMC-5.

Figure 9 illustrates the impact of the number of secondary users on control information transfer time among them. As the number of secondary users increases, transfer time initially grows. However, beyond a certain point, transfer time begins to decrease with increasing user count, proving that the proposed mechanism enables efficient control message transfer.

Figure 10 compares CTMC-5 and CTMC-8 channel utilization with static spectrum access. Static access shows insufficient channel utilization, while CTMC-5 and CTMC-8 achieve significantly higher utilization. Static spectrum access only allows primary users on the channel, preventing opportunistic secondary user access even when no primary user is present, causing substantial resource waste. The proposed adaptive handoff mechanism is a dynamic spectrum access scheme that allows secondary users to utilize spectrum when primary users are absent, resulting in higher channel utilization than static access. Since CTMC-8 queues secondary user services, its utilization exceeds CTMC-5.

Figure 11 compares handoff delay performance with DFH (Dynamic Frequency Hopping) and DSA (Dynamic Spectrum Access) from [**?**]. Handoff delay is the time required for secondary users to pause transmission upon primary user arrival and restart on another available channel. DFH, as a reactive handoff mechanism, exhibits large delay because spectrum sensing and switching occur after primary user arrival. DSA, a hybrid method performing sensing before arrival and switching after, has smaller cumulative delay than DFH. CTMC-5 and CTMC-8 achieve lower handoff delay than both DFH and DSA, with CTMC-8 showing the smallest delay. This is because the proposed adaptive handoff mechanism combines advantages of proactive and reactive approaches with strong adaptability and flexibility.

5 Conclusion

This paper proposes an adaptive spectrum handoff mechanism considering primary user arrival rates and interference power, emphasizing primary user priority. The mechanism establishes continuous-time Markov chains between primary and secondary users under both non-queuing and queuing scenarios, plus a Markov model among secondary users. This effectively improves system throughput and channel utilization while reducing communication time. Numerical results confirm the theoretical analysis.

Future work will investigate various handoff mechanism models and the impact of inter-user communication on handoff performance, building upon results from [**?**]-[**?**].

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Note: Figure translations are in progress. See original paper for figures.