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An Optimal Matching Channel Selection Strategy Based on $(K+1)$ -Layer 3-D CTMC for Suppressing Spectrum Fragmentation in 5G/B5G Cognitive Radio Ad Hoc Networks

Qian Yang^{1b}, Suoping Li^{1b}, Jaafar Gaber^{2b}, *Member, IEEE*, and Sa Yang

Abstract—Dynamic spectrum access (DSA) is one of the pivotal technologies that is widely recognized to be able to cope with the massive demand for limited spectrum resources by massive data in 5G/B5G networks. To address spectrum fragmentation and sharing in 5G/B5G cognitive radio ad hoc networks (CRAHNs), based on the DSA technique, this paper proposes an optimal matched channel selection strategy with finite buffer (OMCS-FB). In the OMCS-FB, a cognitive user (CU) with the transmission request selects the channel whose idle time optimally matches its transmission time rather than selecting the channel with the longest idle time; if the CU fails to access the channel, the CU enters the buffer and waits for the next transmission opportunity. A $(K + 1)$ -layer continuous-time Markov chain (CTMC) with the number of primary users (PUs) and CUs in primary channels and the number of CUs in the buffer as 3-D metrics is established, which can effectively portray the activity behavior of users and the occupancy states of primary channels under the OMCS-FB. The CTMC rate steady-state equations are then solved using the successive over-relaxation (SOR) iterative algorithm to obtain the system steady-state probability distributions and performance metrics. The results show that the OMCS-FB effectively suppresses spectrum fragmentation of the MAC layer in the time dimension and enables efficient spectrum sharing among CUs and PUs, as verified by Monte Carlo simulation.

Index Terms—5G/B5G cognitive radio ad hoc networks, channel selection, spectrum utilization, 3-D CTMC.

I. INTRODUCTION

A. Background

WITH the breakthroughs and developments in mobile communication technologies, 5G/B5G networks will

be able to provide fixed and mobile broadband services to anyone, anywhere, anytime. And cognitive radio (CR) technology and ad hoc communications made it possible for their implementation [1], [2]. In the face of the explosive growth in the number of users and devices accessing 5G/B5G networks, how to adapt to the rapid increase of traffic services generated by massive users/devices over the limited radio spectrum has become one of the crucial challenges to be solved urgently [3]. Traditional spectrum access technology, namely static spectrum access technology, has been unable to meet the needs of 5G/B5G networks. The reason is that cognitive radio networks (CRNs) consist of primary users (PUs) with exclusive rights to the radio spectra and unlicensed cognitive users (CUs). The radio spectra can only be used by licensed PUs, whereas unlicensed CUs with transmission requests cannot effectively use the spectra. Therefore, the static spectrum strategy causes the spectrum resources fixed to the authorized users to be idle in time and space to varying degrees, resulting in spectrum holes due to the underutilization of spectrum resources. Unlike the static spectrum strategy, dynamic spectrum access (DSA) enables CUs to share the spectrum with PUs without PUs being subject to interference. The CUs exploit the frequency bands by searching for spectrum holes and determining their availability. When a PU communication is detected in the frequency band, the CU must stop transmission and quickly vacate the frequency band [4]. Thus, the DSA that can flexibly adjust the access users opens up new ideas for 5G/B5G cognitive radio ad hoc networks (CRAHNs) concerning the demand for radio spectrum.

In 5G/B5G cognitive radio ad hoc networks (CRAHNs), cognitive tasks operate differently from the traditional centralized entity management resource allocation networks, which rely on the local observation information of each CU versus the coordination and cooperation between adjacent CUs [5]. That is, each CU exchanges PU traffic activities and spectrum occupancy information obtained in the spectrum environment with the relevant information obtained by nearby CUs, to transmit through DSA technology and the spectrum search sequence. Therefore, the spectrum search sequence of CU depends on the information obtained in its spectrum environment. However, each CU usually ignores other CUs information to operate selfishly and selects the channel with the longest available time to maximize its interests. If there is only one CU in

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the network, this method is undoubtedly best. However, when considering the entire real network environment, this method may lead to problems such as low spectrum sharing efficiency, low spectrum utilization rate, and network congestion. Specifically, since the randomness of changes in spectrum space and time, this selfish operation leads to a large number of underutilized spectrum segments in a specific time, resulting in spectrum fragmentation (or spectrum holes [6]). Therefore, each CU should cooperate with the others to obtain as much PUs traffic activity and spectrum occupancy information as possible and determine an effective spectrum search sequence, so that more CUs can obtain transmission opportunities and suppress spectrum fragmentation.

B. Contributions

In this paper, an optimal matching channel selection strategy with finite buffer (OMCS-FB) is proposed by considering the randomness of spectrum space and time variation in 5G/B5G CRAHNs, the effect of spectrum fragmentation, and how to allocate CUs resources rationally. A $(K + 1)$ -layer 3-D continuous time Markov chain (CTMC) is established to analyze and predict the user activity processes and the occupied states of the primary channels (PCs) and buffer under this strategy. Finally, the system performances are evaluated based on this strategy. The main contributions are summarized as follows:

- Propose the OMCS-FB. To minimize the impact of spectrum fragmentation as much as possible, the unused spectrum fragments will be optimally matched with CUs that have transmission requirements. CUs select the channels that meet their transmission needs and have the minimum remaining idle time. Once a CU finds an available spectrum hole, it accesses the channel and completes the transmission; otherwise, the CU enters the buffer and waits for the next transmission opportunity. If the buffer is full, the CU is discarded. The OMCS-FB provides a new solution idea to suppress the effects of spectral fragmentation in 5G/B5G CRAHNs.
- Establish a 3-D CTMC with $K + 1$ layers. Based on the dynamic channel access process of PUs and CUs, a CTMC is established with the number of PUs, the number of CUs, and the number of CUs in buffer as 3 D metrics. The model has $K + 1$ layers. Specifically, the first K layers are determined based on the number of CUs that can be buffered in the buffer, and the $(K + 1)$ th layer is determined based on the fact that CUs fail to access the PCs and are discarded. Therefore, it is helpful to analyze their performance by transforming the channel selection process of 5G/B5G CRAHNs based on the OMCS-FB into a mathematical model (that is, mapping to the Markov chain).
- Exploiting the successive over-relaxation (SOR) iterative algorithm to solve the steady-state probabilities and performance metrics (including average CUs throughput, successful transmission probability, and spectrum hole utilization) of 3-D CTMC.
- The complexities of the proposed channel algorithm and the use of SOR to solve the $(K + 1)$ -layer 3-D CTMC are

analyzed in depth, including a discussion on how these complexities change in large-scale scenarios.

- Through numerical analysis and Monte Carlo simulation, the influence of vital parameters (including the number of CUs, the size of CUs packets, and the duration of PUs traffic activities) on the system performance is investigated. And the effectiveness of the proposed strategy is verified. In addition, by analyzing the average idle-channel-search delay and average channel access delay under OMCS-FB and benchmark schemes, including OMCS-FB no-ordering scheme and fixed polling scheme, the advantages of sorting candidate channel sequences are verified. And the impact of estimation accuracy of spectrum hole duration on the performance of OMCS-FB is studied, highlighting potential directions for future work.

The rest of this paper is organized as follows. Section II reviews and summarizes the related work. Section III introduces the system model and details the control procedure of the OMCS-FB, along with an analysis of its complexity. In Section IV, the 3-D CTMC model under OMCS-FB is established and solved, and the complexity of solving CTMC accurately is analyzed. The metrics for evaluating system performance are analyzed in Section V. In Section VI, the analysis results are validated through experimental simulations, and the development direction for the next step is outlined. Finally, in Section VII, the paper is concluded.

II. RELATED WORK

Currently, the more typical distributed channel selection schemes fall into two broad categories: a graph coloring-based approach in which the CRNs is viewed as a bidirectional graph with CUs as the vertex set and spectrum holes as the color list, and the spectrum allocation problem is equated to giving each vertex a color and conforming to the constraints of the primary network [7], [8]. Another category is the game theory approach, which is divided into non-cooperative games (i.e., CUs are selfish, considering only self-interest maximization) and cooperative games (i.e., CUs are non-selfish and happy to cooperate). For example, the authors in [9] modeled the competitive media access problem in CRNs as a two-stage noncooperative game where the channel allocation game is solved first and then the channel access game. Reference [10] proposed a selfish access scheme for the longest idle time channel selection, where each CU selects the channel with the longest idle time. This method can endow CUs with sufficient advantages, but suffers from spectrum waste and inefficient transmission by CUs. For this reason, the authors in [11] proposed a channel selection scheme with a selfishness degree p to make improvements, using the selfishness degree p to indicate the selfishness degree of a CU for channel selection without considering other CUs' selection, i.e., each CU selects a sufficiently long idle channel and does not necessarily select the longest. Thus, the value of p affects the transmission efficiency and spectrum utilization of the whole network. Based on the conclusion reached in [11] the improvement in network performance and the promotion of spectrum sharing

are most significant when the selfishness $p = 0$ is the BFC strategy, the authors in [12] proposed a 2-D CTMC based on the BFC strategy and demonstrated that the BFC strategy has a better improvement in CRNs performance than the longest idle time channel selection strategy. Therefore, CUs consider the overall situation and are willing to cooperate in cooperative games, which is the best choice for this paper to explore distributed channel selection strategies.

To effectively solve the spectrum fragmentation problem in the time domain, few works have been done to further improve spectrum utilization efficiency by adequately scheduling CUs. For example, the authors in [13] proposed a predictive channel selection scheme, which predicts the idle time of different channels based on historical information to select the best channel for control and data transmission. In [14], the authors proposed a flexible multiparameter-based channel prediction and ranking scheme (FMCP) to enable CUs to select the most suitable channels. Reference [15] proposed an optimal channel selection and handover strategy for CRAHNS based on a Q-learning algorithm to reduce the chances of transmission collisions between PUs and CUs. The channel access methods considered in [9], [10], [11], [12], [13], [14], and [15] are conservative, and CUs will be directly discarded if they do not find spectrum opportunities, which affects the quality of service (QoS) of CUs. And the underutilization of CUs resources also potentially leads to spectrum wastage. Moreover, the authors in [16] evaluated the QoS of CUs by modeling the burst traffic for multiple types of CUs in CRNs. Reference [17] proposed a multidimensional analytical Markov model based on reserved channel access schemes and channel aggregation methods to improve the performance of high-priority CUs. The authors in [18] improved the QoS for users in CRNs by establishing a dual server priority queuing system with two PUs and multiple CUs. Although studies [16], [17], [18] have significantly improved the QoS of heterogeneous CUs, spectrum utilization has not been notably improved.

Since CRAHNS are distributed networks that are difficult to synchronize in time, the system should be modeled and analyzed by exploiting the CTMC. Modeling works based on Markov techniques to analyze the performances of CRNs or CRAHNS have been widely applied in [19], [20], [21], [22], and [23]. For example, the authors in [19] tackled the spectrum sharing problem of PUs and CUs in CRNs by modeling a 2-D discrete-time Markov chain to achieve enhanced operation between PUs and CUs. Reference [20] developed a 3-D continuous Markov model based on different access schemes of PUs to study the impact of changing the number of CUs on the system performance in the CR spectrum-sharing system. The authors in [21] evaluated the performance of CUs in CRAHNS under different spectral environments by establishing a 3-D Markov model, considering aspects such as blocking, dropping, and throughput. In [22], the authors developed a 3-D CTMC to obtain service level performance metrics in cognitive cellular networks based on opportunistic spectrum access, which guaranteed the QoS of given PUs traffic and achieved higher spectral efficiency. In [23], the authors modeled a 3-D CTMC based on a dynamic spectrum strategy by analyzing the mutual influence between PUs with primary priority and

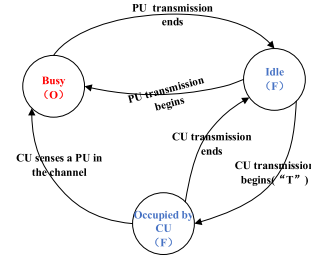


Fig. 1. The PC model.

CUs, which achieved the best compromise between spectrum utilization and fair sharing of spectrum resources between CUs and PUs. Reference [24] evaluated the throughput and channel utilization of the proposed network framework CR-ESU by establishing a CTMC model. All the above models assume that the network has no buffer. However, under actual finite load conditions, the buffer-less model overestimates the ability of CUs access the system and underestimates CUs' throughput.

Therefore, inspired by the above works, the OMCS-FB is proposed. This strategy not only fully utilizes CUs traffic but also tackles the spectrum fragmentation problem in the time domain by providing effective resource allocation at the MAC layer.

III. PROPOSE CHANNEL SELECTION STRATEGY: OPTIMAL MATCHING CHANNEL SELECTION WITH FINITE BUFFER

In this section, the primary channel model is established, and the CRAHNS system with N CUs and M PCs is presented. Following this, the optimal matching channel selection strategy with finite buffer is proposed, and its complexity is analyzed.

A. System Model and Assumptions

Assume that a CRAHN consists of M PCs $\mathcal{A} = \{\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_M\}$ and N CUs that are within interference range of each other. The primary network (PN) of CRAHN is composed of M licensed PCs. And combined with the actual network environment, the number of CUs is greater than or to the number of PUs, i.e., $N \geq M$. Since each PU occupies the channel through a random-access scheme, the PC model is developed based on its activity states instead of individual PU communication.

As shown in Fig. 1, the PC model contains three states due to the CU may access the channel without the PU occupying the spectrum: 1) channel busy: PU activity. 2) channel idle: PU and CU inactivity. 3) channel occupied by the CU. The active and inactive states of PUs correspond to the "O" and "F" states of PCs, respectively. Assuming that channels are homogeneous. Then, the "O" and "F" state durations of channel i obey exponential distributions with parameters $\mu_{PU,i} = \mu_{PU}$ and $\lambda_{PU,i} = \lambda_{PU} (\forall i \in \{1, \dots, M\})$, respectively. For CUs, the "O" and "F" states of PCs correspond to the inactive states and the transmission (T) states of CUs, and the durations of the two states follow the exponential distribution of the parameters μ_{CU} and λ_{CU} , respectively. Both PUs and CUs

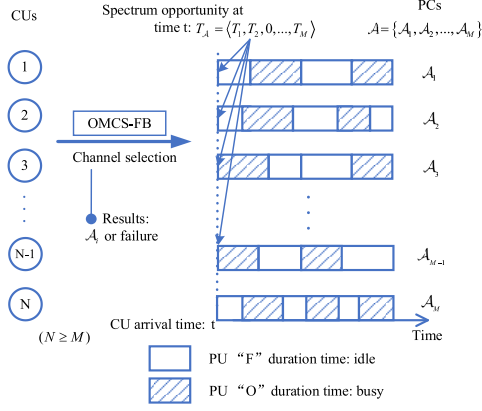


Fig. 2. Systems with N and M PCs.

adopt CSMA/CA random access protocols, and CUs follow a channel selection algorithm to find spectrum holes. Fig. 2 shows the system with N CUs and M PCs from the time and frequency domain perspectives, where CUs select the appropriate available channels according to their transmission needs.

When a PU and a CU in the system coexist in the same channel with the same frequency, this not only interferes with the communication of the PU but also decreases the power of the CU and channel capacity. Therefore, the following assumptions are considered in the system modeling procedure.

- (1) When the PU is present in a certain band (i.e., occupying a certain spectrum resource), the CU cannot occupy that band during this period.
- (2) CUs equipped with spectrum sensors can detect PUs' activities, and CUs know the transmission mode of PUs traffic (for which estimation and modeling methods are referred to [25], [26], and [27]).
- (3) CUs are not allowed to share bands simultaneously.

B. OMCS-FB Strategy

With the core idea that providing reasonable resource allocation at the MAC layer is an efficient approach to improve spectrum utilization and CUs' throughput, an optimal matching channel selection strategy with finite buffer (OMCS-FB) is proposed. In this strategy, each CU determines its transmission channel by estimating the remaining idle time of the channel. Due to the limitation of a single transceiver in the hardware, the CU senses the channel one by one in the order determined by the channel search sequence $\mathcal{L}$. Each CU tries to select the channel that optimally matches its transmission time and has the minimum remaining idle time in the channel search sequence $\mathcal{L}$. If no channels are available for CU transmission in sequence $\mathcal{L}$, it enters the buffer and waits for the next transmission opportunity. Algorithm 1 is the control procedure of the OMCS-FB. It is worth noting that implementing the relevant estimation algorithm is not covered in this paper; however, Section VI-E discusses how estimation accuracy affects the performance of OMCS-FB.

- (1) CUs with self-awareness property know their required transmission time T_O . When CUs have packets to send,

they first perform channel sense and search (CSS), i.e., CUs check the channel occupancy states and estimate each channel available time T_{idle} based on their knowledge of the PCs traffic patterns. And the CUs' queue is sorted incrementally based on CUs' transmission time.

- (2) Add channels that meet the condition $T_O \leq T_{idle}$ to candidate sequence $\mathcal{L}$ and sort in sequence $\mathcal{L}$ with increasing available transmission time (the first element in $\mathcal{L}$ has the shortest available time). CUs sense the channel based on sequence $\mathcal{L}$ and look for transmission opportunities.
- (3) If a CU finds a channel in sequence $\mathcal{L}$ that satisfies its traffic transmission request, it transmits the CU (at this time, the channel state corresponds to the "T" state in Fig. 1; otherwise, the CU enters the buffer k ($0 \leq k \leq K$) to wait for the next transmission opportunity (the channel state corresponds to the "F" state in Fig. 1. Note that the buffer is finite, and its maximum capacity is K . If the CU does not find a suitable transmission opportunity and the buffer is full, it will be discarded.
- (4) For the retransmission of buffered CUs, the first CU located in the buffer starts trying to access the channel only when no new CUs arrive. That is, all CUs staying in the buffer are sorted incrementally by their transmission time T_O . Under the condition that no new CUs arrive, CUs in buffer re-sense the channels before transmitting and estimate each channel available time T'_{idle} . Then, the channels that satisfy $T_O \leq T'_{idle}$ are added into the candidate sequence $\mathcal{D}$ (sorted in an increasing manner of available transmission time), and CUs sense the channels according to sequence $\mathcal{D}$ to find transmission opportunities.
 - 1) If a CU finds a channel in sequence $\mathcal{D}$ that satisfies its traffic transmission need, it transmits its packets.
 - 2) If a CU does not find a channel in sequence $\mathcal{D}$ that satisfies its traffic transmission need, it continues to stay in the buffer.

Next, the complexity of OMCS-FB is analyzed at a unit decision time (i.e., a new user arrival time, or a time when 'no new user arrival' is detected). It is assumed that there are currently n new CUs (only during initial access) and k buffered CUs (only during retransmission) that need to be processed. The total number of CUs in the system, N , includes active transmission CUs, buffered CUs, and potential new arrivals.

- Time complexity

O1. User Queue Sorting (initial access or retransmission): New CUs (nusers) or buffered CUs (k users) are sorted in ascending order based on their T_O . The complexity of this sorting process is $O(n \log n)$ for new CUs or $O(k \log k)$ for buffered CUs. In the worst-case scenario, this complexity can reach $O(N \log N)$ or $O(K \log K)$.

O2. Candidate Sequence Construction and Sorting: For each user (whether it is n new CUs or k buffered CUs):

O2a. Sensing and filtering: Traverse all M channels to check whether the conditions are met (idle and $T_O \leq T_{idle}$ (or T'_{idle})). The complexity is $O(M)$.

Algorithm 1 OMCS-FB Control Flow

```

1 state  $\leftarrow$  CSS and CU next transmission time is  $T_O$ 
2 for each PU channel  $i$  do
3   estimate the remaining idle time:  $T_{idle}$ ;
4   if  $T_O \leq T_{idle}$  then
5     add to channel availability list  $\mathcal{L}$ ;
6   end
7 end
8 if policy is OMCS-FB then
9   sort  $\mathcal{L}$  in increasing order of  $T_{idle}$ ;
10 end
11 for each channel  $i$  in  $\mathcal{L}$  do
12   sense channel  $i$ ;
13   if channel is idle then then
14     transmission channel  $\leftarrow T$  break;
15   end
16 end
17 if no available channel then
18   transmission fails and kept in buffer;
19   state  $\leftarrow F$ ;
20   if the number of CUs in buffer  $k \leq K$  then
21     each CU in buffer waits for the next transmission
22     opportunity;
23   else
24     drop the CU;
25   end
26 end
27 for re-transmission of each CU in buffer do
28   sort in increments of transmission time  $T_O$ ;
29   if no new CU arrives then
30     for each PU channel  $i'$  do
31       re-estimate the remaining idle time:  $T'_{idle}$ ;
32       if  $T_O \leq T'_{idle}$  then
33         add to channel availability list  $D$ ;
34         for channel list  $D$  do
35           sort  $D$  in increasing order of  $T'_{idle}$ ;
36         end
37       end
38     end
39     for each channel  $i'$  in  $\mathcal{D}$  do
40       sense channel  $i'$ ;
41       if channel is idle then
42         transmission channel  $\leftarrow i'$ ;
43         state  $\leftarrow T$  break;
44       end
45       if no available channel then
46         continue to keep in buffer;
47         state  $\leftarrow F$ ;
48       end
49     end
50   else
51     continue to wait for next transmission opportunity;
52   end
53 end

```

O2b. Candidate Sequence Sorting: The selected candidate channels ($0 \leq l \leq M$) are sorted in ascending order based on their available time (T_{idle} (or T'_{idle})). The complexity is $O(l \log l)$, up to $O(M \log M)$.

Therefore, the complexity of this step is $O(M + l \log l)$, and the highest complexity is dominated by $O(M \log M)$.

O3. Channel Search: each user traverses its sorted candidate sequence in order until the first currently available channel

is found. In the worst-case scenario, each user may need to sense every channel in the candidate sequence, which contains l channels. This results in a complexity of $O(l)$ and can go up to $O(M)$.

O4. Buffer Management (when initial access fails): If the buffer is not full, the user is inserted into the appropriate sorting position, with a complexity of $O(\log k)$ to $O(\log K)$. If the buffer is full, the user is discarded, resulting in a complexity of $O(1)$. Overall, the complexity of this process is relatively low and is usually negligible.

O5. Buffer Management (when retransmission fails): the user is discarded, the buffer is updated, and the complexity is $O(1)$.

Thus, for initial access (new users), the total time complexity can reach up to $O(N \log N)(O1) + O(NM \log M)(O2) + O(NM)(O3) + O(N \log K)(O4)$ during a unit decision time. For buffer retransmission, the maximum complexity can reach $O(K \log K)(O1) + O(KM \log M)(O2) + O(KM)(O3) + O(K)(O5)$. In large-scale scenarios, the time complexity is mainly determined by candidate channels sorting. The overall complexity is approximately $O(NM \log M)$ or $O(KM \log M)$.

- Space complexity

The space complexity is primarily influenced by the storage of user information, channel state information, and queue storage. User information includes attributes for each user, such as transmission time, state, and candidate sequence. Each user's candidate sequence can contain a maximum of $l = M$ pieces of channel information, leading to a complexity of $O(NM)$. The channel state information encompasses the states of M channels, resulting in a complexity of $O(M)$. Queue storage includes new users and buffered users. The queue itself occupies either $O(N)$ or $O(K)$ space. If users in the queue are sorted in ascending order, the additional space overhead is $O(N)$ or $O(K)$. Therefore, the total space complexity can be expressed as $O(NM + M + N + K)$. When the system is under high load, the complexity is primarily influenced by the candidate sequence maintained for each user, which is $O(NM)$.

IV. CONSTRUCT 3-D CTMC BASED ON THE OMCS-FB

The OMCS-FB is proposed for distributed networks where it is difficult to synchronize time, so it has a continuous-time nature. Therefore, the model developed in this section is the CTMC. Since CUs share spectrum with PUs, the matching results between CUs and spectrum holes directly affect the channel selection results. Therefore, based on the occupancy of PCs and the buffer, a $(K + 1)$ -layer 3-D CTMC with the number of PUs i , the number of CUs j , and the number of CUs k ($0 \leq k \leq K$) in the buffer as 3-D metrics is established. Additionally, the complexity of solving the model is analyzed.

A. Define State Space

In the system composed of M PCs and N CUs, let $S(t)$, $R(t)$, and $L(t)$ represent the stochastic process of the number of PUs and CUs transmitting and the number of CUs staying in the buffer at time t , respectively. Note that a CU enters

the buffer in the following two cases: 1) The CU senses the channel upon arrival and fails to find an idle channel that optimally matches its transmission time in sequence $\mathcal{L}$, i.e., $T_O \leq T_{idle}$; 2) After the CU arrives, it senses the channel and finds all channels are occupied.

Let $X(t) = H_{i,j,k} = \{S(t) = i, R(t) = j, L(t) = k\}$ denotes the system state at time t , i.e., at time t , PCs are occupied by i PUs and j CUs, and there are k CUs in the buffer waiting for transmission opportunities. Denote by $\mathcal{A}_{PU}$ and $\mathcal{A}_{CU}$ the set of PCs occupied by PUs and CUs, respectively, and obviously $\mathcal{A}_{PU} \cup \mathcal{A}_{CU} = \emptyset$. The sets of busy and idle channels are denoted as $\mathcal{A}_{busy}$ and $\mathcal{A}_{idle}$, respectively. Thus, the set of all PCs is denoted by $\mathcal{A}$ and $\mathcal{A} = \mathcal{A}_{busy} \cup \mathcal{A}_{idle}$, where $\mathcal{A}_{busy} = \mathcal{A}_{PU} \cup \mathcal{A}_{CU}$. Let $\mathcal{B}$ is the set of CUs, $\mathcal{B}_{CU}$ represents the set of CUs transmitting, $\mathcal{B}_{idle}$ represents the set of CUs for which no transmission request has been made, and $\mathcal{B}_{buffer}$ is the set of CUs that are buffered in the buffer waiting for transmission opportunities. Note that $\mathcal{B} = \mathcal{B}_{CU} \cup \mathcal{B}_{idle} \cup \mathcal{B}_{buffer}$ and $\mathcal{B}_{CU}, \mathcal{B}_{idle}$ and $\mathcal{B}_{buffer}$ are empty sets after intersecting each other in pairs.

Since only M PCs in the system, it can transmit up to M users (including PUs and CUs). The state space is represented as follows:

$$\begin{aligned} H &= \{H_{i,j,k} \mid 0 \leq i \leq M, 0 \leq j \leq N, 0 \leq i+j \leq M, 0 \leq k \leq K\} \\ &= \{H_{0,0,0}, H_{0,1,0}, \dots, H_{0,M,0}, H_{0,0,1}, \dots, H_{0,M,K}, \\ &\quad \dots, H_{i,j,0}, \dots, H_{i,j,K}, \dots, H_{M,0,0}, \dots, H_{M,0,K}\}. \end{aligned}$$

where the set of states in which the system is idle, i.e., all PCs are idle, can be expressed by $H_{empty} = \{H_{0,0,k} \mid 0 \leq k \leq K\} = H_{0,0,0}, H_{0,0,1}, \dots, H_{0,0,K}$; The set of states where the entire system is busy, i.e., all PCs are occupied, is $H_{fail} = \{H_{i,M-i,k} \mid 0 \leq i \leq M, 0 \leq k \leq K\} = \{H_{0,M,0}, \dots, H_{0,M,K}, \dots, H_{0,M-i,0}, \dots, H_{i,M-i,K}, \dots, H_{M,0,0}, \dots, H_{M,0,K}\}$, which also indicates that only CUs (i.e., the state set $H_{0,M,k} (0 \leq k \leq K)$) or only PUs (i.e., the state set $H_{M,0,k} (0 \leq k \leq K)$) can occupy all channels in the system.

Since there are N CUs in the system, and the resource flow of CUs is affected by the number of PCs and buffer capacity, the total number of states in the system should be considered in two cases, i.e., $N \geq M + K$ and $N < M + K$. Moreover, the maximum number of PCs that can be used to transmit CUs is $\min(M, N)$, and the maximum number of CUs that can be stored in the buffer is $\min(K, N)$. Thus, the total number $|H|$ of states in the system can be derived (1), as shown at the bottom of the next page.

Combined with practical considerations, the maximum capacity of the buffer to store CUs often cannot fully carry all CUs in the system, so $K < N$. And the number of CUs is generally more than the number of PCs, i.e., $N \geq M$, thus $\min(M - i, N) = M - i$. Then, $|H|$ can be rewritten (2), as shown at the bottom of the next page.

B. CTMC Analysis

Based on the analysis and assumptions in Section III, it is known that PCs are independent of each other and have the

same traffic occupancy distribution. Let U be the duration time of the channel occupied by PU to complete its transmission, and its channel state is successive ‘‘O’’ state, so U obeys the exponential distribution with parameter μ ; V indicates that the channel remains idle for a period, and its channel state is successive ‘‘F’’ state, so V obeys the exponential distribution with parameter λ . And U and V are independent of each other. For example, the active state of channel $\mathcal{A}_1$ in Fig. 2.

Assuming that the system is in state $H_{i,j,k}$ at time t , and the possible state at time $t + T_c$ is affected by the occurrence of the following events: (1) a PU arrival, (2) a PU departure, (3) a CU successful arrival, (4) a CU departure, (5) a CU arrival failure into the buffer, (6) a CU retransmission in the buffer, (7) a CU is discarded because the buffer is full.

- (1) A PU arrival, i.e., $H_{i,j,k} \rightarrow H_{i+1,j,k}$: Due to the presence of $M - i$ PCs that are not being used, the PU may arrive at any of these channels, so the arrival of the first PU with a traffic transmission request prompts state $H_{i,j,k}$ transit to state $H_{i+1,j,k}$. Assuming the first arrival occurs in channel c at $t + T_c$, then $T_{i,j,k|i+1,j,k} = \min(T_c : c \in \mathcal{A} \setminus \mathcal{A}_{PU})$. It is known that all T_c obey exponential distribution and are independent of each other, so $T_{i,j,k|i+1,j,k} \sim \exp\left(\sum_{c=1}^{M-i} \lambda_c\right)$. And assume that all PCs are identically distributed, thus $T_{i,j,k|i+1,j,k} \sim \exp((M-i)\lambda_{PU})$.
- (2) A PU departure, i.e., $H_{i,j,k} \rightarrow H_{i-1,j,k}$: When either of PUs in transmit completes transmission first, the system state changes $H_{i-1,j,k}$. A PU in channel c first completes transmission, the PU releases channel c , and the service time T_c of this channel is the minimum of i PCs ($|\mathcal{A}_{PU}| = i$). Thus, the state transition time to $H_{i-1,j,k}$ is $T_{i,j,k|i-1,j,k} = \min(T_c : c \in \mathcal{A}_{PU})$. Since all T_c follow exponential distribution and are independent of each other and all PCs are identical, $T_{i,j,k|i-1,j,k} \sim \exp(i\mu_{PU})$.
- (3) A CU successful arrival, i.e., $H_{i,j,k} \rightarrow H_{i,j+1,k}$: Since there are j CUs in transmission in the system as well as k CUs stored in the buffer due to access channel failure, the arriving CU may be one of the remaining $(N - j - k)$ CUs in the system. The successful arrival of a CU occurs only if PCs are not fully occupied by PUs and finds an idle channel that optimally matches with its transmission time. Therefore, the probability of a CU successfully accessing the channel is assumed to be P_{cs} . The earliest successfully arrived CU triggers $H_{i,j,k}$ change to $H_{i,j+1,k}$, and this CU matches the channel with the shortest duration time among the idle channels, so $T_{i,j,k|i,j+1,k} = \min(T_c : c \in \mathcal{B}_{idle})$. Therefore, $T_{i,j,k|i,j+1,k} \sim \exp((N - j - k)\lambda_{CU}P_{cs})$.
- (4) A CU departure, i.e., $H_{i,j,k} \rightarrow H_{i,j-1,k}$: If one of CUs in transmit completes its transmission first, it makes state $H_{i,j,k}$ to transit to $H_{i,j-1,k}$. The first CU completes its service at $t + T_c$, and releases the channel c occupied by it, which duration is the shortest available time among the channels occupied by j CUs ($|\mathcal{A}_{CU}| = j$). Hence,

$T_{i,j,k|i,j-1,k} = \min(T_c : c \in \mathcal{A}_{CU})$. From above, it can be deduced that $T_{i,j,k|i,j-1,k} \sim \exp(i\mu_{CU})$.

- (5) A CU arrival failure into the buffer, i.e., $H_{i,j,k} \rightarrow H_{i,j,k+1}$:

- 1) In case of PCs are not fully occupied (i.e., $i + j < M$) and the buffer capacity is not up to maximum K , a CU access the channel failure due to its failure to find an idle channel that is longer than its transmission time, which results in the system may enter the state $H_{i,j,k+1}$. The first CU enters the buffer and fails to match any available channel, meaning that the channel with the longest idle time cannot meet the transmission need of the CU, so $T_{i,j,k|i,j,k+1} = \max(T_c : c \in \mathcal{A}_{idle})$. And $T_{i,j,k|i,j,k+1}$ follows an exponential distribution with parameter $(N - j - k)\lambda_{CU}(1 - P_{CS})$.
- 2) When a CU arrives and discovers that all PCs have been occupied (i.e., $i + j = M$), it enters the buffer, which means state transition to $H_{i,M-i,k+1}$ occurs. The state transition time is $T_{i,j,k|i,j,k+1} = \max(T_c : c \in \mathcal{A}_{busy} = \mathcal{A})$. Thus, $T_{i,j,k|i,j,k+1} \sim \exp((N - (M - i + k))\lambda_{CU})$.
- (6) A CU retransmission in the buffer, i.e., $H_{i,j,k} \rightarrow H_{i,j+1,k-1}$: State transition to $H_{i,j+1,k-1}$ occurs when the following conditions are met simultaneously. (a) No new CUs arrive at $t + T_c$. (b) PCs are not fully occupied. (c) The first CU in the buffer is able to find an idle channel that matches its transmission time. Therefore, the channel matched by the first retransmitted CU in the buffer is the channel that satisfies its transmission need and has the shortest idle time, that is, $T_{i,j,k|i,j+1,k-1} = \min(T_c : c \in \mathcal{B}_{buffer})$. From above, it can be derived that $T_{i,j,k|i,j+1,k-1} \sim \exp(-(N - j - k)\lambda_{CU})$.
- (7) A CU is discarded because the buffer is full, i.e., $H_{i,j,K} \rightarrow H_{i,j,K}$: The system state does not transition in two situations: (a) Under the buffer is full, a CU

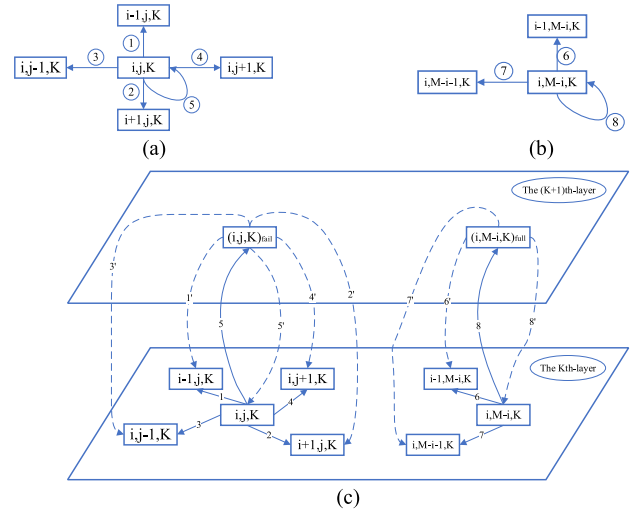


Fig. 3. Modifying self-transition to a two-layer state space. (a) The self-transition in case (7)-(a). (b) The self-transition in case (7)-(b). (c) The state space of the K th layer and the $(K + 1)$ th-layer (where the transition rate $q = q', q, q' \in [1, 8], q, q' \in N^+$), the K th layer is composed of states in $H \setminus H_{fail} \cup H_{fail}$ and states in the $(K + 1)$ th layer from $H_{fail} \cup H_{fail}$.

arrives, but it cannot find a sufficiently long transmission opportunity even though PCs are not fully occupied. (b) When the buffer is full, a CU arrives, but all channels are occupied. And the above cases result in the CU being discarded.

According to the definition and properties of CTMC, the self-transitions of the event (7) are not allowed to occur. Hence, a $(K + 1)$ -layer system is developed, which the $(K + 1)$ th-layer includes state $H_{(i,j,K)_{fail}}$ and $H_{(i,M-i,K)_{fail}}$. As shown in Fig. 3, the self-transition in case (a) is modified to a transition of the state $H_{i,j,K}$ at the K th layer to the state $H_{(i,j,K)_{fail}}$ at the $(K + 1)$ th-layer, and the time of this transition is similar to the derivation of $T_{i,j,k|i,j,k+1}$ as $T_{i,j,K|(i,j,K)_{fail}} =$

$$|H| = \begin{cases} (K+1) \sum_{i=0}^M (\min(M-i, N) + 1), N \geq M+K \\ (K+1)(M+1) + \sum_{j=1}^M (\min(N, K) - j + 1)(M - j + 1), M \leq K, N < K+M \\ (K+1) \sum_{j=0}^{M-K} (M - j + 1) + \sum_{j=M-K+1}^M (N - j + 1)(M - j + 1), M > K, N < K+M \end{cases} \quad (1)$$

$$|H| = \begin{cases} (K+1) \sum_{i=0}^M (M - i + 1) = \frac{(K+1)(M+1)(M+2)}{2}, N \geq M+K \\ (K+1)(M+1) + \sum_{j=1}^M (K - j + 1)(M - j + 1), M \leq K \leq N, N < K+M \\ (K+1) \sum_{j=0}^{M-K} (M - j + 1) + \sum_{j=M-K+1}^M (N - j + 1)(M - j + 1), M > K, N < K+M \end{cases} \quad (2)$$

$\max(T_c : c \in \mathcal{A}_{idle}) \cdot T_{i,j,K|(i,j,K)_{\text{fail}}}$ follows an exponential distribution with parameter $(N - j - K)\lambda_{CU} (1 - P_{CS})$. The self-transition in case (b) is modified as a transition from state $H_{i,M-i,K}$ at the K th-layer to state $H_{(i,M-i,K)_{\text{fail}}}$ at the $(K + 1)$ th-layer. The state transition time can be expressed as $T_{i,M-i,K|(i,M-i,K)_{\text{fail}}} = \max(T_c : c \in \mathcal{A}_{busy} = \mathcal{A})$, and $T_{i,M-i,K|(i,M-i,K)_{\text{fail}}} \sim \exp((N - (M - i + K))\lambda_{CU})$.

Let H_{fail} and H_{fail} represent the set of all states occurring in case (a) and case (b) in the event (7), respectively, so the new state space is reconstructed as a $(K + 1)$ -layer system. Where the first K layers are the set of states consisting of the system with the ability to buffer k ($0 \leq k \leq K$) CUs, and the $(K + 1)$ th layer is the set of states composing of the elements in $H_{\text{fail}} \cup H_{\text{fail}}$ (as shown in Fig. 3c), now the total number of states in the system can be rewritten (3), as shown at the bottom of the next page.

So far, the complete state space has been obtained, namely the $(K + 1)$ -layer 3-D CTMC with the number of PUs and CUs in PCs and the number of CUs in the buffer as metrics, as shown in Fig. 5. In Fig. 5, the vertical-colored arrows indicate the occurrence of either event (1) or event (2), and the horizontal black arrows represent the occurrence of either event (3) or event (4). Other black or blue arrows are associated with the occurrence of either event (5) or event (6). The gray module denotes the $K + 1$ layer of the 3-D CTMC, signifying the occurrence of event (7).

C. Transition Rate Matrix

Based on the discussion in the previous section, all possible state transition cases and their corresponding transition rates have been derived. Before obtaining the transition rate matrix Q , it is necessary to define the probability of channel selection success, i.e., P_{cs} , the probability that CUs with transmission requests can find appropriate spectrum holes to access available channels. Thus, it is inferred that it is closely related to the channel selection strategy and the occupancy status of PCs by the definition of P_{cs} but not to the buffer capacity. Therefore, for the OMCS-FB, the conditional probability P_{cs} of successful channel selection when the system is in state $H_{i,j,k}$ is defined as:

$$\begin{aligned} P_{cs}(i, j, k) &= \Pr \left\{ T_O^{CU} \leq \frac{g_s}{2} \right\} \\ &= 1 - \left(\Pr \left\{ T_O^{CU} > \frac{g_s}{2} \right\} \right)^{M-(i+j)} \\ &= 1 - \left(\frac{\lambda_{g_s}}{\lambda_{g_s} + 2\lambda_O^{CU}} \right)^{M-(i+j)} \end{aligned} \quad (4)$$

where T_O^{CU} is the CU transmission duration, and $T_O^{CU} \sim \exp(\lambda_O^{CU})$; g_s denotes the independent identically distributed random variable for the PC idle durations by the CU observing when a CU arrives, and $g_s \sim \exp(\lambda_{g_s})$. λ_{g_s} is parameter of gap size for OMCS-FB strategy, and the average gap size $\lambda_{g_s}^{-1}$ is proportional to the average PU spectrum hole (or the PC is idle) durations λ_{PU}^{-1} . Fig. 4 clarifies the correlation between the system states and P_{cs} values for the OMCS-FB (set parameters $\lambda_{PU}^{-1} = 2.5, M = 8, N = 10$), which state index(i), from left to right, indicates an increase in the number of active PUs

and, from top to bottom, shows an increase in the number of active CUs.

Let $\pi_{i,j,k}$ be the steady-state probability of state $H_{i,j,k}$, where $0 \leq i \leq M, 0 \leq j \leq N, 0 \leq k \leq K$, then $\pi = [\pi_{H_{i,j,k}}]$ ($\forall H_{i,j,k} \in H$) is the system steady-state distribution. Since the transition conditions triggering state transitions under different events are different, the equilibrium equation system of the 3 D CTMC should be composed of the following (5)-(25).

(1) For $i = 0$,

1) When $j = 0, k = 0$,

$$\begin{aligned} \pi_{0,0,0} [M\lambda_{PU} + N\lambda_{CU}P_{cs}(0) + N\lambda_{CU}(1 - P_{cs}(0))] \\ = \pi_{0,1,0}\mu_{CU} + \pi_{1,0,0}\mu_{PU}. \end{aligned} \quad (5)$$

2) When $0 < j < M, k = 0$,

$$\begin{aligned} \pi_{0,j,0} [j\mu_{CU} + M\lambda_{PU} + (N - j)\lambda_{CU}P_{cs}(j) \\ + (N - j)\lambda_{CU}(1 - P_{cs}(j))] \\ = \pi_{0,j-1,0}(N - (j - 1))\lambda_{CU}P_{cs}(j - 1) + \pi_{1,j,0}\mu_{PU} \\ + \pi_{0,j-1,1} \exp(-(N - j)\lambda_{CU})P_{cs}(j - 1) \\ + \pi_{0,j+1,0}(j + 1)\mu_{CU}. \end{aligned} \quad (6)$$

3) When $0 < j < M, 0 < k < K$,

$$\begin{aligned} \pi_{0,j,k} [j\mu_{CU} + M\lambda_{PU} + (N - j - k)\lambda_{CU}P_{cs}(j) \\ + (N - j)\lambda_{CU}(1 - P_{cs}(j)) + \exp(-(N - j - k)\lambda_{CU})P_{cs}(j)] \\ = \pi_{0,j-1,k}(N - (j + k - 1))\lambda_{CU}P_{cs}(j - 1) + \pi_{0,j+1,k}(j + 1) \\ \cdot \mu_{CU} + \pi_{0,j-1,k+1} \exp(-(N - j - k)\lambda_{CU})P_{cs}(j - 1) \\ + \pi_{0,j,k-1}(N - (j + k - 1))\lambda_{CU}(1 - P_{cs}(j)) + \pi_{1,j,k}\mu_{PU}. \end{aligned} \quad (7)$$

4) When $j = 0, 0 < k < K$,

$$\begin{aligned} \pi_{0,0,k} [M\lambda_{PU} + (N - k)\lambda_{CU}P_{cs}(0) + \exp(-(N - k)\lambda_{CU}) \\ \cdot P_{cs}(0) + (N - k)\lambda_{CU}(1 - P_{cs}(0))] \\ = \pi_{1,0,k}\mu_{PU} + \pi_{0,1,k}\mu_{CU} \\ + \pi_{0,0,k-1}(N - (k - 1))\lambda_{CU}(1 - P_{cs}(0)). \end{aligned} \quad (8)$$

5) When $j = M, k = 0$,

$$\begin{aligned} \pi_{0,M,0} [M\mu_{CU} + (N - M)\lambda_{CU}] = \pi_{0,M-1,0}(N - (M - 1)) \\ \lambda_{CU}P_{cs}(M - 1) + \pi_{0,M-1,1} \exp(-(N - M)\lambda_{CU})P_{cs}(M - 1). \end{aligned} \quad (9)$$

6) When $j = M, 0 < k < K$,

$$\begin{aligned} \pi_{0,M,k} [M\mu_{CU} + (N - M - k)\lambda_{CU}] = \pi_{0,M,k-1}(N - (M + k \\ - 1))\lambda_{CU}(1 - P_{cs}(M)) + \pi_{0,M-1,k}(N - (M + k - 1))\lambda_{CU} \\ P_{cs}(M) + \pi_{0,M-1,k+1} \exp(-(N - M - k)\lambda_{CU})P_{cs}(M - 1). \end{aligned} \quad (10)$$

7) When $j = 0, k = K$,

$$\begin{aligned} \pi_{0,0,K} [M\lambda_{PU} + (N - K)\lambda_{CU}P_{cs}(0) + (N - K)\lambda_{CU} \\ + \exp(-(N - K)\lambda_{CU})P_{cs}(0)] = \pi_{0,1,K}\mu_{CU} + \pi_{1,0,K}\mu_{PU} \\ + \pi_{0,0,K-1}(N - (K - 1))\lambda_{CU}(1 - P_{cs}(0)). \end{aligned} \quad (11)$$

8) When $0 < j < M, k = K$,

$$\pi_{0,j,K} [j\mu_{CU} + M\lambda_{PU} + (N - j - K)\lambda_{CU}P_{cs}(j)$$

$$\begin{aligned}
 & + (N - j - K) \lambda_{CU} + \exp(-(N - j - K) \lambda_{CU}) P_{cs}(j)] \\
 & = \pi_{0,j-1,K} (N - (j + K - 1)) \lambda_{CU} P_{cs}(j - 1) \\
 & + \pi_{0,j+1,K} (j + 1) \mu_{CU} \\
 & + \pi_{0,j,K-1} (N - (j + K - 1)) \lambda_{CU} (1 - P_{cs}(j)) + \pi_{1,j,K} \mu_{PU}. \quad (12)
 \end{aligned}$$

9) When $j = M, k = K$,

$$\begin{aligned}
 & \pi_{0,M,K} [(N - M - K) \lambda_{CU} + (N - M - K) \mu_{CU}] \\
 & = \pi_{0,M,K-1} (N - (M + K - 1)) \lambda_{CU} (1 - P_{cs}(M)) \\
 & + \pi_{0,M-1,K} (N - (M - 1 + K)) \lambda_{CU} P_{cs}(M - 1). \quad (13)
 \end{aligned}$$

(2) For the case of $0 < i < M$,

1) When $j = 0, k = 0$,

$$\begin{aligned}
 & \pi_{i,0,0} [(M - i) \lambda_{PU} + N \lambda_{CU} P_{cs}(i) + i \mu_{PU} \\
 & + N \lambda_{CU} (1 - P_{cs}(i))] \\
 & = \pi_{i,1,0} \mu_{CU} + \pi_{i+1,0,0} \mu_{PU} + \pi_{i-1,0,0} (M - (i - 1)) \lambda_{PU}. \quad (14)
 \end{aligned}$$

2) When $0 < j < M, k = 0$,

$$\begin{aligned}
 & \pi_{i,j,0} [j \mu_{CU} + i \mu_{PU} + (M - i) \lambda_{PU} + (N - j) \lambda_{CU} P_{cs}(i + j) \\
 & + (N - j) \lambda_{CU} (1 - P_{cs}(i + j))] \\
 & = \pi_{i,j+1,0} (j + 1) \mu_{CU} + \pi_{i,j-1,0} \\
 & (N - (j - 1)) \lambda_{CU} P_{cs}(i + j - 1) \\
 & + \pi_{i-1,j,0} (M - (i - 1)) \lambda_{PU} \\
 & + \pi_{i+1,j,0} (i + 1) \mu_{PU} + \pi_{i,j-1,1} \\
 & \exp(-(N - j) \lambda_{CU}) P_{cs}(i + j - 1). \quad (15)
 \end{aligned}$$

3) When $0 < j < M, 0 < k < K$,

$$\begin{aligned}
 & \pi_{i,j,k} [j \mu_{CU} + i \mu_{PU} + (M - i) \lambda_{PU} + \exp(-(N - j - k) \lambda_{CU}) \\
 & \cdot P_{cs}(i + j) + (N - j - k) \lambda_{CU} P_{cs}(i + j) + (N - j - k) \lambda_{CU} \\
 & \cdot (1 - P_{cs}(i + j))] = \pi_{i+1,j,k} (i + 1) \mu_{PU} \\
 & + \pi_{i-1,j,k} (M - (i - 1)) \lambda_{PU} \\
 & + \pi_{i,j-1,k} (N - (j - 1 + k)) \lambda_{CU} P_{cs}(i + j - 1) \\
 & + \pi_{i,j+1,k} (j + 1) \mu_{CU} \\
 & + \pi_{i,j,k-1} (N - (j + k - 1)) \lambda_{CU} (1 - P_{cs}(i + j)) \\
 & + \pi_{i,j-1,k+1} \exp(-(N - j - k) \lambda_{CU}) P_{cs}(i + j - 1). \quad (16)
 \end{aligned}$$

4) When $j = 0, 0 < k < K$,

$$\pi_{i,0,k} [(M - i) \lambda_{PU} + (N - k) \lambda_{CU} P_{cs}(i)$$

$$\begin{aligned}
 & + (N - k) \lambda_{CU} (1 - P_{cs}(i)) + e^{-(N-k) \lambda_{CU}} P_{cs}(i)] \\
 & = \pi_{i,0,k-1} (N - (k - 1)) \lambda_{CU} (1 - P_{cs}(i)) + \pi_{i,1,k} \mu_{CU} \\
 & + \pi_{i+1,0,k} (i + 1) \mu_{PU} + \pi(i - 1, 0, k) (M - (i - 1)) \lambda_{PU}. \quad (17)
 \end{aligned}$$

5) When $i + j = M, k = 0$,

$$\begin{aligned}
 & \pi_{i,M-i,0} [i \mu_{PU} + (M - i) \mu_{CU} + (N - (M - i)) \lambda_{CU} \\
 & (1 - P_{cs}(M))] = \pi_{i-1,M-i,0} (M - (i - 1)) \lambda_{PU} + \pi_{i,M-i-1,0} \\
 & (N - (M - i - 1)) \lambda_{CU} P_{cs}(M - 1) + \pi(i, M - i - 1, 1) \\
 & \exp(-(N - (M - i - 1)) \lambda_{CU}) P_{cs}(M - 1). \quad (18)
 \end{aligned}$$

6) When $i + j = M, 0 < k < K$,

$$\begin{aligned}
 & \pi_{i,M-i,k} [i \mu_{PU} + (M - i) \mu_{CU} \\
 & + (N - (M - i - k)) \lambda_{CU} (1 - P_{cs}(M))] \\
 & = \pi_{i,M-i-1,k+1} \exp(-(N - (M - i + k)) \lambda_{CU}) \\
 & P_{cs}(M - 1) + \lambda_{CU} \\
 & \cdot \pi_{i,M-i-1,k} (N - (M - i - 1 + k)) \\
 & P_{cs}(M - 1) + (1 - P_{cs}(M)) \lambda_{CU} \\
 & \cdot \pi_{i,M-i,k-1} (N - (M - i + k - 1)) \\
 & + \pi_{i-1,M-i,k} (M - (i - 1)) \lambda_{PU}. \quad (19)
 \end{aligned}$$

7) When $j = 0, k = K$,

$$\begin{aligned}
 & \pi_{i,0,K} [i \mu_{PU} + (M - i) \lambda_{PU} + (N - K) \lambda_{CU} P_{cs}(i) \\
 & + (N - K) \lambda_{CU} + \exp(-(N - K) \lambda_{CU}) P_{cs}(i)] \\
 & = \pi_{i,0,K-1} (N - (K - 1)) \lambda_{CU} (1 - P_{cs}(i)) \\
 & + \pi_{i+1,0,K} (i + 1) \mu_{PU} + \pi_{i,1,K} \mu_{CU} \\
 & + \pi_{i-1,0,K} (M - (i - 1)) \lambda_{PU}. \quad (20)
 \end{aligned}$$

8) When $0 < j < M, k = K$,

$$\begin{aligned}
 & \pi_{i,j,K} [j \mu_{CU} + (M - i) \lambda_{PU} + (N - j - K) \lambda_{CU} P_{cs}(i + j) \\
 & + i \mu_{PU} + (N - j - K) \lambda_{CU} \\
 & + \exp(-(N - j - K) \lambda_{CU}) P_{cs}(i + j)] \\
 & = \pi_{i,j-1,K} (N - (j - 1 + K)) \lambda_{CU} P_{cs}(i + j - 1) \\
 & + \pi_{i,j+1,K} (j + 1) \mu_{CU} + \pi_{i-1,j,K} (M - (i - 1)) \lambda_{PU} \\
 & + \pi_{i,j,K-1} (N - (j + K - 1)) \lambda_{CU} (1 - P_{cs}(i + j)) \\
 & + \pi_{i+1,j,K} (i + 1) \mu_{PU}. \quad (21)
 \end{aligned}$$

9) When $i + j = M, k = K$,

$$\pi_{i,M-i,K} [i \mu_{PU} + (N - (M - i + K)) \lambda_{CU} + (M - i) \mu_{CU}]$$

$$|H|_{true} = \begin{cases} (K + 1) \sum_{i=0}^M (M - i + 1) + \sum_{i=0}^M (M - i + 1) = \frac{(K + 2)(M + 1)(M + 2)}{2}, N \geq M + K \\ (K + 1)(M + 1) + \sum_{j=1}^M (K - j + 1)(M - j + 1) + \sum_{j=0}^{N-K} (M - j + 1), M \leq K \leq N, N < K + M \\ (K + 1) \sum_{j=0}^{M-K} (M - j + 1) + \sum_{j=M-K+1}^M (N - j + 1)(M - j + 1) + \sum_{j=0}^{N-K} (M - j + 1), M > K, N < K + M \end{cases} \quad (3)$$

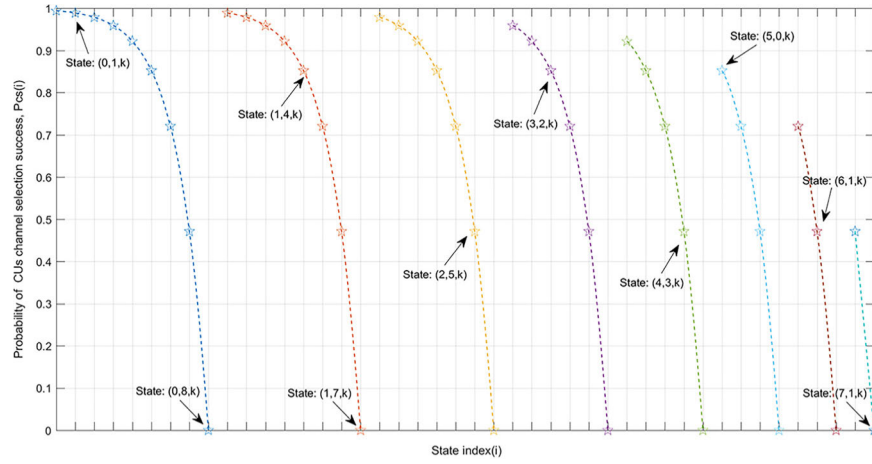


Fig. 4. P_{cs} values related to the system states.

$$\begin{aligned}
 &= \pi_{i-1,M-i,K}(M-(i-1))\lambda_{PU} \\
 &+ \pi_{i,M-i,K-1}(N-(M-i+K-1))\lambda_{CU}(1-P_{cs}(M)) \\
 &+ \pi_{i,M-i-1,K}(N-(M-i-1+K))\lambda_{CU}P_{cs}(M-1).
 \end{aligned} \quad (22)$$

(3) For $i = M$,

1) When $j = 0, k = 0$,

$$\pi_{M,0,0}[M\mu_{PU} + N\lambda_{CU}(1-P_{cs}(M))] = \pi_{M-1,0,0}\lambda_{PU}. \quad (23)$$

2) When $j = 0, 0 < k < K$,

$$\begin{aligned}
 &\pi_{M,0,k}[M\mu_{PU} + (N-k)\lambda_{CU}P_{cs}(M)] \\
 &= \pi_{M,0,k-1}(N-(k-1))\lambda_{CU}(1-P_{cs}(M)) \\
 &+ \pi_{M-1,0,k}\lambda_{PU}.
 \end{aligned} \quad (24)$$

3) When $j = 0, k = K$,

$$\begin{aligned}
 &\pi_{M,0,K}[M\mu_{PU} + (N-K)\lambda_{CU}] \\
 &= \pi_{M-1,0,K-1}(N-(K-1))\lambda_{CU}(1-P_{cs}(M)) \\
 &+ \pi_{M-1,0,K}\lambda_{PU}.
 \end{aligned} \quad (25)$$

Next, the states in the equilibrium equation system formed by (5)-(25) are arranged in lexicographic order. And combined with the normalization condition $\sum_{\forall H_{i,j,k} \in H} \pi_{i,j,k} = 1$ ($\pi_{i,j,k}$ denotes the steady-state probability of state $H_{i,j,k}$), the equilibrium equation system formed by (5)-(25) can be varied to the following form:

$$\Pi Q = 0 \quad (26)$$

$$\Pi e = 1 \quad (27)$$

where $\Pi = [\pi_{0,0,0}, \dots, \pi_{0,M,0}; \dots; \pi_{0,0,K}, \dots, \pi_{0,M,K}; \pi_{1,0,0}, \dots, \pi_{1,M-1,0}; \dots; \pi_{1,0,K}, \dots, \pi_{1,M-1,K}; \dots; \pi_{M,0,0}, \dots, \pi_{M,0,K}] = [\pi_1, \pi_2, \dots, \pi_{|H|_{true}}]$, $e = [1, 1, \dots, 1]_{|H|_{true} \times 1}^T$, Q is the transition rate matrix consisting of transition probabilities from $H_{i,j,k}$ to $H_{m,n,k'}$. Based on the state transitions and P_{cs} defined in part IV.B, the transition rate from $H_{i,j,k}$ to $H_{m,n,k'}$ (denoted as $Q_{(i,j,k)|(m,n,k')} = [q_{(i,j,k)|(m,n,k')}]$) is summarized as shown

in (29). Hence, the main diagonal elements of the transition rate matrix Q are

$$Q_{(i,j,k)|(i,j,k)} = - \sum_{(m,n,k') \neq (i,j,k)} Q_{(i,j,k)|(m,n,k')}.$$

So far, it can be deduced that $Q = [Q_{(i,j,k)|(m,n,k')}]$.

To facilitate understanding, the transition rate matrix with $K = 2, N \geq M + K$ as an example is derived. All states are arranged in lexicographic order as $\Pi = [\pi_{0,0,0}, \dots, \pi_{0,M,0}; \dots; \pi_{0,0,1}, \dots, \pi_{0,M,1}; \pi_{0,0,2}, \dots, \pi_{0,M,2}; \dots; \pi_{1,0,0}, \pi_{1,0,2}, \dots, \pi_{1,M-1,2}; \dots; \pi_{M,0,0}; \pi_{M,0,1}; \pi_{M,0,2}]$, then according to (5) - (25) and (28), the transition rate matrix Q_2 can be derived

$$Q_2 = \begin{bmatrix} E & D & & & & \\ A & E & D & & & \\ & A & E & D & & \\ & & \dots & \dots & \dots & \\ & & & & E & D \\ & & & & A & F \end{bmatrix}_{|H|_{true} \times |H|_{true}}$$

where $E = \begin{bmatrix} -A_0 & B_0 & 0 \\ A_1 & -B_1 & B_0 \\ 0 & A_1 & -C_1 \end{bmatrix}_{[(M-i+1) \times (K+1)]^2}$, B_1 and C_1 , as shown at the bottom of page 12,

$$\begin{aligned}
 F &= \begin{bmatrix} -A_0 & B_0 & 0 \\ 0 & -B_1 & B_0 \\ 0 & 0 & -C_1 \end{bmatrix}_{[(M-i+1) \times (K+1)]^2}, \\
 A &= \begin{bmatrix} A_2 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_2 \end{bmatrix}_{[(M-i) \times (K+1)] \times [(M-i+1) \times (K+1)]}, \\
 D &= \begin{bmatrix} D_0 & 0 & 0 \\ 0 & D_0 & 0 \\ 0 & 0 & D_0 \end{bmatrix}_{[(M-i+2) \times (K+1)] \times [(M-i+1) \times (K+1)]}.
 \end{aligned}$$

where $D_0 = \begin{bmatrix} b_0 + \lambda_{PU} & & \\ & \ddots & \\ & & b_0 + \lambda_{PU} \end{bmatrix}_{(M-i+1) \times (M-i+1)}$,
 B_0 and A_0 , as shown at the bottom of the next page,

$$A_1 = \begin{bmatrix} 0 & e^{-a_0} P_{cs} & & \\ & \ddots & \ddots & \\ & & \ddots & \exp(-a_2) P_{cs} \\ & & & 0 \end{bmatrix}_{(M-i+1) \times (M-i+1)},$$

$$A_2 = \begin{bmatrix} b_1 + \mu_{PU} & & \\ & \ddots & \\ & & b_1 + \mu_{PU} & 0 \end{bmatrix}_{(M-i) \times (M-i+1)},$$

where the dimension of matrix A_0 is $(M-i+1) \times (M-i+1)$. $a_0 = (N-j-k)\lambda_{CU}$, $a_1 = (N-(M-i)-k)\lambda_{CU}$, $b_0 = (M-i)\lambda_{PU}$, $b_1 = i\mu_{PU}$, $c_0 = (M-i)\mu_{CU}$, $c_1 = j\mu_{CU}$.

Since the Markov chain constructed in this paper is irreducible, the linear equation system consisting of (26) and (27) is solvable (i.e., the steady-state probability distributions can be derived). The equilibrium equation system (26)-(27) belongs to a large linear equation system, so the SOR iterative algorithm is adopted to solve it, as shown in Algorithm 2-1. Note that the following should be done before running it.

(1) The equilibrium equation system (26)-(27) is reduced to the following equation:

$$\begin{bmatrix} Q^T \\ 1_{1 \times |H|_{true}} \end{bmatrix} \Pi^T = \begin{bmatrix} 0_{|H|_{true} \times 1} \\ 1 \end{bmatrix} \quad (28)$$

(2) Let $Q' = \begin{bmatrix} Q^T \\ 1_{1 \times |H|_{true}} \end{bmatrix}$ and $b = \begin{bmatrix} 0_{|H|_{true} \times 1} \\ 1 \end{bmatrix}$, equation (28) can be written as $Q'\Pi = b$. (29), as shown at the bottom of the next page.

D. Complexity Analysis of Solving CTMC Model

(1) Time complexity

From the previous section, it is evident that the steady-state probability distribution of the CTMC can be determined by applying Algorithm 2-1 to (26)-(27). The core operation of Algorithm 2-1 is the weighted update of the Gauss-Seidel iteration. For the state $H_{i,j,k}$ and the iteration step r , the formula for updating $\pi_{i,j,k}^{(r+1)}$ by Algorithm 2-1 can be written by [28]:

$$\pi_{i,j,k}^{(r+1)} = (1 - \omega)\pi_{i,j,k}^{(r)} + \frac{\omega}{q(i,j,k)(i,j,k)} [b_{i,j,k}$$

Algorithm 2-1 Successive Over-Relaxation

```

1 Function  $[\pi, n] = \text{sor}(Q', b, \pi, \omega, it_{max})$ 
2    $D = \text{diag}(\text{diag}(Q'))$ ;
3    $L = \text{tril}(Q' - 1)$ ;
4    $U = \text{triu}(Q' - 1)$ ;
5    $M = (D + \omega * L)^{-1} * [(1 - \omega) * D - \omega * U]$ ;
6    $\beta = \omega * [(D + \omega * L)^{-1} * b]$ ;
7    $n = 1$ ;
8   while  $n \leq it_{max}$  do
9      $\pi_{after} = \text{diag}(\text{diag}(M * \pi + \beta))$ ;
10     $\pi = \pi_{after}$ ;
11     $n = n + 1$ ;
12  end
13 end
```

Algorithm 2-2 Successive Over-Relaxation-Calculate.m

```

Input:  $Q', b, \pi, N, \omega$ ,
Output:  $\Pi$ 
1 for  $i = 1 : N$  do
2    $[\pi, n] = \text{sor}(Q', b, \pi, \omega)$ ;
3   fprintf('the result of the d sor.2f iteration: /n', n - 1, \omega);
4   disp(\pi);
5 end
```

$$- \sum_{(m,n,k') < (i,j,k)} q(i,j,k)(m,n,k') \pi_{m,n,k'}^{(r+1)}$$

$$- \sum_{(m,n,k') > (i,j,k)} q(i,j,k)(m,n,k') \pi_{m,n,k'}^{(r)}$$

where the states are accessed in lexicographic order, and ω is the relaxation factor.

The transition rate matrix Q of the CTMC is known to be sparse. Each state $H_{i,j,k}$ can only transition to a limited number of 'neighboring' states $H_{m,n,k}$ (The events that trigger state transitions are discussed in Section IV-B.). Therefore, the single iteration complexity of Algorithm 2-1 is determined by two factors: the number of states in the CTMC, denoted as $|H|_{true}$, and the number of neighbors for each state, represented by d (i.e., the average number of nonzero elements of matrix Q). Where $|H|_{true}$ is given by (3), and according to the state transition events described in Section IV-B and illustrated in Fig. 5, d is typically much smaller than $|H|_{true}$. Consequently, the complexity of a single iteration of Algorithm 2-1 is $O(d|H|_{true})$. In scenarios with high system load, the complexity is dominated by $O(|H|_{true})$.

The number of iterations required for Algorithm 2-1 depends on the desired accuracy, ε , where $\|\pi^{(r+1)} - \pi^{(r)}\| < \varepsilon$, as well as the spectral radius of the iteration matrix, ρ .

$$B_1 = \begin{bmatrix} a_0 + \exp(-a_0) P_{cs} + b_0 + b_1 & a_0 + \lambda_{CU} & \dots \\ c_1 + \mu_{CU} & \dots & \\ \dots & (a_1 + \lambda_{CU}) + \exp(-(a_1 + \lambda_{CU})) P_{cs} + b_0 + b_1 + c_1 & (a_1 + \lambda_{CU}) P_{cs} \\ & c_0 & c_0 + a_1 + b_1 \end{bmatrix}_{(M-i+1) \times (M-i+1)}$$

$$C_1 = \begin{bmatrix} a_0 P_{cs} + \exp(-a_0) P_{cs} + b_0 + b_1 & a_0 + \lambda_{CU} & \dots \\ c_1 + \mu_{CU} & \dots & \\ \dots & (a_1 + \lambda_{CU}) P_{cs} + \exp(-(a_1 + \lambda_{CU})) P_{cs} & (a_1 + \lambda_{CU}) P_{cs} \\ & \dots & + b_0 + b_1 + c_1 \\ & & c_0 + b_1 \end{bmatrix}_{(M-i+1) \times (M-i+1)}$$

However, since the matrix Q in this paper contains coupling transfers (specifically along the parameter k direction), deriving a general expression for the number of iterations is challenging. Nonetheless, we can obtain an approximate expression for the number of iterations of Algorithm 2-1, which is suitable for solving the model presented in this paper. This approximation is derived from the approximate solution of the number of iterations derived by SOR under idealized conditions (uniform transfer rate, ignoring boundary effects, independence of each dimension). Under ideal assumptions, the approximation relies on the asymptotic behavior of the spectral radius:

$$\rho \approx 1 - c \cdot \min \left(\frac{1}{M^2}, \frac{1}{N^2}, \frac{1}{K^2} \right). \quad (30)$$

where c is a constant. Under the optimal ω , the number of iterations can be calculated as [28]: $T_{SOR} = O(\max(M, N, K))$. In the developed CTMC, Algorithm 2-1 may be affected by coupling transfers, varying transfer rates, and boundary conditions; Thus, the actual complexity may deviate from the above approximation. Specifically, coupling transfers along the parameter k direction will slightly increase the spectral radius ρ . If some link transfer rates are significantly higher than others, the condition number of the matrix will increase, resulting in a decrease in convergence speed. The limited transition of boundary states (such as $i = 1, k = K$) will result in the actual number of iterations being higher than the theoretical value. Therefore, based on (30), the coupling factor C and the condition factor α are considered to correct the number of iterations. That is, $T_{it} \approx C \cdot O(\alpha \cdot \max(M, N, K))$, where $C \geq 1$ is a constant, $\max(M, N, K) < \alpha \leq \gamma$.

$\max(M, N, K)$, γ is determined by the maximum/minimum ratio of the link.

In conclusion, the overall time complexity is $O(T_{it} \cdot d \cdot |H|_{true}) = O(C \cdot \alpha \cdot \max(M, N, K) \cdot d \cdot |H|_{true})$. In largescale scenarios, the time complexity is primarily determined by $O(\max(M, N, K) \cdot |H|_{true})$.

(2) Space complexity

The space complexity is mainly determined by the number of steady-state probability vectors and the transfer rate (or matrix Q), where the steady-state probability vectors require storage for $|H|_{true}$ floating-point numbers, resulting in a complexity of $O(|H|_{true})$; matrix Q typically only stores its non-zero elements, leading to a complexity of $O(d \cdot |H|_{true})$. Additionally, it is necessary to store intermediate variables $\pi^{(r)}$ and $\pi^{(r+1)}$ during the iteration in Algorithm 2-1, which usually requires additional $O(|H|_{true})$ space. The space complexity is $O(|H|_{true})$ in large-scale scenarios due to $d \ll |H|_{true}$.

V. PERFORMANCE METRICS

The following system performance metrics can be obtained based on the steady-state distribution, where $\pi_{i,j,k}$ denotes the steady-state probability of state $H_{i,j,k}$.

(1) Average number of CUs transmitting $E[N_{CU}]$:

$$E[N_{CU}] = \sum_{\forall H_{i,j,k} \in H} j \pi_{i,j,k}. \quad (31)$$

(2) Average number of PUs transmitting $E[N_{PU}]$:

$$E[N_{PU}] = \sum_{\forall H_{i,j,k} \in H} i \pi_{i,j,k}. \quad (32)$$

$$B_0 = \begin{bmatrix} (a_0 + \lambda_{CU})(1 - P_{cs}) & & & \\ & \ddots & & \\ & & (a_1 + \lambda_{CU})(1 - P_{cs}) & \\ & & & a_1 \end{bmatrix}_{(M-i+1) \times (M-i+1)},$$

$$A_0 = \begin{bmatrix} a_0 + b_0 + b_1 & a_0 + \lambda_{CU} & & \\ c_1 + \mu_{CU} & \dots & \dots & \\ & \dots & (a_1 + \lambda_{CU}) + b_0 + c_1 & (a_1 + \lambda_{CU}) P_{cs} \\ & & c_0 & c_0 + a_1 \end{bmatrix},$$

$$Q(i,j,k)|(m,n,k') = \begin{cases} (M-i)\lambda_{PU} & m = i+1, 0 \leq i+1 < M, n = j, k' = k, k \in \{0, 1, 2, \dots, K\} \\ i\mu_{PU} & m = i-1, i \geq 1, n = j, 0 \leq i+j \leq M, k' = k, k \in \{0, 1, 2, \dots, K\} \\ (N-j-k)\lambda_{CU}P_{cs} & m = i, n = j+1, 0 \leq i+j < M, k' = k, k \in \{0, 1, 2, \dots, K\} \\ j\mu_{CU} & m = i, n = j-1, j \geq 1, 0 \leq i+j \leq M, k' = k, k \in \{0, 1, 2, \dots, K\} \\ (N-j-k)\lambda_{CU}(1-P_{cs}) & m = i, n = j, 0 \leq i+j \leq M, k' = k, k \in \{0, 1, 2, \dots, K-1\} \\ (N-j-k)\lambda_{CU} & m = i, n = j, i+j = M, k' = k, k \in \{0, 1, 2, \dots, K-1\} \\ \exp(-(N-j-k)\lambda_{CU})P_{cs} & m = i, n = j, 0 \leq i+j < M, k' = k, k \in \{1, 2, \dots, K\} \\ (N-j-K)\lambda_{CU}(1-P_{cs}) & m = i, n = j, 0 \leq i+j < M, k' = K \\ (N-j-K)\lambda_{CU} & m = i, n = j, i+j = M, k' = K \\ 0 & OW. \end{cases} \quad (29)$$

- (3) The average number of channels occupied in the system $E[A_{busy}]$, i.e., the average number of channels occupied by the PUs and CUs transmitting:

$$E[A_{busy}] = E[N_{PU}] + E[N_{CU}] \\ = \sum_{\forall H_{i,j,k} \in H} (i+j) \pi_{i,j,k}. \quad (33)$$

- (4) CUs traffic load δ , i.e., the ratio of the total CUs traffic $E[P]$ generated by N CUs to all spectrum holes (or idle channels) θ in M PCs:

$$\delta = \frac{E[P]}{\theta} \\ = \frac{p_{on} \times N}{p_{idle} \times M}. \quad (34)$$

where p_{on} denotes the probability of generating CUs traffic and $p_{on} = \lambda_{CU} / (\lambda_{CU} + \mu_{CU}) \cdot p_{idle}$ is channel idleness probability and $p_{idle} = \mu_{PU} / (\lambda_{PU} + \mu_{PU})$.

- (5) Average CUs throughput $E[T]$, i.e., the ratio of the average number of CUs transmitting to the total number of CUs:

$$E[T] = \frac{E[N_{CU}]}{N} \\ = \frac{\sum_{\forall H_{i,j,k} \in H} j \pi_{i,j,k}}{N}. \quad (35)$$

- (6) Successful transmission probability p_s , i.e., the probability that CUs with transmission requests can find available channels and can achieve successful transmission on the selected channels:

$$p_s = \frac{E[N_{CU}]}{N \times p_{on}} \\ = \frac{\sum_{\forall H_{i,j,k} \in H} j \pi_{i,j,k}}{N \times p_{on}}. \quad (36)$$

- (7) Spectrum holes utilization Θ , i.e., the ratio of available channels be used to transmit CUs to the total available channels in all M channels:

$$\Theta = \frac{E[N_{CU}]}{M p_{idle}} \\ = \frac{\sum_{\forall H_{i,j,k} \in H} j \pi_{i,j,k}}{M p_{idle}}. \quad (37)$$

VI. SIMULATION RESULTS

In this section, several sets of simulations, including Monte Carlo simulation and numerical analysis based on the results of Section V, are established to verify the effectiveness of the proposed strategy. The relevant parameters are set as follows: $\lambda_{CU} = 1$, $\mu_{CU} = 1$, $\lambda_{PU} = 0.4$, $\mu_{PU} = 2$, $\omega = 1$. And set the number of PCs to $M = 8$ and $M = 16$ for comparison. To facilitate discussion, the maximum buffer capacity is set to $K = 2$. This choice is based on the following considerations. Setting $K = 2$ represents the simplest nontrivial case that effectively demonstrates the core queuing behavior of the system while keeping the state space complexity minimal. Specifically, $K = 2$ allows the system to showcase all essential states: the buffer being empty, the buffer being nonempty, and

buffer overflow. Moreover, during the experiment, a comparative analysis with the BFC scheme [12] (the scheme adopts the discard strategy after the CU transmission fails) is added to highlight the advantages of the buffer setting in the proposed strategy.

A. Effect of the Number of CUs

In this set of simulations, the impact of increasing CUs' traffic demands on the performance of the OMCS-FB versus the BFC strategy is tested. Therefore, the test environment should be conducted with sufficient spectrum holes, i.e., $CU_{demand} \leq PU_{resource}$, the spectrum resources required for CUs traffic should not exceed the total available spectrum resources through all PCs. As shown in Fig. 6, the analysis results are basically consistent with the simulation results, which verifies the effectiveness of the proposed scheme.

Moreover, with the increase of CUs traffic load (ratio range: 0.04 – 1.2), we compare and analyze successful transmission probability and spectrum utilization under the two strategies.

As shown in Fig. 6a, as the demand for CUs traffic increases, the competition for idle spectra becomes more intense. Under both OMCS-FB and BFC strategies, the probability of successful transmission tends to decrease, which is a natural result of competition. And since CUs' transmission requests need to be matched with available spectra, the successful transmission probability cannot be equal to 1 even when only one CU is in the network. In Fig. 6b, as the CUs traffic increases, the probability of successfully matching the idle spectra with CUs' transmission demands becomes larger. Under these two channel selection strategies, spectrum utilizations are on the rise. However, in the OMCS-FB, CUs that fail in transmission have the opportunity to achieve successfully transmit by recompeting for channels due to CUs follow the nonconservative operation principle (i.e., if a CU fails to transmit, it can enter the buffer and wait for the next transmission opportunity). Hence, the spectrum utilization Θ and successful transmission probability p_s of the OMCS-FB are always superior to those of the BFC strategy that adopts the conservative principle (i.e., if a CU transmission fails, it can only be discarded). Moreover, a greater number of PCs implies a higher probability of optimum matching CUs transmission demands with available spectra so that the p_s and Θ for $M = 16$ are better than $M = 8$.

B. Effect of CUs Packet Size

In this set of simulations, we analyze the impact of CUs packet size (equivalent to the "T" duration μ_{CU}^{-1} of CUs) on the performance of BFC and OMCS-FB in terms of both successful transmission probability and the average CU throughput. Set two sets of parameters, $M = 8, N = 10$ and $M = 16, N = 18$, and let $\lambda_{PU}^{-1} = 2.5$. As shown in Fig. 7, the analysis results are in good agreement with the simulation results, which verifies the effectiveness of the proposed scheme.

In Fig. 7a, it can be clearly seen that the successful transmission probability decreases as the average CUs "T" (or "O") duration increases (i.e., the CUs packet become

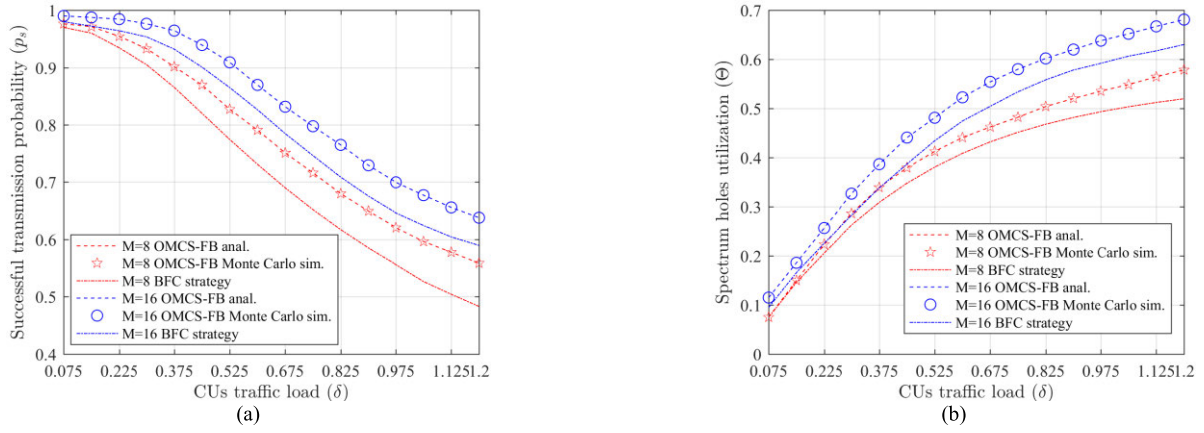


Fig. 6. CUs traffic load (the number of CUs) versus the performance of OMCS-FB and BFC for $\lambda_{CU} = 1$, $\mu_{CU} = 1$, $\lambda_{PU} = 0.4$, $\mu_{PU} = 2$, $K = 2$, $M = \{8, 16\}$. (a) successful transmission probability. (b) spectrum utilization.

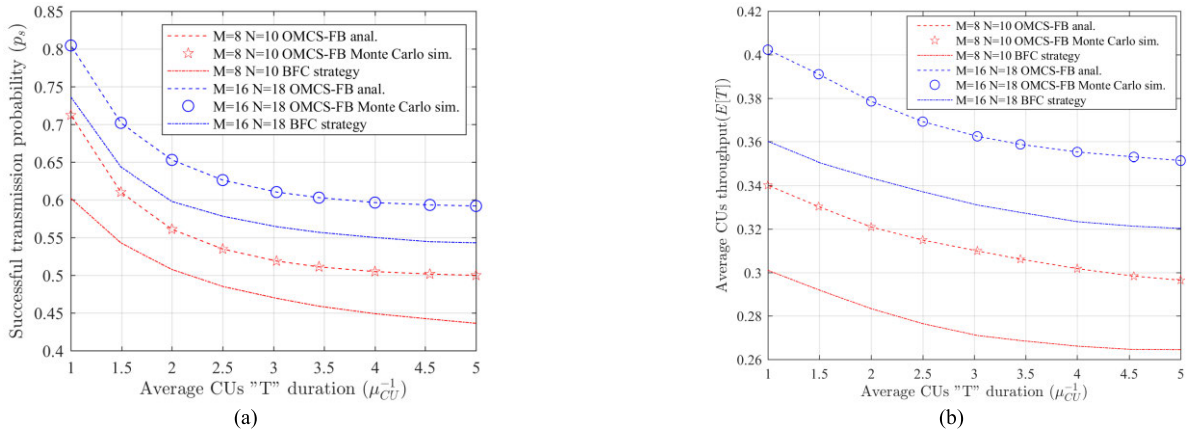


Fig. 7. CUs packet size (average CUs "T" duration) versus the performance of OMCS-FB and BFC for $\lambda_{PU}^{-1} = 2.5$, $\mu_{PU} = 2$, $\lambda_{CU} = 1$, $K = 2$. (a) successful transmission probability. (b) average throughput.

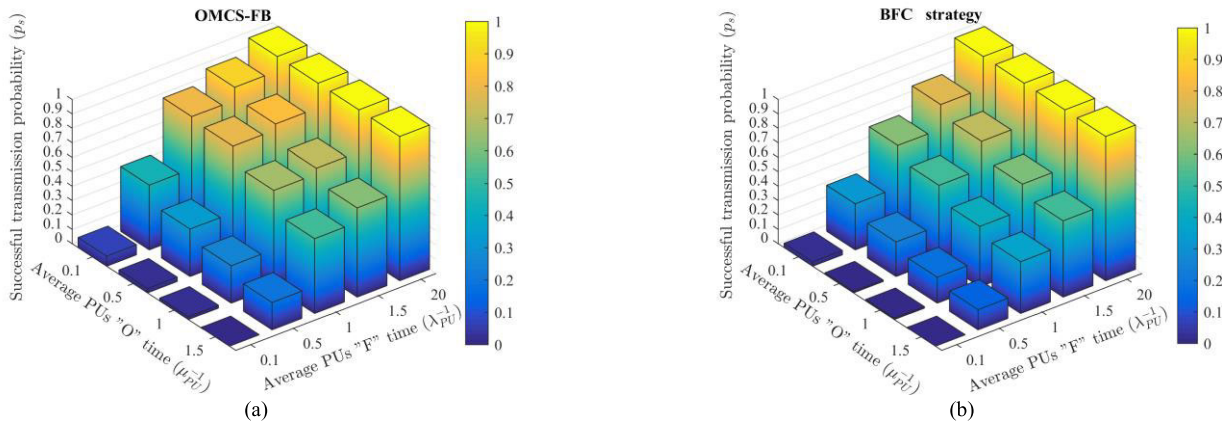


Fig. 8. Successful transmission probability vs. PUs traffic activities for $\lambda_{CU} = 1$, $\mu_{CU} = 1$, $M = 10$, $N = 8$. (a) the OMCS-FB strategy. (b) the BFC strategy.

larger) under both strategies. Since the BFC strategy does not consider whether CUs can have opportunities to transmit again after transmission failure, and it directly chooses discard them, the OMCS-FB has a higher probability of successful transmission than the BFC strategy. As shown in Fig. 7b, as CUs packet become progressively larger, i.e., the average CUs transmission duration time increases (in the range of

1 – 5), the average CUs throughput shows downward trends, which indicates that when the average CUs "T" duration time is significantly shorter than the average "F" duration time of PUs, CUs are more likely to get the opportunity to match the optimal idle spectra. In other words, with the continuous increase of CUs packet, the transmission demands of CUs are getting closer to the average spectrum hole lengths of PUs

and gradually exceeding them, which reduces the possibility of CUs successfully matching with finite spectrum holes, thereby leading to the average CUs throughput being reduced. Since CUs that fail to compete still have opportunities to wait for the next transmission under the OMCS-FB, its average CUs throughput is higher than that of the BFC strategy. Thereby, we can conclude that the longer the spectrum idle duration time of the PC (i.e., the larger λ_{PU}^{-1}) and the CU average “T” duration time μ_{CU}^{-1} is significantly shorter than λ_{PU}^{-1} , the greater the average throughput $E[T]$ and the higher successful transmission probability p_s of the CU.

C. Effect of PUs Traffic Activities

In this group of simulations, let $M = 10, N = 8, \lambda_{CU} = 1$, and $\lambda_{CU} = 1$. By setting different the PC parameters, i.e., letting PUs “O” duration as $\mu_{PU}^{-1} = \{0.1, 0.5, 1, 1.5\}$ and PUs “F” duration as $\lambda_{PU}^{-1} = \{0.1, 0.5, 1, 1.5, 20\}$, the successful transmission probabilities of both OMCS-FB and BFC strategies are analyzed. If the PC is busy for too long, it is difficult for the CU to access it to get the service, so $\mu_{PU}^{-1} = 20$ is not considered in the set of parameters μ_{PU}^{-1} .

As shown in Fig. 8, under the same PUs “O” (“F”) duration, the probabilities of successful transmission under both different strategies trend to increase (decrease) as the PUs “F” (“O”) duration increases, and the performance of the OMCS-FB significantly outperforms that of the BFC strategy. Moreover, it is noted that the relative values of CUs traffic activity parameters and PUs traffic activity parameters are actual parameters that affect system performances, which further confirms the conclusion drawn in part VI.B. Thus, if the parameters of the PN cannot be adapted, we can also ensure the efficient operation of the network by adjusting the CUs traffic parameters. Specifically, the average CUs “T” time can be set to be significantly shorter than the average PUs “F” duration based on the PC characteristics to improve spectrum utilization and CUs throughput, i.e., $\mu_{CU}^{-1} \ll \lambda_{PU}^{-1}$.

D. Effect of the Sequential Sensing Model

In this set of simulations, the effects of the number of PCs and the activity of PUs on the average idle-channel-search delay and average access delay of OMCS-FB are analyzed based on the OMCS-FB candidate sequence no-ordering scheme and the fixed polling scheme. The difference between the OMCS-FB candidate sequence no-ordering scheme and the OMCS-FB is that the available channels in the channel candidate sequence are not sorted. The average idle-channelsearch delay is defined as the time taken by the CU from the beginning of the search until the available channel is found. In the simulation process, the PU “F” duration is set to $\lambda_{PU}^{-1} = \{2, 10\}$, the average CUs “T” duration is $\mu_{CU}^{-1} = 1$, and the sensing delay is $T_{se} = 1$ ms.

As illustrated in Fig. 9(a) and Fig. 9(b), the average idle-channel-search delay and the average channel access delay under the fixed polling scheme are significantly lower than those of the OMCS-FB and OMCS-FB no-ordering schemes as the number of channels increases. That is because in the fixed polling scheme, after the CU arrives, it must wait for

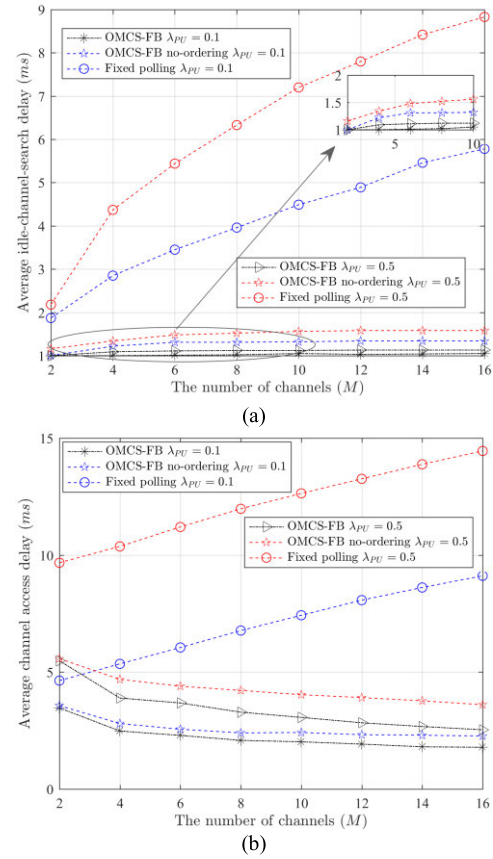


Fig. 9. The number of channels versus the performance of OMCS-FB, OMCS-FB no-ordering, and fixed polling scheme for $\lambda_{PU} = \{0.1, 0.5\}$, $\mu_{CU} = 1$, $N = 10$, $K = 2$. (a) average idle-channel-search delay. (b) average access delay.

its channel to be polled. As the number of channels increases, the polling period also lengthens. The OMCS-FB and OMCS-FB no-ordering schemes improve efficiency by utilizing the candidate channel sequence. Specifically, the available channel that satisfies the channel idle duration greater than or equal to the CU transmission demand is added to the channel candidate sequence in advance, which enables the CU to quickly find its available channel.

In Fig. 9 (a), when $\lambda_{PU} = 0.1$, the average search delay of OMCS-FB and OMCS-FB no-ordering schemes is not much different. That is because the average PU “F” duration is much longer than the average CU “T” duration, that is, $\lambda_{PU}^{-1} = 10 > 1 = \mu_{CU}^{-1}$. As the average PU “F” duration decreases, that is, when λ_{PU} changes from 0.1 to 0.5, the average search delay of the OMCS-FB scheme shows significant improvement compared to the OMCS-FB no-ordering scheme. This improvement can be attributed to the organized arrangement of candidate sequences, which enables CUs to quickly find available channels that meet their transmission requirements, especially during frequent PUs activities. That is also the reason why the average search delay under OMCS-FB is less sensitive to the number of channels. In Fig. 9(b), as the number of channels increases, the average channel access delay for the OMCS-FB and OMCS-FB disorder schemes tends to decrease. That occurs because having more channels spreads out the competition, thereby reducing the collision

TABLE I
ERROR CATEGORIES AND THEIR CORRESPONDING SCENARIO EXAMPLES AND PARAMETER SETTINGS

Error category			Error parameter		
Name	Definitions	Simple example	Scenario	Mean	Variance
Underestimate	Estimated spectrum hole durations are shorter than the actual hole durations.	CU request 	UE I	-0.9	0.1
		Estimated hole size 	UE II	-0.5	0.1
		Actual hole size 	UE III	-0.1	0.1
Overestimate	Estimated spectrum hole durations are longer than the actual hole durations.	CU channel access result 	OE I	0.1	0.1
		CU request 	OE II	0.5	0.1
		Estimated hole size 	OE III	0.9	0.1
Rand	Estimated hole duration may be shorter or longer than the actual duration.	Actual hole size 	R I	-0.1	0.1
		CU channel access result 	R II	-0.5	0.5
		Refer to the example diagrams of the first two error categories.	R III	-0.9	0.9
Exact	Previous research scenarios (Exact estimation)	CU request 	E	0	0
		Estimated hole size 			
		Actual hole size 			
		CU channel access result 			

backoff delay, especially when the number of channels significantly exceeds the number of CUs. As the average PU “F” duration decreases, the average access delay performance of both the OMCS-FB and the OMCS-FB no-ordering schemes declines. This decline occurs because fewer available spectrum holes result in intensified competition, leading to longer collision backoff delay. However, the OMCS-FB scheme consistently outperforms the OMCS-FB disordered scheme. This advantage is due to the disorganized nature of the candidate channel sequences in the OMCS-FB no-ordering scheme; channels with longer durations of available spectrum holes may be occupied first by CUs with lower transmission requirements, resulting in CUs with higher transmission requirements experiencing increased backoff delays.

E. Effect of Channel Idle Time (or Spectrum Hole) Durations Estimation Error

The previous sections were conducted under the assumption that CUs can accurately estimate the duration of spectral holes. However, this assumption is considered unrealistic. Therefore, in this set of simulations, taking $M = 8, N = 12$ as an example, the impacts of estimation errors on the spectrum utilization success and the total number of spectrum utilization attempts (including both successful and failed attempts) for the OMCS-FB and BFC strategies are investigated.

At present, many spectra sensing methods (including energy-based [29], cooperative [30], and machine learning

methods [27]) are exploited to estimate or predict the duration of spectrum holes. However, due to the inherent feedback delay and quantization flaws in actual wireless systems, the existing methods inevitably lead to false detection [27]. Therefore, estimation errors can be divided into the following three categories:

- 1) Underestimate: Estimated spectrum hole durations are always shorter than the actual hole durations. In this case, since CUs are underestimating the actual hole durations, they may consider that the actual hole durations are not long enough for their transmission, thereby resulting in channel access failures. That may cause the spectrum holes that originally meet their transmission requirements to be wasted, resulting in low spectrum utilization and low CU throughput.
- 2) Overestimate: Estimated spectrum hole durations are always longer than the actual hole durations. In this situation, the cognitive user will overestimate the actual spectrum hole durations and believe that the actual hole durations can meet their transmission requirements, thus attempting to access PCs. Moreover, this process may cause interference with PUs. Therefore, in this scenario, it is assumed that the PUs’ tolerable interference threshold I_{th} is 0.1. If the interference I to PUs during CUs transmission attempts is higher than the threshold I_{th} that PUs can tolerate, that is, $I \geq I_{th}$ (where I is the ratio of the interference duration to

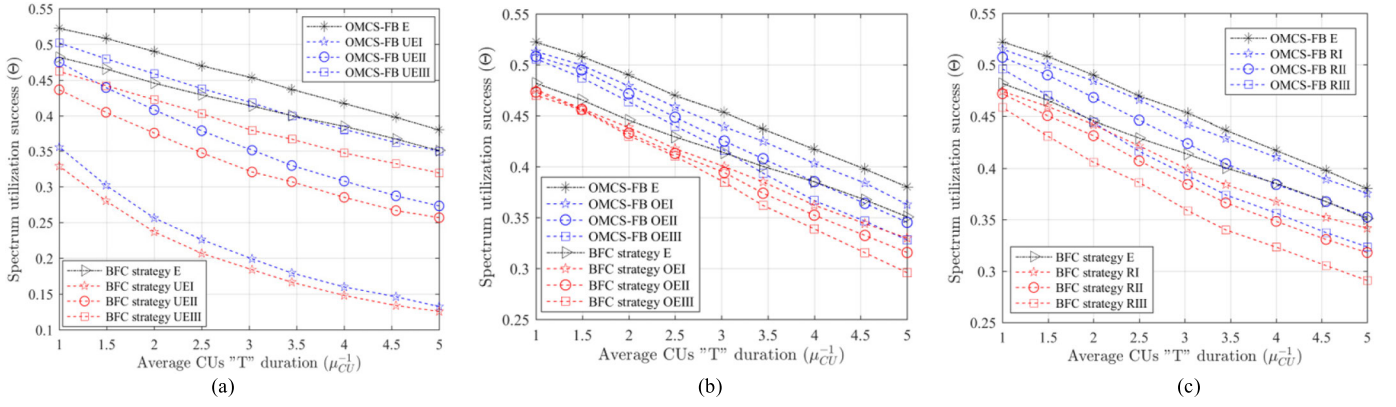


Fig. 10. Average CUs' T duration versus the spectrum utilization success of OMCS-FB and BFC under various error categories for $\lambda_{PU} = 0.4, \lambda_{CU} = 1, \mu_{CU} = 1, M = 8, N = 10$. (a) Underestimate: UE I, UE II and UE III. (b) Overestimate: OE I, OE II and OE III. (c) Rand: RI, RII and RIII.

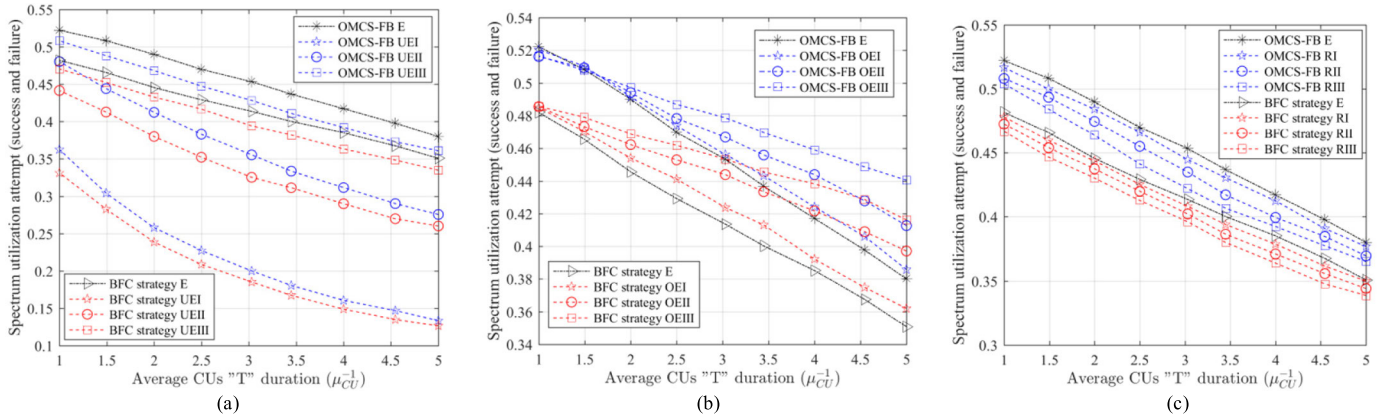


Fig. 11. Average CUs "T" duration versus the spectrum utilization attempt of OMCS-FB and BFC for $\lambda_{PU} = 0.4, \lambda_{CU} = 1, \mu_{CU} = 1, M = 8, N = 10$. (a) Underestimate: UE I, UE II and UE III. (b) Overestimate: OE I, OE II and OE III. (c) Rand: RI, RII and RIII.

the transmission duration), CUs transmission attempt fails.

- 3) Rand: Estimated spectrum hole durations may be shorter or longer than the actual.

Table I provides an overview of the above three error categories, and simple examples of these three error categories are attached. The Exact category refers to the previously studied scenario with precise estimation, where CUs can accurately estimate the durations of the actual spectrum holes without interfering with PUs.

The estimated duration can be calculated as $\hat{L} = L + F(L \times v, L \times \rho)$ [11], where L represents the actual size of the spectral hole, and $F(L \times v, L \times \rho)$ is the error function, where v is the mean parameter and ρ is the variance parameter. In the Rand scene, F obeys uniform distribution, while in other scenes, F obeys normal distribution. In the simulation process, the low, medium and high error scenarios under three error categories are discussed respectively, that is, Underestimate: UE I, UE II and UE III; Overestimate: OE I, OE II and OE III; Rand: RI, RII and RIII, the corresponding values of v and ρ are shown in Table I (including the Exact category).

As shown in Fig. 10 and Fig. 11, the influence of average CUs "T" duration on the spectrum utilization success and spectrum utilization attempt of OMCS-FB and BFC strategies under three error categories, Underestimate, Overestimate,

and Rand, is analyzed, respectively. To facilitate comparative analysis, the performance curves in the Exact scenario are added to each scenario diagram. It is noted that the spectrum utilization success means the success of CUs transmission attempts, that is, spectrum holes are successfully utilized. The spectrum utilization attempt includes all the transmission attempt results, that is, CUs transmission attempts to succeed or fail. Obviously, with the increase of the average CUs "T" duration, the spectrum utilization success and spectrum utilization attempt of OMCS-FB and BFC strategies in each error scenario show a downward trend. That is because the longer CU "T" duration is, the more difficult it is to find the spectrum hole that meets its transmission requirement, especially when the CU "T" duration is close to or longer than the average PU "F" duration. That again verifies the conclusion in Section VI-B. Furthermore, in all scenarios, the performance of the OMCS-FB is consistently superior to that of the BFC strategy. That is attributed to the non-conservative operation principle of the OMCS-FB, which enables CU to still have the opportunity to find the available spectrum after competition failure.

Under the Underestimate category, as shown in Fig. 10(a) and Fig. 11(a), since the estimated spectrum hole durations are longer than the actual hole durations, the probabilities of CUs attempting transmission are very low. Especially in the

high error scenario UE I, the spectrum opportunity attempt is significantly lower than the results in the exact estimation E scenario. That resulted in the original available spectrum holes not being used reasonably, thereby causing lower spectrum utilization. This phenomenon is more obvious when the transmission demand of CU is larger. Although the nonconservative operation principle of OMCS-FB increases the chances of transmission attempts for CUs, the severe “Underestimate” error makes its gain effect worse than the medium (UEII) and low (UEIII) error scenarios. For example, when $\mu_{CU}^{-1} = 3$, when the Θ of the accurately estimated OMCS-FB scenario E is 0.4533, the Θ in the UE I scenario is 0.1991, while the Θ in the UE II and UE III scenarios is 0.3516 and 0.4182, respectively.

Under the Overestimate category, as shown in Fig. 10(b) and Fig. 11(b), the opportunities of CU attempting transmission are significantly higher than those in the Underestimate category. That is precisely because, under the Overestimate category, the CU’s estimation of the actual spectrum hole is too optimistic. Even if the transmission time of the CU is longer than the actual hole duration, the transmission of the CU cannot be interrupted as long as its interference with the PU is lower than the threshold. That is also the reason why the spectrum utilization attempts in the three estimation error scenarios in Fig. 11(b) are higher than those in the E scenarios. When the transmission demand of the CU is significantly lower than the duration of the spectrum hole (i.e., the PU “F” duration), the performance in these three error scenarios is close to the E scenario. That is because the shorter the duration of CU “T”, the greater the probability of finding available spectrum. Even if there is an estimation error, that is, the estimated value is greater than the actual value, the actual spectrum hole duration is sufficient to meet its demand, so that it cannot cause interference or slight interference with the PU, and transmission interruption cannot occur. Therefore, in Fig. 10(b), although the non-conservative operation principle adopted by OMCS-FB has significant advantages, when the spectrum hole duration fails to meet the transmission requirement of CU, the spectrum utilization success in the high-error scenario is still not as good as that in the BFC E scenario.

The Rand category is shown in Fig. 10(c) and Fig. 11(c). The performance of OMCS-FB with low error in the R I scenario is not significantly different from that in the E scenario. That is due to the non-conservative operation principle adopted by OMCS-FB, which is that the existence of the buffer increases the retransmission opportunities for CU and reduces the impact of low Rand error estimation. However, the spectrum utilization success in the medium or high error scenario is much lower than that in the E scenario.

Therefore, the performance of OMCS-FB is closely related to the accuracy of spectrum hole estimation, and the higher the transmission demand of CU, the higher the accuracy of spectrum hole estimation is.

F. Discussions and Next Work

In CRAHNS, for CUs to effectively utilize the spectrum holes and minimize interference to PUs, it is necessary to

complete the following three basic actions: spectrum sensing, spectrum management, and autonomous communication. Cognitive users need to identify spectrum holes and determine whether they are available during spectrum sensing; Based on sensing results, CUs determine whether to access through the channel selection strategy. Finally, CUs communicate in the specified frequency band according to the selection results. It can be seen that CU throughput and spectrum utilization depend on whether the spectrum sensing is accurate and the spectrum management is efficient. Moreover, spectrum sensing and spectrum management are complementary and interdependent [31].

The performance of OMCS-FB proposed in this paper depends on the assumption that CU can accurately estimate the PU traffic transmission mode, that is, the duration of PU “O” and “F”. A considerable number of studies have focused on exploring ways to enhance the estimation accuracy of the available duration of spectrum holes in CRNs or the prediction accuracy of the activity cycle of PUs traffic. Reference [32] utilized the alternating update theory to predict PUs’ on and off cycles. The results show that the proposed scheme can discover more than 98% of the analytical maximum of available spectrum holes. In [33], the author determined the sensing duration of each user/channel pair by utilizing the diversity of the signal-to-noise ratio (SNR) of primary signals received at CUs. By integrating CRN-cooperative spectrum sensing with 5G, the authors in [30] designed a network containing spectrum agents responsible for spectrum sensing to detect PU channel availability. In [29], a PUs activities detection algorithm based on energy detection is proposed, which determines whether PUs exist by the method based on power spectral density. The authors in [27] utilized machine learning techniques to track the variability of channel selection and predict the channel access mode in the temporal dimension. The model they proposed achieved an accuracy of approximately 96.6% in estimating the channel availability.

The above work has demonstrated that it is feasible to predict the availability of spectrum holes with high precision, and their sensing methods can be applied to the CRAHNS channel selection scheme, namely OMCS-FB. In future work, it is necessary to consider implementing a highly accurate prediction algorithm and evaluating OMCS-FB. Based on section VI-E, the transmission requirements or retransmission of CUs may affect the accuracy of the prediction algorithm. Moreover, to make the scheme better fit realistic 5G/B5G CRAHNS, it is necessary to consider the impact of spectrum sensing errors (i.e., $P_f \neq 0$ and $P_m \neq 0$) and CUs transmission interruption. Therefore, OMCS-FB should be improved from the above aspects.

Furthermore, to avoid the high complexity resulting from the space model with continuous states, the developed model is simplified to establish a 3-D Markov model with continuous time and discrete states in the procedure of elucidating the spectrum management principle of the OMCS-FB in this paper. However, in extremely large-scale scenarios, accurately solving Markov models may still encounter problems such as the expansion of the state space and the significant increase in the computational cost of iterative solutions. Therefore,

in future work, the aim is to develop a modeling method that can overcome the high complexity of the model while avoiding continuous state space explosion to enhance the precision of the model.

VII. CONCLUSION

An optimal matching channel selection strategy with finite buffer based on the 3-D CTMC is proposed in this paper. This strategy not only effectively mitigates the spectrum fragmentation in 5G/B5G CRAHNS but also promotes CUs spectrum sharing with PUs to a certain extent, while improving the average throughput of CUs. In the OMCS-FB, each CU with a transmission request chooses the spectrum hole that is long enough to satisfy its transmission needs rather than selecting the longest idle spectrum. The CU that fails to compete can enter the buffer to wait for the next transmission opportunity. Moreover, the newly arrived CUs have absolute priority transmission rights over the retransmitted CUs, and the retransmitted users can only attempt to access the channel when no new users arrive. Therefore, this strategy is more suitable for self-organizing networks with high real-time requirements or energy sensitivity.

To evaluate the performances of 5G/B5G CRAHNS under the OMCS-FB, we define the state space and analyze the dynamic access channel procedure, followed by a 3-D Markov model with $(K + 1)$ -layer. We utilize the SOR iterative algorithm to solve the Markov chain rate steady-state equations system to obtain performance metrics such as the average CUs throughput, spectrum utilization, and successful transmission probability. Through Monte Carlo simulations and comparison with the BFC scheme operating on the conservative principle, the results show that OMCS-FB can further improve network performance. That verifies that it is more effective in suppressing spectrum fragmentation. In addition, by comparing OMCS-FB with the benchmark schemes, including OMCS-FB candidate sequence noordering and fixed polling schemes, the advantages of candidate channel sequences with a sorting function in improving delay are verified. By evaluating the performance of OMCS-FB under different spectrum hole estimation errors, the influence of estimation accuracy on the performance of OMCS-FB is discussed. It is concluded that the higher the transmission demand of CUs, the higher the requirement for estimation accuracy.

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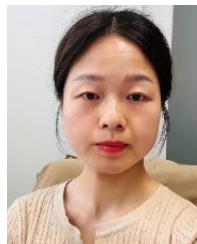
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A Sustainable Design for MIoT-Based WBANs: A Cooperative CR Intra-WBAN With Integrated Backscatter and RF Energy Harvesting

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Abstract—Energy constraints and spectrum scarcity are two main challenges hindering the widespread adoption of wireless body area networks (WBANs) for the Medical Internet of Things (MIoT). This article tackles these issues by proposing a novel cooperative cognitive radio (CR) intra-WBAN system that effectively integrates ambient backscatter communication (AmBC) and radio frequency energy harvesting (RFEH). In the proposed design, body sensors (BSNs) are categorized into primary BSNs and cognitive BSNs based on their data latency requirements. A hybrid BSN's coexistence/cooperative energy and information transmit protocol is established, which enables cognitive BSNs to: 1) opportunistically backscatter their data onto the primary source signal, thereby improving spectral efficiency (SE); 2) harvest RF energy from the primary signal for sustainable operation; and 3) act as amplify-and-forward relays for the primary network (PN) in exchange for dedicated spectrum access. We derive analytical expressions for the outage probabilities of both primary and cognitive networks (CNs) and analyze the impact of key parameters, including the backscattering coefficient, spectrum-sharing power allocation factor, and time segmentation factor, on the outage probability of the network. Simulation results validate our analysis and demonstrate that the proposed scheme achieves a remarkable improvement in both network throughput and energy efficiency (EE) compared to existing work and other benchmark schemes, showcasing its significant potential for sustainable MIoT.

Index Terms—Ambient backscatter communication (AmBC), cooperation cognitive radio (CR) intra-WBAN, optimal outage probability, RF energy harvesting, spectrum-sharing power allocation.

I. INTRODUCTION

WITH the aggravation of population aging, the increase in chronic disease prevalence, and the shortage of medical resources, high-quality and low-cost intelligent remote health monitoring services have attracted much attention.

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The Medical Internet of Things (MIoT), based on the new generation of wireless communication technology 5G/B5G, is expected to play a significant role in implementing intelligent telemedicine and smart healthcare projects [1]. A wireless body area network (WBAN) composed of wearable or implantable mobile sensors with communication capabilities is a vital component of the effective implementation of intelligent telemedicine and healthcare [2].

WBAN, unlike traditional wired patient monitoring systems, offers excellent computing power, transmission range, and bandwidth capabilities. WBAN uploads physiological data collected by body sensors (BSNs) deployed on or within the human body to the intelligent medical cloud platform through the coordinator. This allows patients who are not in medical centers or remote areas to enjoy real-time medical services [1]. Especially when such patients face a mandatory emergency, WBANs will immediately send alarms to inform medical staff to provide efficient medical assistance services.

In WBAN, BSNs with ultralow power consumption and miniaturization are typically powered by battery packs, which need to be replaced or recharged when their battery energy is exhausted [3]. The current low-power wireless technology allows sensors to operate for only 1–3 years before needing a battery replacement [4]. Frequent battery changes can negatively impact user experience, degrade the quality of medical services, and increase costs. This issue is particularly significant for implantable BSNs, where replacing the battery through surgery can lead to infections and extend the patient's recovery time. Additionally, discarded batteries contribute to environmental pollution, which goes against the principles of green communication that are currently being promoted. On the other hand, the low power consumption and energy limitations of WBANs significantly affect their outage performance (OP) and spectrum efficiency. To address these challenges, it is essential to innovate the traditional WBAN communication paradigm and enhance both performance and network longevity.

A. Related Work

Recently, radio frequency energy harvesting (RFEH) technology [5], which captures energy from surrounding RF signals, and ambient backscatter communication (AmBC) technology [6], with the advantages of low power consumption

and low cost, are considered potential solutions to address the above challenges.

Most research on using RFEH and AmBC to improve WBAN performances, such as energy efficiency (EE) and throughput, focuses on the design of energy and information transmission protocol and media access control (MAC) protocol. Liu et al. [7] studied the sum throughput maximization problem of WBAN under the time switching (TS) protocol and a hybrid TS and power allocation protocol based on RFEH technology. By redesigning the superframe structure, Hu et al. [8] proposed an RFEH WBAN cross-layer MAC protocol, which can provide superior system performance for long-term periodic health monitoring applications. To improve the endurance capability of WBAN sensors, EH and energy-saving technology were combined to study the energy consumption of human motion state and static state in [9]. In [10], a bidirectional backscatter transmission protocol was proposed for a wireless-powered WBAN. This protocol utilizes backscatter to enhance both energy and information transmission. It significantly improves overall throughput, particularly when the transmission power is low or when the number of sensors is large. To facilitate ultralow power communication in WBANs, an AmBC WBAN model powered by a multiantenna base station was developed in [11]. Amjad et al. [12] combined AmBC with RF technology and proposed an energy-saving resource allocation framework suitable for electronic medical systems to maximize WBAN EE. The above studies show that incorporating RFEH or AmBC technology into WBAN can significantly improve the system performance.

However, in the context of the Internet of Everything, the increasing number of devices and the vast amount of data being generated intensify issues related to spectrum scarcity and energy shortages [4]. These challenges can significantly impact the timeliness and reliability of medical data uploads in WBANs. As a result, it may be difficult to address these issues solely with RFEH or AmBC technologies. At present, it is generally believed that cognitive radio (CR) technology, which can “redevelop” licensed spectrum, is an effective means to tackle the scarcity of spectrum resources [13]. Under the CR architecture, wireless ad hoc network devices can dynamically adjust the transmitter parameters according to the environment and opportunistically utilize the authorized frequency band to achieve spectrum sharing and improve spectrum utilization. Shukla et al. [14] first studied an RFEH-based CR-WBAN, which realizes primary (medical sensors) and secondary (motion sensors) communication on the human body through cooperative spectrum-sharing technology. By integrating CR, Cicioğlu and Çalhan [15] proposed a WBAN architecture that can cope with disaster situations. The results show that CR-based WBAN performs better than traditional WBAN in terms of throughput and EE. In [16], a dynamic resource allocation algorithm was introduced, utilizing CR to sense the spectrum environment. This algorithm allocates the best access link for secondary users, enabling optimal use of the available bandwidth. On the other hand, cooperative communication is also an effective way to reduce energy consumption and enhance system reliability, particularly in systems utilizing technologies like RFEH to

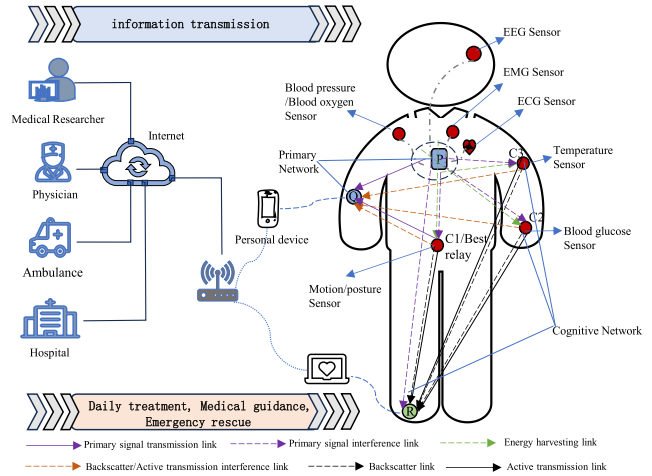


Fig. 1. Cooperative CR intra-WBAN supporting backscatter and energy harvesting.

assist relays [17]. Many studies have incorporated cooperative communication into WBAN. For example, in [18], an optimal relay selection protocol for RFEH-based WBAN was proposed under TS or power splitting schemes. The results show that the protocol has the optimal OP when the number of candidate relays is half of the total available relays. Mosavat-Jahromi et al. [19] studied the problem of maximizing the spectral efficiency (SE) in EH WBAN under single-hop and dual-hop transmission scenarios with decode-and-forward relay nodes. The performances of noncooperative WBAN and cooperative WBAN with relays in different frequency bands were evaluated in [20]. The results show that cooperative communication performs better than noncooperative communication in terms of outage probability and SE.

The above studies [14], [15], [16], [18], [19], [20] have proved that incorporating CR and cooperative communication into RFEH/AmBC WBAN can further improve the EE and spectrum utilization of WBAN. However, most work focuses on exploring RFEH-based cooperative WBAN or CR-WBAN. To the best of the authors' knowledge, the application of AmBC in electronic health systems has not been thoroughly researched. Therefore, in the current work, AmBC, RFEH, CR, and cooperative communication are considered to be incorporated into WBAN at the same time to explore the performance of cooperative CR intra-WBAN with the support of AmBC and RFEH assistive technologies, such as EE and SE, so as to provide an effective solution to the challenges of limited lifetime and spectrum scarcity of wearable health monitoring networks for MIIoT.

B. Motivation and Contribution

This article presents a novel cooperative CR WBAN communication paradigm that supports RFEH and AmBC and proposes an energy and information transmission protocol for this communication architecture. To the author's knowledge, [14] is the first recent work to propose and implement CR WBAN on the body. However, this work classifies BSNs based on the priority of the application, and this classification method does not fully consider the specific needs of clinical diagnosis.

For this reason, considering that the timeliness and reliability of data transmission are two high-standard requirements for WBAN users in emergency rescue situations, this article classifies them based on the eight user priority categories stipulated in the 802.15.6 standard according to the sensitivity of BSNs to delay. The primary BSNs are determined according to the clinical diagnostic characteristics of patients, while the cognitive BSNs are noncritical clinical characteristic BSNs. As shown in Fig. 1, taking patients with heart disease as an example, primary BSNs include EEG, ECG, EMG, blood oxygen, and blood pressure sensors; cognitive BSNs include motion/posture, body temperature, and blood glucose sensors.

On the other hand, existing energy and information transmission protocols (such as [7], [10], and [14]) typically only consider EH or primary signal transmission during the first transmission phase. That may be fatal for WBAN users in emergencies. The reason is that in the emergency rescue scenario, the time is urgent, the fault tolerance rate is ultralow, and it is usually not accurate enough for doctors to diagnose patients only through biomedical data with vital characteristics, which makes doctors need the assistance of other noncritical biological information to make a precise diagnosis efficiently.

Unlike previous works, a hybrid BSN's coexistence/cooperative energy and information transmission protocol (H-CE/CO-EITP) is designed. In the first transmission phase, known as the BSN's coexistence phase, the underlay paradigm of CR technology is adopted to allow cognitive BSNs to opportunistically share spectrum with the primary BSNs through backscattering, thereby ensuring the integrity and timeliness of WBAN physiological data information transmission. During the remaining time block period, namely, the BSN's cooperation phase, the relay node (determined by the optimal relay selection strategy) first performs energy harvesting and information processing through the power splitting factor. Then, when the primary BSNs are inactive, the overlay spectrum-sharing mode is adopted to actively transmit its own signal while preferentially cooperating with the primary signal transmission (the spectrum sensing method of cognitive BSNs can be referred to [16] and [21]), thereby further enhancing the reliability of the primary BSNs' data transmission. Other cognitive BSNs convert the received primary (P) signal into their own energy during P signal transmission and actively transmit their own signal during the P idle. It is noted that the relay node and other cognitive BSNs are transmitted in TDMA mode to avoid interference.

The main contributions of this article are as follows.

- 1) A cooperative CR intra-WBAN energy and information transmit protocol supporting AmBC and RHEH is established, namely, the H-CE/CO-EITP. The protocol facilitates spectrum sharing between primary and cognitive BSNs, enhances spectrum utilization, and ultimately improves system throughput. With limited transmit power from the primary source, the energy utilization is improved through backscatter and relay cooperation, thereby extending the network lifetime.
- 2) The outage probabilities of each link in the BSN's coexistence versus cooperation phase and the optimal

outage probabilities of the primary network (PN) and cognitive network (CN) are derived, and the throughput and EE of CR intra-WBAN under H-CE/CO-EITP are obtained. In particular, the optimal OP of the PN in the BSNs' coexistence phase provides guidance for subsequent WBAN users to configure cognitive BSNs (which is explained in detail in the simulation part).

- 3) The effects of the backscatter coefficient, time segmentation factor, co-relay spectrum-sharing factor, and power splitting factor on the performance of the cooperative CR intra-WBAN supporting AmBC and RHEH are investigated. That provides a reasonable solution for designing CR intra-WBAN, which is suitable for MIIOT and has the advantages of low cost, high energy efficiency, and high spectrum utilization.
- 4) The proposed scheme is compared with existing work and other benchmark schemes (including direct link (DL) transmission, cooperative transmission without backscatter [14], and noncooperative transmission with backscatter). The results show that the system performance under the proposed scheme is optimal, and the DL transmission is as expected; its performance is not as good as that of the system incorporating cooperative communication or backscatter communication technology. Moreover, the challenges and feasibility of system implementation are discussed.

II. SYSTEM MODEL

A. CR Intra-WBAN Transmission Model With RFEH and Backscatter Communication

As shown in Fig. 2, a CR intra-WBAN transmission model with RFEH and backscatter communication is considered, where T is the transmission time block. In this transmission model, the PN consists of a transmitting node P and a receiving node Q ; the CN is composed of N cognitive BSNs $C = \{C_1, \dots, C_i, \dots, C_N\}$ with energy harvesting and backscatter circuits and the receiving node R . Hereby, cognitive BSNs can communicate through backscatter and active transmission. During the node P transmission, N cognitive BSN nodes harvest energy and backscatter their own signals to share the spectrum with node P in underlay mode. When node P is inactive, cognitive BSN nodes actively transmit their information, and one of the nodes is willing to actively act as an amplify and forward (AF) relay to assist the primary signal transmission. This node shares the spectrum with node P in overlay mode to actively transmit its own signals. Therefore, nodes P and Q can establish direct communication as well as through cognitive node relay cooperation.

Assume that the channel power gain from node m to node j is h_{mj} , where $m = \{P, C\}$ and $j = \{Q, C, R\}$. All links are subject to the small-scale fading applicable to intra-WBAN communication, i.e., lognormal distribution. The path loss model is defined by [22]

$$P_L(d_{mj}) [\text{dB}] = P_L(d_0) + 10\log_{10}\left(\frac{d_{mj}}{d_0}\right) + \chi_r \quad (1)$$

where d_{mj} denotes the distance between the transmitting node m and the receiving node j ; d_0 represents the reference

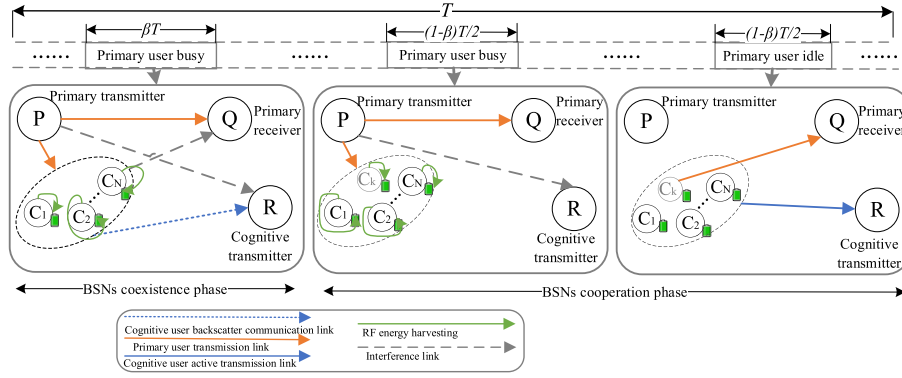


Fig. 2. CR intra-WBAN transmission model.

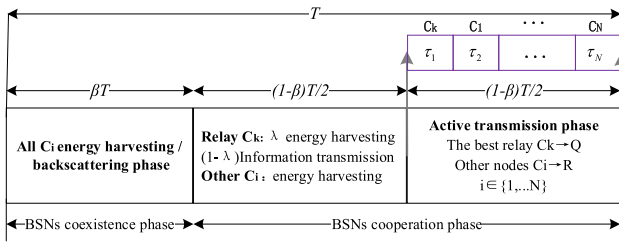


Fig. 3. Transmission time block structure of H-CE/CO-EITP.

distance; n is the path loss exponent; and χ_r is a normal random variable, which represents the deviation caused by the environment.

In the proposed CR intra-WBAN transmission model, all BSN nodes are transmitted in half-duplex mode, and their energy and information transmission follow the H-CE/CO-EITP, as detailed in Section II-B.

B. Hybrid BSN's Coexistence/Cooperative Energy and Information Transmission Protocol (H-CE/Co-EITP)

In this protocol, the time block T is divided into three subblocks, as shown in Fig. 3. During the βT period, P transmits its signal to Q , and N cognitive BSNs harvest energy. At the same time, one of N cognitive BSNs is opportunistically selected [23] to modulate its information into the P transmitted signal and backscatter the modulated signal to R . This period is called the BSN's coexistence phase. Note that if the i th cognitive BSN is selected to backscatter its information to R , the remaining backscatter links remain silent. Since each BSN operates in half-duplex mode, half of the time $(1 - \beta)T/2$ is used for nodes C , Q , and R to receive signals from node P during the remaining $(1 - \beta)T$ period, while the other half of the time $(1 - \beta)T/2$ is utilized for active transmission of all cognitive BSNs, including active transmission (self-signal) and cooperative transmission (primary signal) of the optimal relay. The $(1 - \beta)T$ period is called the BSN's cooperative phase.

1) *BSN's Coexistence Phase*: During the BSN's coexistence phase, that is, during βT , for the PN, P sends its signal x_p ($\mathbb{E}[x_p] = 1$) to Q . At the same time, the i th cognitive BSN

(node C_i) receives the signal y_{c_i} , i.e.,

$$y_{c_i} = \sqrt{P_p} h_{PC_i} x_p + n_{PC_i}. \quad (i = 1, 2, \dots, N) \quad (2)$$

where P_p is the transmit power of P and $n_{PC_i} \sim \mathcal{CN}(0, N_0)$ is the additive white Gaussian noise (AWGN) at node C_i .

The signal received at node C_i is split into two parts by the reflection coefficient α_i : $(\alpha_i)^{1/2} y_{c_i}$ is used for energy harvesting and the remaining part $(1 - (\alpha_i)^{1/2}) y_{c_i}$ is utilized for backscatter. Then, the total harvested energy at node C_i can be expressed by

$$E_1^{C_i} = \eta_i \alpha_i P_p |h_{PC_i}|^2 \beta T \quad (3)$$

where η_i is the energy conversion efficiency. Assuming that the energy conversion efficiency is stationary and all cognitive BSNs have the same energy conversion efficiency, η_i can be simplified as η .

Let P_{CU_i} be the minimum average power consumption required by the internal circuit (including the microcontroller and impedance modulator) of the node C_i when performing backscatter communication. When $E_1^{C_i} \geq P_{CU_i} \beta T$, node C_i has enough energy to complete its backscatter transmission; otherwise, it cannot successfully backscatter its signal to R . The SINR received at Q and R in the above two cases is derived as follows.

- 1) If $E_1^{C_i} \geq P_{CU_i} \beta T$, node C_i modulates the received signal $(1 - (\alpha_i)^{1/2}) y_{c_i}$ into its own signal x_{CU_i} ($\mathbb{E}[x_{CU_i}] = 1$) and reflects the modulated signal to R . Thus, the received signal at R is written as

$$y_{C_i R}^b = \underbrace{\sqrt{P_p} h_{PR} x_p}_{\text{Interference from the PN}} + \underbrace{\sqrt{\varepsilon_i (1 - \alpha_i) P_p} h_{PC_i} h_{C_i R} x_p x_{CU_i}}_{\text{Required signal}} + \underbrace{n_R}_{\text{Noise}} \quad (4)$$

where ε_i is the reflection efficiency of node C_i and $n_R \sim \mathcal{CN}(0, N_0)$ is the AWGN at R . Then, the SINR for decoding x_{CU_i} at R can be expressed as

$$\gamma_{C_i R}^b = \frac{\varepsilon_i (1 - \alpha_i) P_p |h_{PC_i}|^2 |h_{C_i R}|^2}{P_p |h_{PR}|^2 + N_0}. \quad (5)$$

Since the backscatter signal causes interference to Q , the signal received by Q can be derived by

$$y_{C_iQ}^1 = \underbrace{\sqrt{P_p} h_{PR} x_p}_{\text{Required signal}} + \underbrace{\sqrt{\varepsilon_i (1 - \alpha_i) P_p} h_{PC_i} h_{C_iQ} x_p}_{\text{Interference from the CN}} x_{CU_i} + \underbrace{n_{C_iQ}}_{\text{Noise}}. \quad (6)$$

where $n_Q \sim \mathcal{CN}(0, N_0)$ is the AWGN at Q . Therefore, the SINR at Q can be calculated as

$$\gamma_{C_iQ}^1 = \frac{P_p |h_{PQ}|^2}{\varepsilon_i (1 - \alpha_i) P_p |h_{PC_i}|^2 |h_{C_iQ}|^2 + N_0}. \quad (7)$$

- 2) If $E_1^{C_i} < P_{CU_i} \beta T$, node C_i remains silent and the backscatter link $C_i \rightarrow R$ is interrupted. Currently, the received signal at Q is written as

$$y_{C_iQ}^2 = \sqrt{P_p} h_{PQ} x_p + n_{PQ}. \quad (8)$$

Thus, the SINR at Q can be represented as

$$\gamma_{C_iQ}^2 = \frac{P_p |h_{PQ}|^2}{N_0}. \quad (9)$$

2) *BSN's Cooperative Phase:* As demonstrated in Fig. 3, during the BSN's cooperative phase or during $(1 - \beta)T$, cognitive BSNs first harvest energy before transmitting information. Specifically, during the second subblock $(1 - \beta)T/2$, the node P continuously sends a signal x_p to Q . Then, the received signals at nodes Q , R , and C_i are y_{PQ} , y_{PR} , and y_{PC_i} , respectively, i.e.,

$$y_{Pj} = \sqrt{P_p} h_{Pj} x_p + n_{Pj} \quad (10)$$

where $j \in \{Q, R, C_i\}$ and $n_{Pj} \sim \mathcal{CN}(0, N_0)$ is the AWGN at the receiving node.

Based on the channel information and battery energy state in the first transmission phase (the sensing method can be referred to [24] and [25]), a cognitive BSN node C_k actively acts as an AF relay to assist P information transmission. The node is not selected randomly but follows the optimal relay selection strategy. Inspired by [18] and [22], the relay selection scheme is designed as follows.

- 1) The cognitive BSN nodes with the best channel $P \rightarrow C_i$ are added to the list of candidate relay nodes, namely

$$C_k = \arg \max_{1 \leq i \leq N} \left\{ |h_{PC_i}|^2 \right\}.$$

- 2) The node with the best channel $C_i \rightarrow Q$ is selected from M candidate relay nodes as the optimal relay, i.e.,

$$C_k = \arg \max_{1 \leq j \leq M} \left\{ |h_{C_iQ}|^2 \right\}.$$

where step 1) can ensure the maximum energy harvesting capacity of the optimal relay and step 2) ensures that the optimal relay can complete the cooperative transmission with less power as much as possible during future cooperative transmission and active transmission to allocate more power to the active transmission.

Hence, the relay node C_k splits the received signal y_{PC_k} into two parts by the power splitting factor λ : $(\lambda)^{1/2} y_{PC_k}$ is used

for energy harvesting and the remaining part $((1 - \lambda))^{1/2} y_{PC_k}$ is used for information processing. Thus, the total energy harvested at node C_k can be expressed as

$$E_2^{C_k} = \frac{\eta_k \lambda P_p |h_{PC_k}|^2 (1 - \beta) T}{2}. \quad (11)$$

The other nodes C_i ($1 \leq i \leq N, i \neq k$) utilize all the received signals from node P for energy collection. Therefore, during $(1 - \beta)T/2$, the energy harvested by node C_i is given by

$$E_2^{C_i} = \frac{\eta_i P_p |h_{PC_i}|^2 (1 - \beta) T}{2}. \quad (12)$$

Since the energy of cognitive BSNs to transmit their own signals comes from the RF signal emitted by P , the transmit powers of cognitive BSNs are usually much smaller than P_p . Thus, the noise statistics are ignored when calculating (11) and (12).

In the third transmission subblock phase, that is, during $(1 - \beta)T/2$, the primary source P is inactive, and N cognitive BSNs actively transmit, in which the node C_k actively transmits its own information and acts as an AF relay to assist the primary signal transmission. To avoid interference among cognitive BSNs, based on the active beacon interleaving and beacon shifting technology stipulated in the IEEE 802.15.6 protocol [26], N cognitive BSN nodes can be scheduled using the TDMA scheme.

As shown in Fig. 3, the third time subblock is divided into N parts, where the first subblock τ_1 is used for the relay node C_k to complete cooperative transmission and active transmission.

According to (11), the transmit power of node C_k can be represented as

$$P_{C_k} = \frac{E_2^{C_k}}{\tau_1}. \quad (13)$$

During τ_1 , node C_k amplifies AF the signal received during the second subblock transmission to Q while sending its own signal x_{CU_k} to R . Therefore, C_k splits the power by the spectrum-sharing power splitting factor θ ($0 < \theta < 1$), where θP_{C_k} used for cooperative transmission of the primary signal $((1 - \lambda))^{1/2} y_{PC_k}$ and $(1 - \theta) P_{C_k}$ utilized for actively transmitting its own signal x_{CU_k} . A combined signal is generated by superimposing the above two parts of the signals, i.e.,

$$x_{C_k} = \sqrt{\theta P_{C_k}} \frac{\sqrt{(1 - \lambda)} y_{PC_k}}{A} + \sqrt{(1 - \theta) P_{C_k}} x_{CU_k} \quad (14)$$

where $A = 1/(1 - \lambda) P_p |h_{PC_k}|^2$ is the AF factor. Then, the received signals at nodes Q and R can be expressed as y_{C_kQ} and y_{C_kR} , respectively,

$$y_{C_kj} = h_{C_kj} x_{C_k} + n_{C_kj} \quad (15)$$

where $j = \{Q, R\}$ and $n_{C_kj} \sim \mathcal{CN}(0, N_0)$ is the AWGN at the receiving node.

Thereby, for the PN, if it only transmits information through the DL $P \rightarrow Q$, the SINR at Q can be obtained based on (10) as follows:

$$\gamma_{PQ} = \frac{P_p |h_{PQ}|^2}{N_0}. \quad (16)$$

If it transmits information through the relay link $P \rightarrow C_k \rightarrow Q$, based on (10) and (13)–(15), the SINR at Q can be obtained as

$$\gamma_{C_k Q} = \frac{\delta \theta \gamma_{PC_k} |h_{C_k Q}|^2}{\theta \rho |h_{C_k Q}|^2 + (1 - \theta) \delta \gamma_{PC_k} |h_{C_k Q}|^2 + 1} \quad (17)$$

where $\gamma_{PC_k} = P_p |h_{PC_k}|^2 / N_0$, $\delta = \eta \lambda (1 - \beta) T / 2 \tau_1$, and $\rho = \eta \lambda (1 - \beta) T / 2 (1 - \lambda) \tau_1$.

For the CN, it can be seen from (15) that the received signal at R includes the primary signal, and the primary signal is an interference signal in terms of R . According to [14] and [27], the interference signal can be eliminated by the primary signal received by R in the second transmission phase. Thus, the SINR at R can be calculated as

$$\gamma_{C_k R} = \frac{(1 - \theta) \delta \gamma_{PC_k} |h_{C_k R}|^2}{\theta \rho |h_{C_k R}|^2 + 1}. \quad (18)$$

During the remaining time of the third transmission phase, each node C_i ($i = 1, 2, \dots, N$ and $i \neq k$) transmits a signal in the TDMA mode. Therefore, combined with (12), the SINR of the link C_i ($i \neq k$) $\rightarrow R$ is given by

$$\gamma_{C_i R} = \frac{E_2^{C_i} |h_{C_i R}|^2}{\tau_i N_0}. \quad (19)$$

III. PERFORMANCE ANALYSIS

This section analyzes the performance of CR intra-WBAN based on the H-CE/CO-EITP, including the outage probabilities of the PN and the CN in the BSN's coexistence versus cooperative phase, the throughput, and EE of CR intra-WBAN. In particular, to explore the influence of θ and time segmentation factor β on network performance, the θ constraint model of spectrum-sharing power allocation factor for the optimal relay node in the third transmission phase is obtained by finding the relationship between θ and β .

A. Outage Probability of Intra-WBAN in the BSN's Coexistence Phase

1) *Outage Probability of Cn*: In this section, the outage probability of the backscatter link $C_i \rightarrow R$ and the optimal OP of the CN during the BSN's coexistence phase, that is, during βT , are considered.

Let the given SINR threshold of backscatter communication be γ_{th}^b . Then, the outage probability of the i th backscatter link $C_i \rightarrow R$ can be expressed by

$$P_{out,b}^{C_i} = \Pr(E_1^{C_i} < P_{CU_i} \beta T) + \Pr(E_1^{C_i} \geq P_{CU_i} \beta T, \gamma_{C_i R}^b < \gamma_{th}^b) \quad (20)$$

where $\gamma_{th}^b = 2^{R_c/\beta} - 1$, in which R_c is the target rate of CN; the first item is the energy outage probability of the i th cognitive BSN battery with insufficient energy to support its backscattering; and the second term is the probability of R decoding C_i backscatter information failure when the C_i battery energy is sufficient to support it to complete backscatter.

Based on (3)–(5), $P_{out,b}^{C_i}$ can be calculated as

$$P_{out,b}^{C_i} = \Pr \left(\underbrace{|h_{PC_i}|^2}_{I_1} < \frac{P_{CU_i}}{\eta P_p \alpha_i} \right)$$

$$+ \Pr \left(\underbrace{|h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}, \frac{S_i}{P_p |h_{PR}|^2 + N_0} < \gamma_{th}^b}_{I_2} \right) \quad (21)$$

where $S_i = \varepsilon_i (1 - \alpha_i) P_p |h_{PC_i}|^2 |h_{C_i R}|^2$ when $|h_{PC_i}|^2 \geq (P_{CU_i})/(\eta P_p \alpha_i)$; otherwise, $S_i = 0$.

Since (21) contains multiple variables and addition and multiplication operations regarding channel gain, a proposition about S_i probability density function (pdf) is presented before deducing the outage probability $P_{out,b}^{C_i}$.

Proposition 1: Based on $|h_{C_i R}|^2 \sim \text{LogN}(2\mu_{C_i R}, 4\sigma_{C_i R}^2)$ and the condition $|h_{PC_i}|^2 \geq (P_{CU_i})/(\eta P_p \alpha_i)$, the cumulative distribution function (cdf) $F_{S_i}(x)$ and pdf $f_{S_i}(x)$ are given by

$$F_{S_i}(x) = \frac{\sigma_{C_i R}}{2\sigma_{PC_i}} \left(1 + \frac{1}{2} \text{erf} \left(\frac{\ln(x) - \ln(\varepsilon_i (1 - \alpha_i) P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}} \right) \right) \quad (22)$$

$$f_{S_i}(x) = \frac{1}{8\sqrt{\pi}\sigma_{PC_i} x} \cdot \exp \left(- \left(\frac{\ln(x) - \ln(\varepsilon_i (1 - \alpha_i) P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}} \right)^2 \right) \quad (23)$$

where $\text{erf}(\cdot)$ is the error function.

Proof: See Appendix A.

Based on Proposition 1, the outage probability $P_{out,b}^{C_i}$ of the i th backscatter link $C_i \rightarrow R$ can be deduced as (24), shown at the bottom of the next page.

Its derivation is shown in Appendix B.

Next, the optimal OP of the CN in the BSN's coexistence phase is considered. Specifically, the backscatter link with the maximum SINR at the cognitive receiving node R is selected. Since sensors will be distributed across different parts of the body in actual WBAN deployments, $\{S_i/(P_p |h_{PR}|^2 + N_0)\} (i = 1, \dots, N)$ are independent of each other. Thus, the optimal outage probability $P_{out,b}^{CN}$ of the CN in the BSN's coexistence phase can be written as

$$P_{out,b}^{CN} = \Pr \left(\max \left(\frac{S_1}{P_p |h_{PR}|^2 + N_0}, \dots, \frac{S_N}{P_p |h_{PR}|^2 + N_0} \right) < \gamma_{th}^b \right) = \prod_{i=1}^N \Pr \left(\frac{S_i}{P_p |h_{PR}|^2 + N_0} < \gamma_{th}^b \right) = \prod_{i=1}^N P_{out,b}^{C_i}. \quad (25)$$

The expression of SINR in (25), namely, $S_i/(P_p |h_{PR}|^2 + N_0)$, implicitly implies an inherent tradeoff between energy harvesting and communication efficiency; increasing the reflected power ($\varepsilon_i (1 - \alpha_i)$) will boost the molecule, but may reduce the power used for energy harvesting. Therefore, the selection of the optimal backscatter link is essentially about seeking a balance between the strength of the reflected signal and the sustainability of the nodes. That is discussed in Section IV-A, namely, the influence of the backscatter coefficient on the OP of CN.

2) *Outage Probability of PN*: This section analyzes the impact of backscatter communication on the OP of the PN during the BSN's coexistence phase, that is, during βT .

Initially, the effect of node C_i backscatter communication on the outage probability of PN is considered. There are two cases: 1) the battery energy of C_i is insufficient to support it to complete backscatter communication and the received SINR at Q is less than the given threshold and 2) C_i has enough energy to complete backscatter communication and the received SINR at Q is less than the given threshold. Therefore, when C_i is selected, the outage probability $P_{\text{out},C_i}^{\text{PN}}$ of PN for a given threshold γ_{th} can be expressed as

$$P_{\text{out},C_i}^{\text{PN}} = \Pr(E_1^{C_i} < P_{CU_i}\beta T, \gamma_{C_iQ}^2 < \gamma_{\text{th}}) + \Pr(E_1^{C_i} \geq P_{CU_i}\beta T, \gamma_{C_iQ}^1 < \gamma_{\text{th}}) \quad (26)$$

where $\gamma_{\text{th}} = 2^{R_p/\beta} - 1$, in which R_p is the target rate of PN.

According to (3), (7), and (9), $P_{\text{out},C_i}^{\text{PN}}$ can be represented as

$$P_{\text{out},C_i}^{\text{PN}} = \underbrace{\Pr\left(|h_{PC_i}|^2 < \frac{P_{CU_i}}{\eta P_p \alpha_i}, \frac{P_p |h_{PQ}|^2}{N_0} < \gamma_{\text{th}}\right)}_{I_3} + \underbrace{\Pr\left(|h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}, \frac{P_p |h_{PQ}|^2}{G_i + N_0} < \gamma_{\text{th}}\right)}_{I_4} \quad (27)$$

where $G_i = \varepsilon_i(1 - \alpha_i)P_p|h_{PC_i}|^2|h_{C_iQ}|^2$ when $|h_{PC_i}|^2 \geq (P_{CU_i})/(\eta P_p \alpha_i)$; otherwise, $G_i = 0$.

Since $|h_{PC_i}|^2 \sim \text{LogN}(2\mu_{PC_i}, 4\sigma_{PC_i}^2)$ and $|h_{PQ}|^2 \sim \text{LogN}(2\mu_{PQ}, 4\sigma_{PQ}^2)$ are independent of each other, I_3 can be derived as follows:

$$I_3 = \frac{1}{2} \left(1 + \text{erf} \left(\frac{\ln(P_{CU_i}/\eta P_p \alpha_i) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}} \right) \right) \cdot \frac{1}{2} \left(1 + \text{erf} \left(\frac{\ln(\gamma_{\text{th}} N_0 / P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}} \right) \right). \quad (28)$$

Similar to Proposition 1, the pdf of G_i ($i = 1, \dots, N$) can be written as

The derivation process of I_4 is the same as that of Appendix B. Based on (29), as shown at the bottom of the page, I_4 can be obtained by

Therefore, by substituting (28) and (30), as shown at the bottom of the next page, into (27), $P_{\text{out},C_i}^{\text{PN}}$ can be obtained. Furthermore, the final analytical expression of $P_{\text{out},C_i}^{\text{PN}}$ reveals that the reflected power $[\varepsilon_i(1 - \alpha_i)]$ of the cognitive node is a significant parameter influencing the outage probability of the PN, and the two are positively correlated. As a result, the backscatter communication of the cognitive node competes with the communication reliability of the PN.

Thus, to maintain the quality of service (QoS) of the PN, it is essential to determine the backscattering coefficient through interference analysis. This process involves assessing how the entire backscattering system affects the optimal OP of the PN. By setting an appropriate reflection coefficient, we can enhance the performance of the CN while ensuring that the QoS of the PN remains uncompromised. This is discussed in further detail in Section IV-A.

First, the effect of the entire backscatter communication system on the optimal OP of the PN is investigated, which can be divided into two cases: 1) when at least one cognitive BSN C_i is unable to backscatter communication due to insufficient energy, the optimal outage condition of PN is that the selected backscattered C_i is inactive and the received SINR $\gamma_{C_iQ}^2$ at Q is less than the given threshold and 2) when all cognitive BSNs have sufficient energy for backscatter communication, the optimal outage condition of PN is that the maximum received SINR γ_{CQ}^{max} at Q is still less than the threshold γ_{th} . That is to say, the backscatter link with the minimum interference value $G_{\min} = \min G_1, \dots, G_N$ to PN is selected, where $\gamma_{CQ}^{\text{max}} = P_p|h_{PQ}|^2/(G_{\min} + N_0)$. Thus, the outage probability of PN can be derived by

$$P_{\text{out},b}^{\text{PN}} = P_{\text{out}}^{pq} (1 - P_{\text{out},b}^{\text{No-CN}}) + P_{\text{out},C}^{\text{PN}} \quad (31)$$

where P_{out}^{pq} is the outage probability of PN in the absence of backscatter communication and $P_{\text{out},b}^{\text{No-CN}}$ is the probability that all cognitive BSNs have enough energy for backscatter communication. $P_{\text{out},C}^{\text{PN}}$ is the probability that all cognitive

$$P_{\text{out},b}^{C_i} = \frac{1}{2} \left(1 + \text{erf} \left(\frac{\ln(P_{CU_i}) - \ln(\eta \alpha_i P_p) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}} \right) \right) + \frac{1}{4\sqrt{\pi}} \cdot \left[\frac{\sqrt{\pi}\sigma_{C,R}}{2\sigma_{PC_i}} \text{erfc} \left(\frac{\ln(\gamma_{\text{th}}^b N_0) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C,R}}{4\sigma_{C,R}} \right) - \int_{\gamma_{\text{th}}^b N_0}^{+\infty} \frac{1}{4\sigma_{PC_i}x} \text{erf} \left(\frac{\ln(x - \gamma_{\text{th}}^b N_0) - \ln(\gamma_{\text{th}}^b P_p) - 2\mu_{PR}}{2\sqrt{2}\sigma_{PR}} \right) \times \exp \left(- \left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C,R}}{4\sigma_{C,R}} \right)^2 \right) dx \right]. \quad (24)$$

$$f_{G_i}(x) = \frac{1}{8\sqrt{\pi}\sigma_{PC_i}x} \cdot \exp \left(- \left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_iQ}}{4\sigma_{C_iQ}} \right)^2 \right). \quad (29)$$

BSNs have enough energy for backscatter communication and $\gamma_{CQ}^{\max} < \gamma_{th}$.

Based on $|h_{PQ}|^2 \sim \text{LogN}(2\mu_{PQ}, 4\sigma_{PQ}^2)$ and (9), P_{out}^{pq} can be expressed by

$$\begin{aligned} P_{out}^{pq} &= \Pr\left(\frac{P_p |h_{PQ}|^2}{N_0} < \gamma_{th}\right) \\ &= \frac{1}{2} \left(1 + \text{erf}\left(\frac{\ln(\gamma_{th}N_0/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right)\right). \end{aligned} \quad (32)$$

Similarly, $P_{out,b}^{\text{No-CN}}$ can be derived based on (3)

$$\begin{aligned} P_{out,b}^{\text{No-CN}} &= \Pr\left(|h_{PC_1}|^2 \geq \frac{P_{CU_1}}{\eta P_p \alpha_1}, \dots, |h_{PC_N}|^2 \geq \frac{P_{CU_N}}{\eta P_p \alpha_N}\right) \\ &= \prod_{i=1}^N \frac{1}{2} \left(1 - \text{erf}\left(\frac{\ln(P_{CU_i}) - \ln(\eta P_p \alpha_i) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}}\right)\right). \end{aligned} \quad (33)$$

Proposition 2: The cdf of the minimum interference value $G_{\min} = \min G_1, \dots, G_N$ is given by (34), as shown at the bottom of the page.

Proof: See Appendix C.

From Proposition 2, $P_{out,C}^{\text{PN}}$ can be deduced by where the distributed integral formula is applied to the transformation from step e_1 to step e_2 .

Thus, by substituting (32), (33), and (35), as shown at the bottom of the next page, into (31), the optimal outage probability $P_{out,b}^{\text{PN}}$ of PN in the BSN's coexistence phase can be obtained.

B. Outage Probability of Intra-WBAN in the BSN's Cooperation Phase

1) *Outage Probability of PN:* In this section, the outage probabilities of the PN in the BSN's cooperation phase are analyzed, including the outage probability in the case of only DL (direct link $P \rightarrow Q$) transmission and the outage

probability of relay cooperative transmission ($P \rightarrow C_k \rightarrow Q$) in the presence of DL transmission.

a) *Only direct link transmission:* Based on (16) and the given γ_{th}^d , it can be inferred that

$$P_{out,d}^{\text{PN}} = \Pr(\gamma_{PQ} < \gamma_{th}^d) = \Pr\left(|h_{PQ}|^2 < \frac{\gamma_{th}^d N_0}{P_p}\right)$$

where $\gamma_{th}^d = 2^{R_p/(1-\beta)} - 1$.

According to $|h_{PQ}|^2 \sim \text{LogN}(2\mu_{PQ}, 4\sigma_{PQ}^2)$, $P_{out,d}^{\text{PN}}$ can be further expressed as

$$P_{out,d}^{\text{PN}} = \frac{1}{2} \left(1 + \text{erf}\left(\frac{\ln(\gamma_{th}^d N_0) - \ln(P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right)\right). \quad (36)$$

b) *Relay cooperative transmission with direct link:* Based on (16) and (17) and applying the maximum ratio combination, $P_{out,r}^{\text{PN}}$ is given by

$$\begin{aligned} P_{out,r}^{\text{PN}} &= \Pr(\gamma_{PQ} + \gamma_{C_kQ} < \gamma_{th}^1) \\ &= \int_0^{\gamma_{th}^1} \int_0^{\gamma_{th}^1 - y} f_{\gamma_{C_kQ}}(x) f_{\gamma_{PQ}}(y) dx dy \end{aligned} \quad (37)$$

where $\gamma_{th}^1 = 2^{tR_p} - 1$, in which $t = 2/(1-\beta)$.

To derive (37), cdf $F_{\gamma_{C_kQ}}(x)$ is obtained first by Theorem 1.

Theorem 1: Since the spectrum-sharing power splitting factor θ affects the OP of the relay link, that is, if $x < \theta/1 - \theta$, it means that the relay cooperation is available; if $x \geq \theta/1 - \theta$, the relay link is interrupted. Therefore, $F_{\gamma_{C_kQ}}$ can be represented by

$$F_{\gamma_{C_kQ}}(x) = \begin{cases} 1, & \text{if } x \geq \frac{\theta}{1-\theta} \\ \Psi(x), & \text{if } x < \frac{\theta}{1-\theta} \end{cases} \quad (38)$$

where

$$\begin{aligned} \Psi(x) &= \int_0^{+\infty} \frac{1}{2} \left[1 + \text{erf}\left(\frac{\ln\left(\frac{x(1+\theta py)}{\delta(\theta-(1-\theta)x)y}\right) - 2\mu_{PC_k}}{2\sqrt{2}\sigma_{PC_k}}\right)\right] \\ &\quad \times \frac{1}{2\sqrt{2\pi}\sigma_{C_kQ}y} \exp\left(-\left(\frac{\ln(y) - 2\mu_{C_kQ}}{2\sqrt{2}\sigma_{C_kQ}}\right)^2\right) dy. \end{aligned} \quad (39)$$

$$\begin{aligned} I_4 &= \Pr\left(|h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}, |h_{PQ}|^2 < \frac{\gamma_{th}(G_i + N_0)}{P_p}\right) \\ &= \int_0^{+\infty} \frac{1}{2} \left[1 + \text{erf}\left(\frac{\ln(\gamma_{th}(x + N_0)/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right)\right] f_{G_i}(x) dx \\ &= \frac{1}{4\sqrt{\pi}} \left[\int_0^{+\infty} \frac{1}{4\sigma_{PC_i}x} \text{erf}\left(\frac{\ln(x + N_0) + \ln(\gamma_{th}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right) \right. \\ &\quad \left. \times \exp\left(-\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_iQ}}{4\sigma_{C_iQ}}\right)^2\right) dx + \frac{\sqrt{\pi}\sigma_{C_iQ}}{2\sigma_{PC_i}} \right]. \end{aligned} \quad (30)$$

$$F_{G_{\min}}(x) = \prod_{i=1}^N \left(\frac{\sigma_{C_iQ}}{2\sigma_{PC_i}} + \frac{\sigma_{C_iQ}}{4\sigma_{PC_i}} \text{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_iQ}}{4\sigma_{C_iQ}}\right) \right). \quad (34)$$

Proof: See Appendix D.

Thus, the OP of the PN under relay cooperation can be obtained by substituting (38) and (39) into (37), but it is difficult to solve. It is considered that the approximate solution of $P_{\text{out},r}^{\text{PN}}$ is obtained by using the M -step staircase approximation method [14] for the triangular integral region in (37), i.e.,

$$\begin{aligned} P_{\text{out},r}^{\text{PN}} &= \sum_{l=0}^{M-1} \int_{\frac{l}{M}\gamma_{\text{th}}^1}^{\frac{l+1}{M}\gamma_{\text{th}}^1} f_{\gamma_{PQ}}(y) dy \int_0^{\frac{M-l}{M}\gamma_{\text{th}}^1} f_{\gamma_{C_kQ}}(x) dx \\ &\approx \sum_{l=0}^{M-1} \left\{ F_{\gamma_{PQ}}\left(\frac{l+1}{M}\gamma_{\text{th}}^1\right) - F_{\gamma_{PQ}}\left(\frac{l}{M}\gamma_{\text{th}}^1\right) \right\} \\ &\quad \times F_{\gamma_{C_kQ}}\left(\frac{M-l}{M}\gamma_{\text{th}}^1\right) \end{aligned} \quad (40)$$

where cdf $F_{\gamma_{PQ}}(x)$ of γ_{PQ} is (36). For mathematical insights into the M -step approximation method, refer to [28].

c) *Spectrum-sharing power allocation factor θ :* According to (38), under the condition of $\gamma_{\text{th}}^1 < \theta/(1-\theta)$, the θ value satisfying the service quality limit of the PN can be deduced, i.e.,

$$\frac{\gamma_{\text{th}}^1}{1 + \gamma_{\text{th}}^1} < \theta < 1 \quad (41)$$

where γ_{th}^1 is related to R_p and t , and $t = (1 - \beta)/2$. The smaller the value of θ , the more spectrum opportunities for C_k active transmission. Therefore, under the given R_p and β , the minimum θ can be deduced to realize the spectrum-sharing cooperation of relay node C_k .

2) *Outage Probability of C_n :* During the BSN's cooperation phase, N cognitive BSNs are active transmission in the TDMA mode, where C_k acts as an AF relay to assist the PN transmission while transmitting its own signal. Thereby, $\{\gamma_{C_kR}\}_{k=1,\dots,N}$ is independent of each other. For a given SINR threshold γ_{th}^a , the outage probability $P_{\text{out},a}^{\text{CN}}$ of the CN in the BSN's cooperative phase can be calculated as

$$\begin{aligned} P_{\text{out},a}^{\text{CN}} &= \Pr(\max(\gamma_{C_1R}, \dots, \gamma_{C_kR}, \dots, \gamma_{C_NR}) < \gamma_{\text{th}}^a) \\ &= P_{\text{out},a}^{C_k} \cdot \prod_{\substack{i=0, \\ i \neq k}}^N P_{\text{out},a}^{C_i} \end{aligned} \quad (42)$$

where $\gamma_{\text{th}}^a = 2^{R_c/\tau_i} - 1$, $P_{\text{out},a}^{C_k}$ is the outage probability of the link $C_k \rightarrow R$, and $P_{\text{out},a}^{C_i}$ is the outage probability of the link $C_i \rightarrow R$ ($i \neq k$). Then, $P_{\text{out},a}^{C_k}$ and $P_{\text{out},a}^{C_i}$ are derived as follows.

From (18), $P_{\text{out},a}^{C_k}$ can be expressed as

$$\begin{aligned} P_{\text{out},a}^{C_k} &= \Pr(\gamma_{C_kR} < \gamma_{\text{th}}^a) \\ &= \int_0^{+\infty} \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{\ln\left(\frac{\gamma_{\text{th}}^a(1+\theta py)}{(1-\theta)\delta y}\right) - 2\mu_{PC_k}}{2\sqrt{2}\sigma_{PC_k}}\right) \right] \\ &\quad \times \frac{1}{2\sqrt{2\pi}\sigma_{C_kR}y} \exp\left(-\left(\frac{\ln(y) - 2\mu_{C_kR}}{2\sqrt{2}\sigma_{C_kR}}\right)^2\right) dy. \end{aligned} \quad (43)$$

The derivation process of (43) is similar to that of (39), see Appendix D.

$$\begin{aligned} P_{\text{out},C}^{\text{PN}} &= \Pr\left(\gamma_{CQ}^{\max} < \gamma_{\text{th}}, |h_{PC_1}|^2 \geq \frac{P_{CU_1}}{\eta P_p \alpha_1}, \dots, |h_{PC_N}|^2 \geq \frac{P_{CU_N}}{\eta P_p \alpha_N}\right) \\ &= \int_0^{+\infty} \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{\ln(x + N_0) + \ln(\gamma_{\text{th}}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right) \right) \cdot f_{G_{\min}}(x) dx \\ &= {}^{e_1} \int_0^{+\infty} \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{\ln(x + N_0) + \ln(\gamma_{\text{th}}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right) \right) dF_{G_{\min}}(x) \\ &= {}^{e_2} \left(\frac{1}{2} F_{G_{\min}}(x) \cdot \left(1 + \operatorname{erf}\left(\frac{\ln(x + N_0) + \ln(\gamma_{\text{th}}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right) \right) \right) \Big|_0^{+\infty} \\ &\quad - \prod_{i=1}^N \left[\frac{\sigma_{C_iQ}}{4\sigma_{PC_i}} + \int_0^{+\infty} \frac{\sigma_{C_iQ}}{4\sqrt{\pi}\sigma_{PC_i}} \operatorname{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1-\alpha_i)P_p) - 4\mu_{C_iQ}}{4\sigma_{C_iQ}}\right) \right. \\ &\quad \times \frac{1}{2\sqrt{2}\sigma_{PQ}(x + N_0)} \exp\left(-\left(\frac{\ln(x + N_0) + \ln(\gamma_{\text{th}}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right)^2\right) dx \Big] \\ &= \prod_{i=1}^N \frac{\sigma_{C_iQ}}{4\sigma_{PC_i}} \left[\frac{3}{2} - \frac{1}{2} \operatorname{erf}\left(\frac{\ln(\gamma_{\text{th}}N_0/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right) \right. \\ &\quad - \int_0^{+\infty} \frac{1}{2\sqrt{2\pi}\sigma_{PQ}(x + N_0)} \operatorname{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1-\alpha_i)P_p) - 4\mu_{C_iQ}}{4\sigma_{C_iQ}}\right) \\ &\quad \times \exp\left(-\left(\frac{\ln(x + N_0) + \ln(\gamma_{\text{th}}/P_p) - 2\mu_{PQ}}{2\sqrt{2}\sigma_{PQ}}\right)^2\right) dx \Big] \end{aligned} \quad (35)$$

From (19), $P_{out,a}^{C_i}$ can be derived as

$$P_{out,a}^{C_i} = \Pr(\gamma_{C_iR} < \gamma_{th}^a) = \frac{1}{4} \left[1 + \operatorname{erf} \left(\frac{\ln \left(\frac{2\gamma_{th}^a \tau_i N_0}{\eta P_p (1-\beta) T} \right) - 2\mu_{C_iR} - 2\mu_{PC_i}}{\sqrt{\sigma_{C_iR}^2 + \sigma_{PC_i}^2}} \right) \right]. \quad (44)$$

The derivation of (44) is shown in Appendix E.

C. Throughput Analysis of CR Intra-WBAN Under H-CE/Co-EITP

Throughput is a vital performance metric that characterizes the spectrum utilization of CR intra-WBAN, and it can also be referred to as average spectrum efficiency [14]. Thus, the throughput of CR intra-WBAN under the H-CE/CO-EITP is defined as the sum of the target rates obtained by the PN and CN without outage. The target rates of the PN and CN are set to R_p and R_c , respectively. The throughput of CN can be obtained from (25) and (42) as follows:

$$\Phi_{CN} = \beta (1 - P_{out,b}^{CN}) R_c + \frac{(1-\beta)}{2} (1 - P_{out,a}^{CN}) R_c. \quad (45)$$

Based on (31) and (37), the throughput of PN is given by

$$\Phi_{PN} = \beta (1 - P_{out,b}^{PN}) R_p + \frac{(1-\beta)}{2} (1 - P_{out,r}^{PN}) R_p. \quad (46)$$

So far, the total throughput of CR intra-WBAN under the H-CE/CO-EITP can be obtained from (45) and (46) as follows:

$$\Phi = \Phi_{PN} + \Phi_{CN}. \quad (47)$$

D. EE of CR Intra-WBAN Under H-CE/Co-EITP

The EE of CR intra-WBAN under the H-CE/CO-EITP is defined as the ratio of the total amount of data transmission to the total energy consumption. Under the H-CE/CO-EITP, the total energy consumption of CR intra-WBAN is the energy consumed by the node P in the BSN's coexistence phase (βT period) and the BSN's cooperation phase (the first $(1-\beta)T/2$ period). Note that the energy consumed by the cognitive BSNs active transmission phase in the BSN's cooperation phase is the energy harvested by the cognitive BSNs during the previous $(1-\beta)T/2$ period. Therefore, the EE of CR intra-WBAN under the H-CE/CO-EITP is given by

$$\Theta = \frac{\Phi}{P_p (1 + \beta)/2}. \quad (48)$$

IV. RESULTS AND DISCUSSION

This section evaluates the performance of CR intra-WBAN under the H-CE/CO-EITP through numerical analysis and Monte Carlo simulation. Comparative analysis is performed with existing work and other schemes to validate the effectiveness of the proposed approach.

The WBAN monitoring subject in this study is a patient with heart disease. The PN consists of a node P located in the chest and a node Q located in the right arm. The CN consists

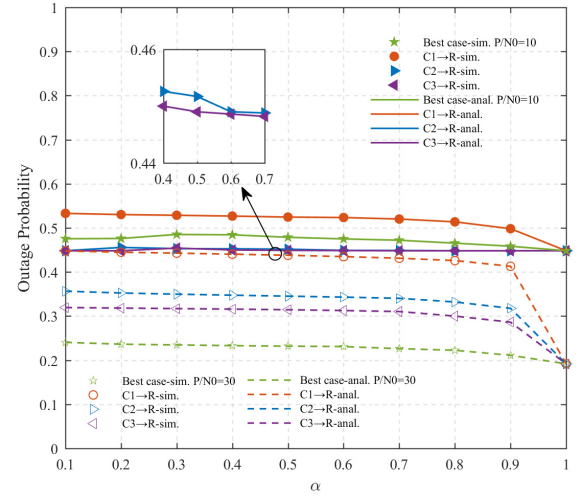


Fig. 4. Effects of backscattering coefficient and SNR on PN OP.

of a node R located in the right foot and nodes C_1 – C_3 located in the waist center, left arm, and left hand, respectively. The relevant parameters of the channel model in CR intra-WBAN come from [29]. Since van Roy et al. [29] ignored the deviation χ_r caused by the environment during the experiment, based on (1), the surface channel gain is modeled as

$$h_{mj} = \sqrt{10^{-P_L(d_0)/10 - n \log_{10}(d_{mj}/10)}}$$

where $d_0 = 10$ cm, $n = 1.29$, $P_L(d_0) = -16.6$, and the value of d_{mj} is shown in Table I. Correspondingly, the lognormal fading distribution parameters are shown in Table II. Based on the above experimental scheme settings and the proposed optimal relay selection scheme, C_1 can be determined as the optimal relay node under this scheme. Moreover, unless otherwise specified, other parameters are set as shown in Table III.

In the follow-up work, the corresponding outage probability analytical curves based on (24), (30), (35), (40), and (43) are obtained by Mathematica, where $M = 50$ in (40). The analysis results (shown in curves-anal.) are compared with those from the Monte Carlo simulation (shown in curves-sim.). Except for the experimental results concerning the OP of the CN during the BSN's coexistence phase, the analysis results of the other experiments are generally consistent with the simulation results.

A. OP Analysis

Fig. 4 shows the effects of the backscattering coefficient α and the signal-to-noise ratio (SNR) P_p/N_0 on the OP of the PN during the BSN's coexistence phase. It found that as the $(1-\alpha)$ increases, the outage probability of the PN gradually increases and tends to saturation. This rise is attributed to the interference generated by the backscattering transmission from the CN. Furthermore, the analysis results are basically consistent with the Monte Carlo results. This proves the correctness of the derived outage probabilities [see (27) and (31)]. Moreover, it has been observed that at a low SNR ($P_p/N_0 = 10$ dB), the OP of the PN changes very little with increases in the backscatter coefficient $(1-\alpha)$ when the

TABLE I
VALUE OF NODE DISTANCE d_{mj} [29]

Distance/cm	Right arm Q	Waist center C_1	Left hand C_2	Left arm C_3	Right foot R
Chest P	39	21	34	70	114
Waist center C_1	34	--	--	--	94
Left hand C_2	62	--	--	--	91
Left arm C_3	55	--	--	--	105

TABLE II
LOGNORMAL FADING DISTRIBUTION PARAMETERS [29]

$\mu_{m,j}, \sigma_{m,j}$	Right arm Q	Waist center C_1	Left hand C_2	Left arm C_3	Right foot R
Chest P	-2.17, 4.92	-0.77, 2.89	-2.99, 6.41	-1.35, 3.88	-4.62, 7.58
Waist center C_1	-0.15, 1.18	--	--	--	-3.86, 6.98
Left hand C_2	-2.98, 6.04	--	--	--	-3.42, 6.36
Left arm C_3	-3.09, 6.18	--	--	--	-3.58, 6.40

TABLE III
SETTINGS OF OTHER PARAMETERS

Parameter	Value
Energy conversion efficiency η	0.8
Reflection efficiency ($\varepsilon_1 = \varepsilon_2 = \varepsilon_3$)	0.9
Transmission time block T [14]	1ms
Time segmentation factor β [14]	0.2
Node P target rate R_p [14]	0.8bps/Hz
Noise power at the receiver	-30dBm
Backscatter power threshold ($P_{CU_1} = P_{CU_2} = P_{CU_3}$)	0.02μW

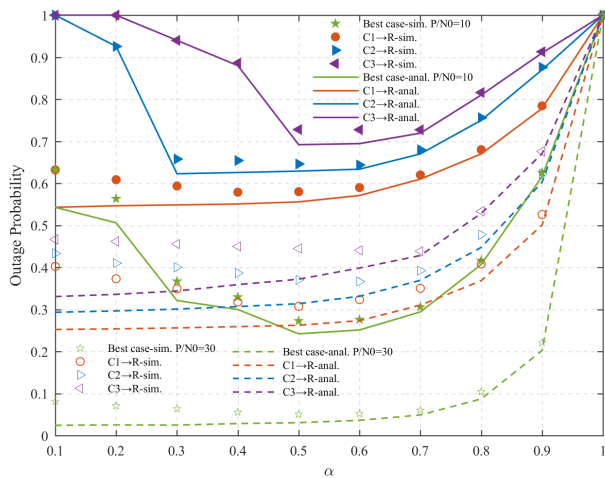


Fig. 5. Effects of backscattering coefficient and SNR on CN outage performance.

backscatter link $C_2 \rightarrow R$ or $C_3 \rightarrow R$ is happening. When the $(1 - \alpha)$ is large, the outage probabilities for both links are nearly identical. In contrast, when the link $C_1 \rightarrow R$ is

active, the OP of the PN shows a significant decline and is the least effective. This is due to the fact that the channel quality for the links $P \rightarrow C_2$ or $P \rightarrow C_3$ ($C_2 \rightarrow R$ or $C_3 \rightarrow R$) is considerably poorer than that of the link $P \rightarrow C_1$ ($C_1 \rightarrow R$). As discussed in Section II-B1, the occurrence of backscattering is limited by energy constraints. When the SNR is low, only nodes with better channel conditions can harvest enough energy for backscattering. In contrast, nodes with poorer channel conditions must harvest more energy to enable backscattering. Therefore, under low SNR conditions, the node that causes the least interference to PN often has the weakest energy harvesting capability, which prevents it from participating in communication. At this stage, the optimal OP of the PN is primarily influenced by node C_1 , which generates higher interference to the PN. This effect is corroborated in Fig. 5. This is also the reason why the optimal OP curve of the PN is slightly higher than that of the PN when the backscatter link $C_2 \rightarrow R$ (or $C_3 \rightarrow R$) occurs. The main reason for its small influence amplitude is that under a low SNR, the noise power at the primary receiver (Q) is significantly higher than the interference caused by the CN. However, at an SNR ($P_p/N_0 = 30$ dB), the optimal OP of the PN is dominated by the interference introduced by the CN. Therefore, the optimal OP of the PN is notably superior to that observed when the backscatter link $C_1 \rightarrow R$ ($C_2 \rightarrow R$ or $C_3 \rightarrow R$) is active. When the backscatter link $C_1 \rightarrow R$ is active, the OP of the PN is the worst. This can be primarily attributed to the superior channel conditions of $C_1 \rightarrow R$, which, under high SNR, yields higher gains and consequently imposes more significant interference on the PN.

Fig. 5 illustrates the effects of the backscattering coefficient α and the SNR on the OP of the CN during the BSN's coexistence phase. As $(1 - \alpha)$ increases, the deviation between the analytical and simulated results for the OP of the CN gradually becomes more pronounced. This discrepancy arises because the analytical results [with outage probabilities given by (20) and (25)] only account for the energy constraint and

the interference from the PN to the CN, without considering the restriction that the interference from the CN to the PN should remain within the PN's tolerable interference threshold (which has incorporated in the simulation). As observed from the curve trends, under high SNR ($P_p/N_0 = 30$ dB), the analytical results indicate that the OP of the CN gradually improves with increasing $(1 - \alpha)$. In contrast, the simulated results show that the OP initially improves, but after reaching an optimum point, it gradually deteriorates and eventually saturates. This behavior is a direct consequence of the interference threshold constraint. At low SNR ($P_p/N_0 = 10$ dB), the trends of the analytical and simulated results for the OP of the backscatter link $C1 \rightarrow R$ follow a pattern similar to that under high SNR. However, the magnitude of the performance variation is less pronounced compared to the high-SNR case, and the discrepancy between analytical and simulated results is less. This can be attributed to the energy constraint governing backscatter operation. Under low SNR conditions, even nodes with favorable channel conditions require sufficient energy and backscatter power to activate transmission. This also explains why the OP of backscatter links $C2 \rightarrow R$ or $C3 \rightarrow R$, as well as the optimal OP of the CN, initially improves significantly but then degrades as $(1 - \alpha)$ increases. Notably, the energy constraint effect is more pronounced for nodes with poorer channel conditions. Specifically, the energy harvested by node C_1 increases with both the transmit power P_p of the source node and the value of α . Therefore, an increase in α initially leads to improved OP. However, a continued rise in α results in reduced power available for backscatter transmission, consequently gradually degrading the OP. This is particularly evident when $\alpha = 1$, at which point the power allocated for backscatter transmission drops to zero, thereby resulting in an outage probability of 1.

Therefore, based on the simulation results, there is an optimal value of α that minimizes the outage probability of the CN under the interference threshold constraint. As previously analyzed, this optimal α is influenced by the SNR. At low SNR (i.e., $P_p/N_0 = 10$ dB), the optimal α values for the backscatter links $C_1 \rightarrow R$, $C_2 \rightarrow R$, and $C_3 \rightarrow R$ are approximately 0.4, 0.6, and 0.7, respectively. Under the high SNR condition (i.e., $P_p/N_0 = 30$ dB), the corresponding optimal α values are around 0.5, 0.6, and 0.7. The variation in optimal α among the links $C_i \rightarrow R$ at low SNR is primarily due to the combined effects of energy availability and channel quality. However, under high SNR conditions, the interference threshold becomes the dominant factor determining the optimal α . This also explains why the optimal α for the $C_1 \rightarrow R$ link is larger under high SNR conditions than under low SNR conditions. Hence, by selecting the appropriate α , the CN can achieve the optimal performance in the BSN's coexistence phase.

Figs. 6 and 7 demonstrate the relationship between the OP and SNR of the CN and the PN under different β 's in the BSN's coexistence phase, respectively. During the experiment, α_1 – α_3 are set to 0.1 to evaluate the performance of both the PN and the CN under poor conditions. It can be observed that the OP of both the cognitive and PNs improves as β increases. The analytical curve for the CN's outage probability decreases

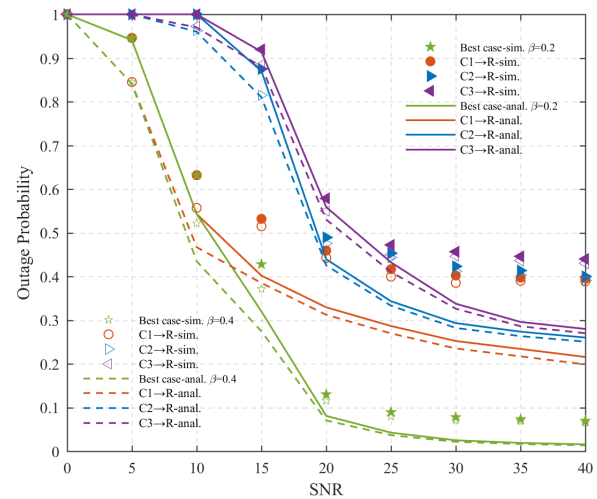


Fig. 6. OP of CN versus SNR in the BSN's coexistence phase.

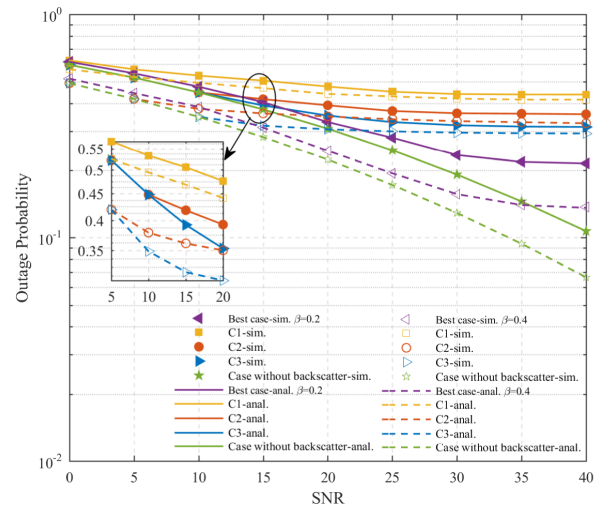
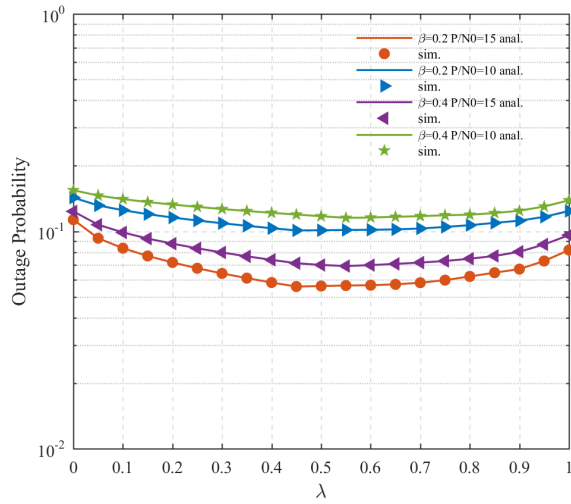


Fig. 7. OP of PN versus SNR in the BSN's coexistence phase.

with rising SNR, yet its rate of improvement slows and eventually saturates under high SNR conditions. This behavior is primarily attributed to the interference from node P during its transmission. Meanwhile, the deviation between the simulated and analytical outage probability curves widens with increasing SNR and eventually stabilizes. This discrepancy arises because the simulation accounts for the interference threshold tolerable by the PN, a constraint not reflected in the analytical results [see (20) and (25)]. As SNR continues to increase, the declining trend of the simulated curve gradually saturates. At this point, the OP of the CN becomes predominantly limited by the interference threshold of the PN.

In Fig. 7, the relationship between the outage probability of the PN and the SNR is primarily considered in the following cases: 1) when there is no backscatter transmission (see (32) and (33) for outage probability); 2) when the i th cognitive BSN is selected for backscattering transmission [outage probability is shown in (26)]; and 3) when the backscatter link with the slightest interference to the PN is selected for backscatter [outage probability is shown in (31)]. Obviously, under the


 Fig. 8. Impact of λ on OP of PN.

interference of the backscatter link, the OPs of cases 2) and 3) are usually not as good as case 1). When the existence of the interference, the OP of case 3) is optimal. Therefore, when configuring BSNs for patients, a backscatter sensor with minimal interference should be utilized to collect critical physiological parameters. In other words, in addition to the essential life data obtained from the PN, the parameters gathered through backscatter provide vital information to assist doctors in making diagnoses.

Fig. 8 illustrates the influence of β , P_p/N_0 , and λ on the OP of the PN in the BSN's cooperative phase. During the experiment, it is assumed that $\beta = 0.2$ [14] and $\beta = 0.4$. Thus, based on (41), the minimum value of θ of the relay C_1 under the condition of ensuring the cooperative primary signal transmission can be calculated, i.e., $\theta = 0.76$ and $\theta = 0.85$. As the curve in the graph, the OP gradually improves with an increase in λ . However, after reaching an optimal state, further increases in λ lead to a deterioration of the OP. This indicates that there is an optimal λ that minimizes the outage probability of the PN. The reason for this is that too large a λ results in less power being available for information processing, which subsequently decreases the OP in relay cooperation. In the subsequent experiments, the influence of θ change on the network OP and the reason for taking the minimum value of θ that satisfies (41) are discussed when β is constant. Moreover, as β increases, the OP of the PN reduces. That is because, at a constant rate, the reduction in the time allocated for the BSN's cooperation phase leads to a higher bandwidth occupancy rate. Thereby, when $\beta = 0.2$ and $\theta = 0.76$, the optimal OP can be obtained when λ is 0.4.

Figs. 9 and 10 show the relationship between the OP and SNR of the CN and PN under different target rates, β , and θ in the BSN's cooperation phase, respectively. In the experiment, $\lambda = 0.4$. It can be observed that with the same other parameters, the OP of CN and PN (including relay cooperation and DL) decreases with the increase of the target rate (or β), and the OP of both networks gradually improves with the increase of SNR. With the increase of θ , the OP of the PN with relay cooperation improves, while the OP of the link

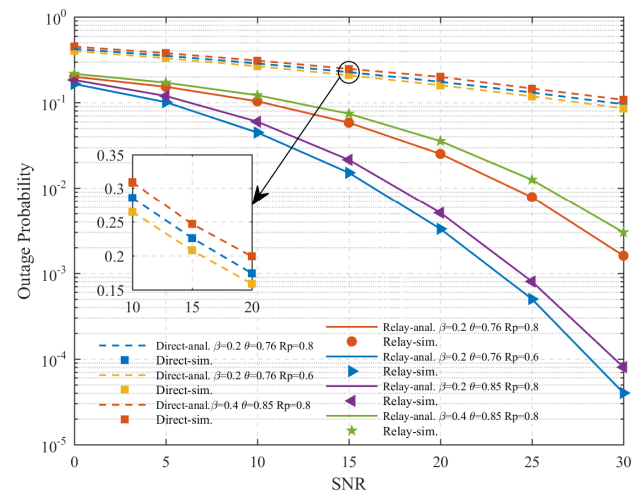


Fig. 9. OP of PN versus SNR in the BSN's cooperation phase.

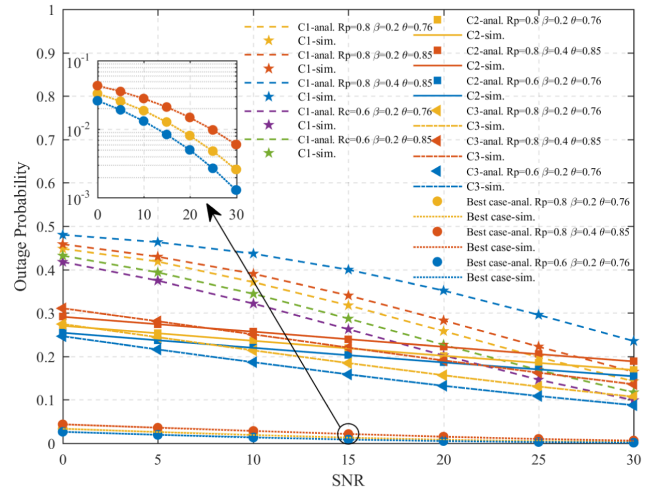


Fig. 10. OP of CN versus SNR in the BSN's cooperation phase.

$C_1 \rightarrow R$ reduces. This phenomenon verifies the conclusion of the spectrum-sharing factor proposed in Section III-B1, that is, the larger the value of θ , the more power allocated to the primary signal cooperation, and the less power to provide active transmission for C_1 . Furthermore, in Fig. 9, the OP of CR intra-WBAN with H-CE/CO-EITP is significantly better than that of the DL transmission scheme. This is because the cooperative relay link under the H-CE/CO-EITP can acquire additional diversity gain.

B. System Throughput and EE Analysis

This section compares and analyzes the network throughput and EE under the proposed scheme with advanced working and benchmark schemes to verify its effectiveness and advantages.

1) *DL Transmission*: This scheme serves as the benchmark scheme and adopts direct link transmission during T .

2) *Noncooperative Transmission With Backscattering*: This scheme is a variant of the protocol proposed in this article. Specifically, the βT period is the BSN's coexistence phase [where the outage probability can be seen in (20) and (25)], and the remaining time $(1 - \beta)T$ adopts DL transmission [its outage probability is demonstrated in (36)].

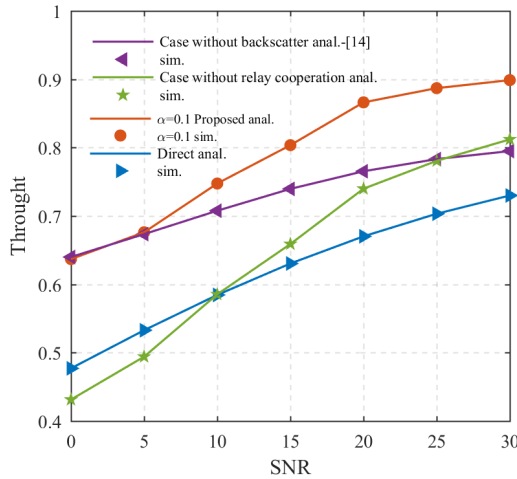


Fig. 11. Throughput versus SNR for CR intra-WBAN.

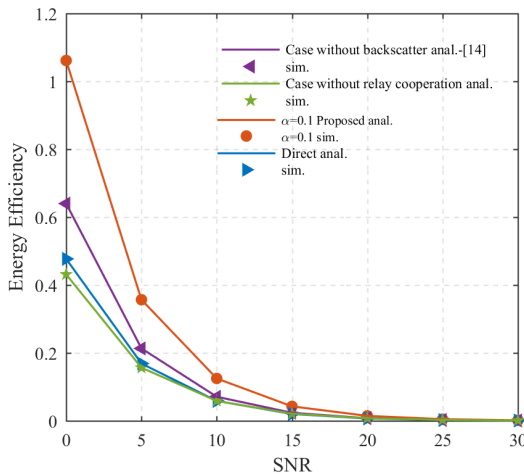


Fig. 12. EE versus SNR for CR intra-WBAN.

3) *Cooperative Transmission Without Backscattering*: This scheme is the work in [14]. Shukla et al. [14] proposed two energy-harvesting-based spectrum-sharing protocols, namely, TSC and PSC, and presented a comparative analysis; their results demonstrated that the system exhibits superior performance under the PSC protocol. Therefore, this article selects the PSC protocol, which showed the best performance in [14], for comparative analysis with the proposed scheme. It is noteworthy that the protocol proposed in this article reduces to the PSC scheme in [14] when $\beta = 0$. However, unlike this work, work [14] assumed only a single cognitive node, which also served as the amplify-and-forward relay. To ensure a fair comparison, the number of cognitive nodes in the scheme [14] is extended to match that of this work, namely, nodes C_1 – C_3 , with C_1 being the optimal relay node.

4) *H-CE/Co-EITP*: This refers to the scheme proposed in this article. To validate its advantages, the backscattering coefficients in the BSN coexistence phase are set as $\alpha_1 = \alpha_2 = \alpha_3 = 0.1$. As analyzed in Section IV-A, this configuration corresponds to the least favorable performance for the CN, particularly under low SNR conditions. By comparing this worst case scenario with other schemes, the superiority of the proposed approach can be effectively demonstrated.

For all the aforementioned schemes, the common parameter settings are specified as follows: $R_p = 0.8$ bps/Hz, $R_c = 0.6$ bps/Hz, $\alpha_1 = \alpha_2 = \alpha_3 = 0.1$, and $\lambda = 0.4$. Figs. 11 and 12 evaluate the relationships between throughput and EE versus SNR of CR intra-WBAN under the four aforementioned schemes, respectively. Apparently, the throughput and EE of the proposed scheme are significantly better than other schemes. In Fig. 11, with the increase of SNR, the throughput performance under the four schemes gradually improves and tends to be stable. At very low SNR levels, the throughput of the proposed scheme is closely matched with that of Scheme 3). However, as the SNR increases, the proposed scheme exhibits a more significant throughput performance gain. This behavior can be attributed to the strong dependence of the backscatter communication in the BSN coexistence phase of the proposed scheme on the transmit power of the source node, P . At lower SNR values, backscatter links are more susceptible to outage and may even fail to operate due to insufficient energy availability under stringent energy constraints. Scheme 2) exhibits the poorest throughput performance at low SNR, while it achieves the second-best performance after the proposed scheme at high SNR. That is because, under low SNR conditions, backscatter communication experiences a high outage probability, and the PN is susceptible to noise interference. Conversely, at high SNR, these limitations are alleviated, and the PN can tolerate a higher interference threshold from the CN. In Fig. 12, it is noted that as SNR increases, the EE under the four schemes is significantly reduced, mainly because the throughput achieved at high SNR is much lower than the power consumed.

C. System Implementation Challenges and Feasibility Discussion

As previously discussed, this article introduces a novel CR intra-WBAN communication paradigm capable of supporting both backscattering and energy harvesting, along with a corresponding energy and information transmission protocol, and has demonstrated its effectiveness. However, given that the system incorporates multiple technologies, including RFEH, CR, cooperative communications, and the emerging AmBC, its practical deployment may involve complex hardware and software. Therefore, this section discusses potential challenges in the real-world implementation of the proposed system, as well as promising solutions to address them.

1) Hardware Integration Complexity:

a) *Challenges*: Implementing the proposed system requires sensor nodes to integrate multiple functionalities, including RF energy harvesting, backscatter modulation, active data transmission/reception, and spectrum sensing. This integration is expected to increase the hardware complexity, physical dimensions, and initial costs of the nodes.

b) *Feasibility analysis and potential solutions*: Recent advances in integrated circuit technology have enabled the monolithic integration of multifunctional radio frequency front ends. The study by Ensworth [30] has demonstrated the feasibility of co-designing energy harvesting and backscatter communication. Their proposed system architecture (refer to

[30, Fig. 1.1]) integrates RF energy harvesting, an ultralow-power backscatter uplink, and a receiver utilizing an external carrier, all within a single node, while maintaining the capability for direct communication with low-power devices. The work further highlights that application-specific integrated circuit (ASIC) design can significantly optimize the system's form factor and EE. In a similar vein, Huang et al. [31] have successfully achieved the integration of complex functionalities in resource-constrained wearable devices. They developed a battery-free insole sensing platform that incorporates piezoelectric energy harvesting, power management, sensing, processing, as well as Bluetooth and AmBC modules, demonstrating stable operation in real-world scenarios. These results strongly indicate that, through careful system-level optimization and dedicated circuit design, the implementation of such multitechnology systems is practically achievable.

Future work may focus on developing ASICs that holistically integrate functional modules for energy harvesting, backscattering, active communication, and spectrum sensing. Such an approach would ultimately optimize the overall system size, cost, and energy consumption without compromising performance.

2) Protocol Management and Computational Overhead:

a) *Challenge*: Strategies such as the optimal relay selection and dynamic time/power/spectrum allocation in hybrid protocols require certain computing resources and may impose a burden on resource-constrained sensor nodes.

b) *Feasibility analysis and potential solutions*: It is worth noting that many key parameters in the proposed protocol, such as the backscattering coefficient α , the time segmentation factor β , and the power splitting factor λ for cooperative relaying, can be preconfigured or computed offline during the initial network deployment phase by a network coordinator (e.g., a personal terminal), based on channel statistics and service requirements. This approach does not require each sensor node to perform real-time complex optimizations.

The assignment of parameters such as α , β , and λ can be preconfigured according to specific user or patient requirements. For instance, in the case of long-term monitoring of chronic conditions, where emphasis is placed on continuous data acquisition and integrity, backscatter communication becomes relatively less critical. In such scenarios, a larger value can be assigned to the duration of the BSN cooperative phase, $(1 - \beta)T$, and the relay power splitting factor λ can be set around 0.5, as supported by the evaluation in Section IV-A. Conversely, for acute disease monitoring, where timeliness of information transmission is essential, the initial backscatter communication phase plays a vital role. Accordingly, a larger value should be allocated to the duration of the BSN coexistence phase, βT , and, based on the analysis in Section IV-A, the backscattering coefficient α can be set between 0.5 and 0.7. For relay selection, a low-complexity criterion based on channel state information (CSI), such as selecting the node with the maximum SNR or the best channel condition, can be adopted instead of exhaustive search methods. As in the experimental evaluation process, based on previous work on the measurement results of channel quality between sensor nodes and the location information of the sensor nodes to be

deployed, the optimal relay node can be determined according to the optimal relay selection strategy, which is C_1 .

In addition, the dynamic real-time allocation strategy may be more intelligent, enabling the network performance to be optimized in real time. We can consider implementing an intelligent real-time allocation algorithm on the coordinator. However, the complexity of such algorithms must remain within the processing capabilities of the coordinator. The development of such adaptive strategies warrants in-depth investigation in future work.

V. CONCLUSION

In this article, a cooperative CR intra-WBAN supporting backscatter and RFEH for MIIOT is studied. In this network, a hybrid BSN's coexistence/cooperative energy and information transmit protocol is established to promote spectrum and EE utilization. Therefore, under this protocol architecture, the OP of each link in the coexistence phase and the cooperation phase, the optimal OP of the PN and the CN are investigated. During the research process, it is revealed that several key parameters, including the backscatter coefficient, the cooperative relay power splitting factor, and the SNR, significantly impact the aforementioned OP. For example, the optimal OP of the CN in the coexistence phase has an inherent tradeoff between energy harvesting and communication efficiency [i.e., backscatter signal strength ($\varepsilon_i(1 - \alpha_i)$)]; the optimal OP of the PN is limited by interference from backscattering. This finding provides a practical insight into the actual deployment of cognitive BSNs, namely, sensors operated with minimal interference should be employed to monitor critical physiological parameters when configuring wearable sensors for patients. In the BSN's cooperative phase, the relay-assisted link provides additional diversity gain to the PN compared to the direct link, and an optimal tradeoff between energy harvesting and information processing exists for PN performance. Besides, the throughput and EE of CR intra-WBAN under the H-CE/CO-EITP are studied and compared with advanced working and benchmark schemes. The results show that the system performance under the proposed protocol is optimal.

Therefore, compared to previous studies (such as [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [18], [19], and [20]), this work enhances the traditional WBAN capabilities for responding to emergencies. In addition, it further enhances the capabilities of conventional telemedicine monitoring services in spectrum and energy utilization and is ready for the next generation MIIOT. However, the proposed network architecture and its corresponding energy and information transmission protocol can be further extended in the following way: 1) as discussed in Section IV-C, a joint optimization strategy with low computational complexity should be developed for dynamically and intelligently allocating key parameters; 2) a more practical nonlinear energy harvesting model; and 3) adoption of more realistic channel fading models, such as the Nakagami- m distribution that accounts for small-scale fading, or measurement-based channel models, along with a more accurate path loss model whose precision depends on signal frequency, body location, and orientation of wearable antennas.

APPENDIX

A. Derivation of CDF $F_{S_i}(x)$ and PDF $f_{S_i}(x)$ of S_i

First, the cdf of $F_{S_i}(x)$ is derived by (A.1), as shown at the bottom of the page, where $b_i = P_{CU_i}/\eta P_p \alpha_i$ and $y = |h_{PC_i}|^2$ in step e_1 ; step e_2 makes the transformation of $z = \varepsilon_i(1 - \alpha_i)P_p y$. Next, F_1 and F_2 are derived.

Based on $\int_{-\infty}^{+\infty} e^{-x^2} dx = (\pi)^{1/2}$, F_1 can be calculated as

$$F_1 = \frac{\sigma_{C_i R}}{2\sqrt{\pi}\sigma_{PC_i}} \int_{-\infty}^{+\infty} \exp\left(-\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) d\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right) \\ \stackrel{e_3}{=} \frac{\sigma_{C_i R}}{2\sqrt{\pi}\sigma_{PC_i}} \int_{-\infty}^{+\infty} e^{-t^2} dt = \frac{\sigma_{C_i R}}{2\sigma_{PC_i}} \quad (A.2)$$

where the integral transformation of $t = (\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R})/(2(2)^{1/2}\sigma_{C_i R})$ is performed in step e_3 .

In order to derive F_2 , it is necessary to calculate the integral, including the error function and the Gaussian function. Inspired by [19], the following equation holds:

$$\int_0^{+\infty} e^{-(wx+u)^2} \operatorname{erf}(gx+v) dx = \frac{\sqrt{\pi}}{2w} \operatorname{erf}\left(\frac{wv-ug}{\sqrt{w^2+g^2}}\right). \quad (A.3)$$

Its proof process can be referred to [19, Appendix E]. Hence, based on (A.3), F_2 is given by

$$F_2 = \frac{1}{2} \int_0^{+\infty} \frac{\sigma_{C_i R}}{\sqrt{\pi}\sigma_{PC_i}} \operatorname{erf}\left(\frac{\ln(x) - \ln(z) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)$$

$$\times \exp\left(-\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) \\ d\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right) \\ \stackrel{e_4}{=} \frac{1}{2} \int_0^{+\infty} \frac{\sigma_{C_i R}}{\sqrt{\pi}\sigma_{PC_i}} \operatorname{erf}\left(\frac{\ln(x) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}} - t\right) \\ \times \exp\left(-\left(t - \frac{\ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) dt \\ = \frac{\sigma_{C_i R}}{4\sigma_{PC_i}} \cdot \operatorname{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right) \quad (A.4)$$

where the integral transformation of $t = (\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R})/(2(2)^{1/2}\sigma_{C_i R})$ is performed in step e_4 .

So far, $F_{S_i}(x)$ can be written as (A.5), shown at the bottom of the page.

Then, the pdf of S_i can be expressed as

$$f_{S_i}(x) = \frac{\partial F_{S_i}(x)}{\partial x} = \frac{1}{8\sqrt{\pi}\sigma_{PC_i}x} \cdot \exp\left(-\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right)^2\right). \quad (A.6)$$

B. Derivation of (24)

According to $|h_{PC_i}|^2 \sim \operatorname{LogN}(2\mu_{PC_i}, 4\sigma_{PC_i}^2)$, I_1 can be derived by

$$I_1 = \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{\ln(P_{CU_i}) - \ln(\eta\alpha_i P_p) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}}\right)\right). \quad (B.1)$$

$$F_{S_i}(x) = \Pr\left(S_i \leq x, |h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}\right) \\ \stackrel{e_1}{=} \int_{b_i}^{+\infty} \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p y) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)\right] \cdot \frac{1}{2\sqrt{2\pi}\sigma_{PC_i}y} \exp\left(-\left(\frac{\ln(y) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}}\right)^2\right) dy \\ \stackrel{e_2}{=} \int_0^{+\infty} \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{\ln(x) - \ln(z) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)\right] \cdot \frac{1}{2\sqrt{2\pi}\sigma_{PC_i}z} \exp\left(-\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) dz \\ = \underbrace{\frac{1}{2} \int_0^{+\infty} \frac{1}{2\sqrt{2\pi}\sigma_{PC_i}z} \exp\left(-\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) dz}_{F_1} \\ + \underbrace{\frac{1}{2} \int_0^{+\infty} \frac{1}{2\sqrt{2\pi}\sigma_{PC_i}z} \operatorname{erf}\left(\frac{\ln(x) - \ln(z) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right) \exp\left(-\left(\frac{\ln(z) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 2\mu_{C_i R}}{2\sqrt{2}\sigma_{C_i R}}\right)^2\right) dz}_{F_2} \quad (A.1)$$

$$F_{S_i}(x) = \frac{\sigma_{C_i R}}{2\sigma_{PC_i}} \left[1 + \frac{1}{2} \operatorname{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right)\right]. \quad (A.5)$$

Based on proposition 1, I_2 can be expressed as (B.2), shown at the bottom of the page. where $\text{erfc}(\cdot)$ in step e_5 is the complementary error function and $\text{erfc}(x) = 1 - \text{erf}(x)$.

C. Derivation of CDF $F_{G_{\min}}(x)$ of G_i

Similar to the cdf derivation of S_i in Appendix A, the cdf of G_i can be represented as

$$\begin{aligned} F_{G_i}(x) &= \Pr\left(G_i \leq x, |h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}\right) \\ &= \frac{\sigma_{C_i Q}}{2\sigma_{PC_i}} \left[1 + \frac{1}{2} \text{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i Q}}{4\sigma_{C_i Q}}\right) \right]. \end{aligned} \quad (\text{C.1})$$

Based on (C.1), the cdf $F_{G_{\min}}(x)$ of $G_{\min} = \min G_1, \dots, G_N$ can be calculated as (C.2), shown at the bottom of the page.

D. Derivation of (39) and (43)

Based on (17), the cdf $F_{\gamma_{C_k Q}}(x) = \Pr(\gamma_{C_k Q} < \gamma_{\text{th}}^1)$ when $x < \theta/(1 - \theta)$

$$F_{\gamma_{C_k Q}}(x)$$

$$= \Pr\left(\gamma_{PC_k} < \frac{\gamma_{\text{th}}^1 (1 + \theta \rho |h_{C_k Q}|^2)}{\delta (\theta - (1 - \theta) \gamma_{\text{th}}^1) |h_{C_k Q}|^2}\right) \triangleq \Psi(x). \quad (\text{D.1})$$

Let $y = |h_{C_k Q}|^2$, and according to $|h_{PC_k}|^2 \sim \text{LogN}(2\mu_{PC_k}, 4\sigma_{PC_k}^2)$ and $|h_{C_k Q}|^2 \sim \text{LogN}(2\mu_{C_k Q}, 4\sigma_{C_k Q}^2)$, (D.1) can be written as follows:

$$\begin{aligned} \Psi(x) &= \int_0^{+\infty} F_{\gamma_{PC_k}}\left(\frac{\gamma_{\text{th}}^1 (1 + \theta \rho y)}{\delta (\theta - (1 - \theta) \gamma_{\text{th}}^1) y}\right) \cdot f_{|h_{C_k Q}|^2}(y) dy \\ &= \int_0^{+\infty} \frac{1}{2} \left[1 + \text{erf}\left(\frac{\ln\left(\frac{\gamma_{\text{th}}^1 (1 + \theta \rho y)}{\delta (\theta - (1 - \theta) \gamma_{\text{th}}^1) y}\right) - 2\mu_{PC_k}}{2\sqrt{2}\sigma_{PC_k}}\right) \right] \\ &\quad \times \frac{1}{2\sqrt{2\pi}\sigma_{C_k Q} y} \exp\left(-\left(\frac{\ln(y) - 2\mu_{C_k Q}}{2\sqrt{2}\sigma_{C_k Q}}\right)^2\right) dy. \end{aligned} \quad (\text{D.2})$$

Similarly, $P_{\text{out},a}^{C_k}$ can be derived from (18), that is, cdf $F_{\gamma_{C_k R}}(x) = \Pr(\gamma_{C_k R} < \gamma_{\text{th}}^a)$

$$F_{\gamma_{C_k R}}(x)$$

$$\begin{aligned} I_2 &= \Pr\left(|h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}, |h_{PR}|^2 > \frac{S_i - \gamma_{\text{th}}^b N_0}{\gamma_{\text{th}}^b P_p}\right) \\ &= \int_{\gamma_{\text{th}}^b N_0}^{+\infty} \frac{1}{2} \left[1 - \text{erf}\left(\frac{\ln((x - \gamma_{\text{th}}^b N_0)/\gamma_{\text{th}}^b P_p) - 2\mu_{PR}}{2\sqrt{2}\sigma_{PR}}\right) \right] f_{S_i}(x) dx = \frac{1}{4} \\ &\quad \times \frac{1}{\sqrt{\pi}} \left[\int_{\gamma_{\text{th}}^b N_0}^{+\infty} \frac{1}{4\sigma_{PC_i} x} \left[1 - \text{erf}\left(\frac{\ln(x - \gamma_{\text{th}}^b N_0) - \ln(\gamma_{\text{th}}^b P_p) - 2\mu_{PR}}{2\sqrt{2}\sigma_{PR}}\right) \right] \right. \\ &\quad \times \exp\left(-\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right)^2\right) dx \left. \right] \\ &\stackrel{e_5}{=} \frac{1}{4\sqrt{\pi}} \left[\frac{\sqrt{\pi}\sigma_{C_i R} \text{erfc}\left(\frac{\ln(\gamma_{\text{th}}^b N_0) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right)}{2\sigma_{PC_i}} \right. \\ &\quad - \int_{\gamma_{\text{th}}^b N_0}^{+\infty} \frac{1}{4\sigma_{PC_i} x} \text{erf}\left(\frac{\ln(x - \gamma_{\text{th}}^b N_0) - \ln(\gamma_{\text{th}}^b P_p) - 2\mu_{PR}}{2\sqrt{2}\sigma_{PR}}\right) \\ &\quad \times \exp\left(-\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i R}}{4\sigma_{C_i R}}\right)^2\right) dx \left. \right] \end{aligned} \quad (\text{B.2})$$

$$\begin{aligned} F_{G_{\min}}(x) &= \Pr\left(\min(G_1, \dots, G_N) \leq x, |h_{PC_1}|^2 \geq \frac{P_{CU_1}}{\eta P_p \alpha_1}, \dots, |h_{PC_N}|^2 \geq \frac{P_{CU_N}}{\eta P_p \alpha_N}\right) \\ &= 1 - \Pr\left(G_1 > x, \dots, G_N > x, |h_{PC_1}|^2 \geq \frac{P_{CU_1}}{\eta P_p \alpha_1}, \dots, |h_{PC_N}|^2 \geq \frac{P_{CU_N}}{\eta P_p \alpha_N}\right) \\ &= 1 - \prod_{i=1}^N \Pr\left(G_i > x, |h_{PC_i}|^2 \geq \frac{P_{CU_i}}{\eta P_p \alpha_i}\right) = \prod_{i=1}^N \left[\frac{\sigma_{C_i Q}}{2\sigma_{PC_i}} \right. \\ &\quad \left. + \frac{\sigma_{C_i Q}}{4\sigma_{PC_i}} \text{erf}\left(\frac{\ln(x) - \ln(\varepsilon_i(1 - \alpha_i)P_p) - 4\mu_{C_i Q}}{4\sigma_{C_i Q}}\right) \right]. \end{aligned} \quad (\text{C.2})$$

$$\begin{aligned}
&= \Pr \left(\gamma_{PC_k} < \frac{\gamma_{th}^a (1 + \theta \rho |h_{C_kR}|^2)}{(1 - \theta) \delta |h_{C_kR}|^2} \right) \\
&= \int_0^{+\infty} F_{\gamma_{PC_k}} \left(\frac{\gamma_{th}^a (1 + \theta \rho y)}{(1 - \theta) \delta y} \right) \cdot f_{|h_{C_kR}|^2}(y) dy \\
&= \int_0^{+\infty} \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\ln \left(\frac{\gamma_{th}^a (1 + \theta \rho y)}{(1 - \theta) \delta y} \right) - 2\mu_{PC_k}}{2\sqrt{2}\sigma_{PC_k}} \right) \right] \\
&\quad \times \frac{1}{2\sqrt{2\pi}\sigma_{C_kR}y} \exp \left(- \left(\frac{\ln(y) - 2\mu_{C_kR}}{2\sqrt{2}\sigma_{C_kR}} \right)^2 \right) dy. \quad (D.3)
\end{aligned}$$

E. Derivation of (44)

From (19), $P_{out,a}^{C_i}$ can be derived by

$$\begin{aligned}
P_{out,a}^{C_i} &= \Pr(\gamma_{C_iR} < \gamma_{th}^a) \\
&= \Pr \left(|h_{C_iR}|^2 < \frac{2\gamma_{th}^a \tau_i N_0}{\eta P_p |h_{PC_i}|^2 (1 - \beta) T} \right). \quad (E.1)
\end{aligned}$$

Let $y = |h_{PC_i}|^2$, and based on $|h_{PC_i}|^2 \sim \operatorname{LogN}(2\mu_{PC_i}, 4\sigma_{PC_i}^2)$ and $|h_{C_iR}|^2 \sim \operatorname{LogN}(2\mu_{C_iR}, 4\sigma_{C_iR}^2)$, (E.1) can be written as

$$\begin{aligned}
P_{out,a}^{C_i} &= \int_0^{+\infty} \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\ln \left(\frac{2\gamma_{th}^a \tau_i N_0}{\eta P_p (1 - \beta) T y} \right) - 2\mu_{C_iR}}{2\sqrt{2}\sigma_{C_iR}} \right) \right] \\
&\quad \times \frac{1}{2\sqrt{2\pi}\sigma_{PC_i}y} \exp \left(- \left(\frac{\ln(y) - 2\mu_{PC_i}}{2\sqrt{2}\sigma_{PC_i}} \right)^2 \right) dy. \quad (E.2)
\end{aligned}$$

Applying the integral equation (A.3) to (E.2), $P_{out,a}^{C_i}$ is given by

$$P_{out,a}^{C_i} = \frac{1}{4} \left[1 + \operatorname{erf} \left(\frac{\ln \left(\frac{2\gamma_{th}^a \tau_i N_0}{\eta P_p (1 - \beta) T} \right) - 2\mu_{C_iR} - 2\mu_{PC_i}}{\sqrt{\sigma_{C_iR}^2 + \sigma_{PC_i}^2}} \right) \right]. \quad (E.3)$$

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Article

Statistical Model of Accurately Estimating Service Delay Behavior in Saturated IEEE 802.11 Networks Based on 2-D Markov Chain

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Abstract: To accurately estimate the service delay behavior of IEEE 802.11 networks, this paper comprehensively considers four main factors that affect the performance of IEEE 802.11 networks and establishes a service delay model with statistical characteristics. We analyzed the operation mechanism of 802.11 DCF, using the backoff stage and the backoff counter to portray the dynamic change characteristics of the system regarding the data frame transmission states. Afterward, we calculated the one-step transition probability of these states, establishing a 2-D Markov model, including the ICS procedure and the backoff procedure. Based on this model, we constructed steady-state equations to derive a relationship between the transmission probability and collision probability for each node transmission queue. By analyzing the ICS delay and the backoff delay, we obtained the probability generating function (PGF) of the average idle time. The analytical expressions of other service delays, such as the successful transmission time and collided transmission time, were derived to obtain the PGF of the total service delay. In the numerical simulation, we compared the first two statistical moments of the PGF with the Nav model, and it was found that our delay evaluation results were significantly better than the traditional evaluation results. The average service delay of the Nav model in all the scenarios was larger than that of the proposed model due to the lack of the ICS procedure in the Nav model. Since a DIFS duration is generally much shorter than a random backoff duration, our model saves the bandwidth and improves transmission efficiency.

Keywords: 802.11 DCF; initial carrier-sensing (ICS); 2-D Markov chain; average idle time; service delay; PGF; Nav model



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1. Introduction

While ensuring a stable and consistent user experience, the fifth-generation (5G) communication network provides ultra-high speed, low delay, ultra-reliability, and low-cost service quality, creating unprecedented new opportunities and convenience for society and the economy. Therefore, the large-scale commercialization of 5G networks is a current research hotspot in communication technology [1]. In the field of wireless technology, massive Multiple-Input Multiple-Output (MIMO), millimeter-Wave (mmWave) technology, carrier aggregation technology, new multi-access access, and other technologies are important means to enhance the performance of 5G [2]. In particular, massive MIMO systems can handle large network throughput and support a large number of client connections, which is expected to radically improve the capacity limitations of base stations and enable individual base stations to talk to more devices, thus driving the development of the Internet of Everything (IoE) [3]. MmWave technology, which is higher than 4G radio frequency, can provide ultra-high speed and ultra-high spectral efficiency while reducing network connectivity costs [4,5]. These emerging 5G technologies can deliver a variety of extreme

services more flexibly and reliably, supporting applications in various vertical industries to enable the IoE.

Even with the rapid development of wireless network technologies, IEEE 802.11 protocol-based network technology, as a reliable and economic information network construction method, is still considered a promising technology affecting the future communication industry and is also an important component of 5G and future wireless local area networks (WLANs). The transmission of emergency information and data with ultra-high reliability and low delay is one of the challenges faced by WLANs. Therefore, when numerous real-time emergency traffic is loaded on WLANs, it is necessary to provide it with a higher quality of service, which makes us think first of reducing the delay, so analyzing this parameter is a vital step to solving the problem [6].

There have been many works on IEEE 802.11 network performance analysis and modeling [2–6], but few works simultaneously consider the following factors to analyze the service delay of the medium access control (MAC) layer, such as the initial-carrier-sensing (ICS) procedure, the backoff counter freezing, up-to-date standard parameters, and computational complexity, etc. In [7], Bianchi proposed a representative 2-D Markov model to analyze the saturated throughput of the IEEE 802.11 distribution coordination function (DCF). Afterward, based on the model of [7], Ziouva et al. In [8], the authors introduced the initial state before the node entered the backoff procedure and analyzed the throughput and delay of the 802.11 DCF. In [9], the authors compared the proposed 2-D Markov model with a model that considered continuous packet transmission without activating the backoff procedure and demonstrated that the Markov model is more accurate in predicting the performance of the 802.11 protocol, obtaining the relationship between the data rate of the transmitted packets and the packet delay, packet discard time, and throughput. In [10], the state of the channel when the buffer is idle is described, and the authors proposed a 2-D Markov model to analyze the throughput performance of the IEEE 802.11 MAC layer under non-ideal conditions. In [11], the authors proposed a system model based on the 802.11 MAC protocol applicable to multiple contentions and proved that the stochastic evolution of different station backoff states converges to deterministic evolution in the limit state. The authors in [12] analyzed an accurate MAC delay model, which considered the backoff counter decrementing time. Tadayon et al. [13] proposed a service delay model to track the service delay behavior of 802.11 networks. The authors in [14] studied the fair issue of access to the channel by vehicles with different speeds and its impact on the network throughput. All the above research works used the queueing theory approach or the Markov approach to model the performance of the 802.11 MAC layer. In addition, in [15–18], the use of machine learning methods (supervised learning [15], reinforcement learning [16], deep reinforcement learning [17], joint learning [18], etc.), which have been hotter in recent years, is proposed to study the performance of the MAC layer of 802.11 networks in terms of the throughput and channel utilization.

However, a great deal of research has been conducted on modeling the service delay of 802.11 networks. These studies generally conducted modeling in the form of non-closed expressions or individual statistical moments. For example, the authors in [19] deduced the queuing delay and channel access delay of the 802.11 p DCF, but which were the non-closed model. In [20], the author used the limiting probability, p , of successful transmission head-of-line (HOL) grouping to represent the saturated or unsaturated state of the network to study the performance of homogeneous cached IEEE 802.11 DCF networks, such as the delay, but the delay model was in the form of a single statistical moment. In [21], the authors derived the access delay of the IEEE 802.11 DCF in the saturated state, as well as in [22], where the authors derived the MAC delay and queuing delay using z-transform, which all investigated the mean, variance, and probability distributions of the MAC delay, but none of the resulting models could estimate the total delay spent in the transmitting packets. Furthermore, for the delay analysis of the point coordination function (PCF), see [23,24].

In this paper, we comprehensively consider four primary factors affecting the performance of IEEE 802.11 networks, including the ICS procedure, the backoff counter freezing, up-to-date standard parameters, and computational complexity, and constructed a novel statistical model for the service delay in 802.11 networks; it is a 2-D Markov model including the ICS procedure and the backoff procedure. The model can identify the service delay's behavior and fully characterize the network performance. By analyzing the ICS delay and the backoff delay, we obtained the probability generating function (PGF) of the average idle time. The analytical expressions of the other service delays, such as the successful transmission time and collided transmission time, were derived to obtain the PGF of the total service delay. It was found that our delay evaluation results were significantly better than the traditional evaluation results. The average service delay of the Nav model in all the scenarios was larger than that of the analysis model due to the lack of the ICS procedure in the Nav model. Since a DIFS duration is generally much shorter than a random backoff duration, our model saves the bandwidth and improves transmission efficiency.

The rest of the paper is organized as follows. In Section 2, we briefly analyze the transmission procedure of the IEEE 802.11 DCF mechanism and put forward the corresponding modeling ideas. In Section 3, a 2-D Markov model is established to simulate the operating mechanism of the 802.11 DCF, and the transmission probability is obtained. In Section 4, we calculate the average idle time experienced by a node between two consecutive successful transmissions. In Section 5, we establish the total service delay model in the IEEE 802.11 network. In Section 6, the validity and accuracy of the proposed model are verified by numerical simulation. Finally, the paper is concluded in Section 7.

2. Analysis of IEEE 802.11 DCF Mechanism and Modeling Ideas

The basic operating principle of the 802.11 DCF mechanism is that the node should sense the channel activities before sending a data frame [25]. The channel is usually busy or idle, so the node sensing channel activities are divided into two situations: (1) If the channel is sensed to be idle for a DCF interframe space (DIFS), the data frame will be sent. (2) If the channel is sensed to be busy, the node will continuously sense the channel until it becomes idle for a DIFS. At this moment, in order to avoid collisions as much as possible, the nodes will generate a random backoff interval that follows the binary exponential backoff algorithm. That is, when a node tries to transmit a data frame, the backoff timer (or the backoff counter) is uniformly chosen in the range of $t \in (0, W_i - 1)$, and the backoff window length in the i -th backoff stage is $W_i = 2^i \times W_0$, $0 \leq i \leq m$. When the first attempt to send is made, the backoff window's original length is $W_0 = W_{min}$, and after each failed attempt to send, the backoff window length is two times that of the previous one until the maximum backoff stage is reached, $W_m = W_{max}$. During the backoff, whenever the node senses that the channel is idle for a slot time, the backoff counter is decremented by one, and the node cannot send data frames until it decrements to zero. It should be noted that nodes send data frames only at the beginning of each slot time, where the time slot length is the time required by any node to sense the farthest node transmission. Furthermore, the value of the DIFS can be expressed as $T_{DIFS} = DIFSN \times \delta + T_{SIFS}$, where $DIFSN$, δ , and T_{SIFS} stand for the DIFS number, a time slot length, and a SIFS length, respectively.

The DCF has two transmission modes [26]. In the basic mode, after the data frame is sent, its successful reception is confirmed by the receiving node sending an acknowledgment (ACK) frame. Additionally, if no ACK frame is received, it will go through a backoff procedure and start to retransmit. This mode does not solve the problem of conflicts that may be caused by hidden nodes. However, the ready-to-send (RTS)/clear-to-send (CTS) transmission mode avoids the conflicts caused by the hidden nodes during transmission [11]. Its main principle is to control the transmission status of the node (transmitting data or in the backoff procedure) using the transmitting data frames' information carried by the RTS/CTS frames. Therefore, we mainly discuss the RTS/CTS transmission mode. The main feature of this mode is that before sending data frames to the receiving node B, the sending node A must send the RTS frames to make a reservation channel and to inform

the other nodes, except node B, to postpone sending while node B will send the CTS frames to node A after receiving the RTS frames. The specific transmission process is shown in Figure 1.

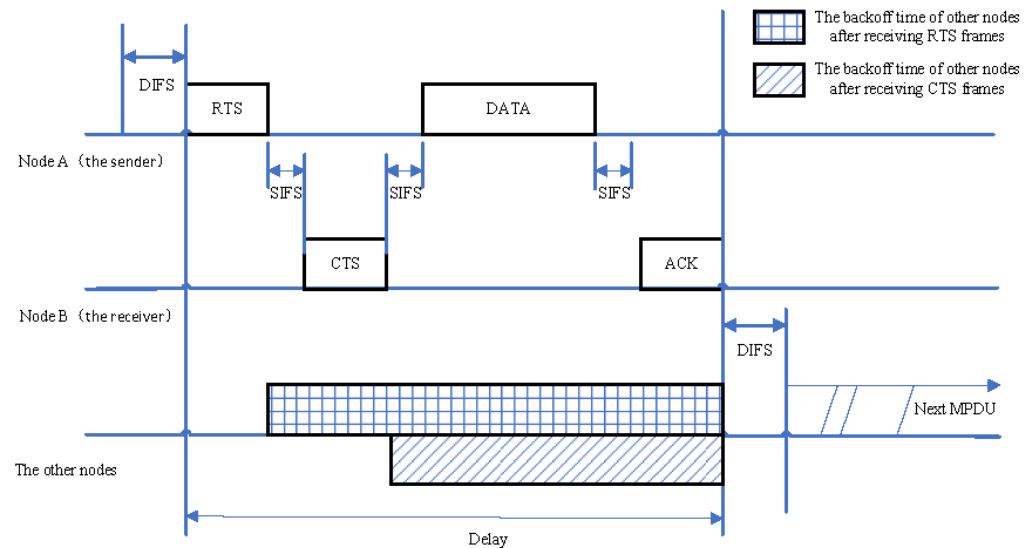


Figure 1. RTS/CTS transmission in the proposed model.

In order to describe the service delay's behavior more accurately in real WLANs, different from existing research, this paper comprehensively considers the following four major factors to build a system model:

1. ICS procedure: If a new data frame arrives when the channel is idle, the frame will start the ICS procedure, i.e., if the channel is idle for a DIFS, the data frame will be transmitted immediately at the end of the DIFS without entering the backoff procedure. Otherwise, if the channel is detected to be busy during the DIFS, the data frame will enter the backoff procedure;
2. Backoff counter freezing: When the channel is sensed to be busy, the backoff counter will pause its decrementing process. Once the channel is sensed to be idle, the backoff counter will be activated again to continue its decrement procedure;
3. Up-to-date standard parameters: to make our model suitable for the real network environment, some parameters need to be updated, including the DIFS, SIFS, time slot length, retransmission limit, and contention window size, and so on;
4. Computational complexity: In order to solve the problem more clearly and simply, the model should minimize the complexity of the calculation. Therefore, the transmission model considers a 2-D Markov model, and to verify the model's accuracy, we only need to focus on the first two statistical moments of the service delay model.

3. Markov Modeling Analysis of IEEE 802.11 Operations

In this section, we will improve the model by adding the ICS procedure based on the Bianchi model [7]. i.e., if the node senses that the previous data frame has been successfully received and the channel is idle for a DIFS, the node will directly send a new data frame, which the process of the new data frame waits for sending is called the ICS procedure.

As shown in Table 1, to further illustrate the difference between the proposed model and the original Bianchi model, we briefly summarize it, and we assume that after the node successfully transmits the previous frame, the node has a new data frame waiting to be sent (the successful transmission of the previous data frame can be seen in Figure 1). Obviously, the proposed model does not need to enter the backoff procedure after successfully transmitting the previous frame but directly starts the ICS procedure, which greatly reduces the idle time of the channel. This work can not only reduce the service delay of the network but also reduces the waste of the bandwidth so as to improve the network throughput and

channel utilization. In particular, a low delay and high throughput are the desired goals when the network is loaded with large amounts of emergency traffic.

Table 1. Comparison of transmission procedure between Bianchi model and proposed model in the 802.11 DCF protocol.

Markov Model	Channel State	Terminal Transmission Status	Next MDPU (The Legend is Shown on the Right)
Bianchi model	Busy	Backoff	
	Idle	Backoff	
Proposed model	Busy	Backoff	
	Idle	Initial carrier-sensing (ICS)	

Next, we assume that the channel condition is a single-cell environment with n terminals. The channel has no defects, i.e., the data frames' collision (probability p) is the only factor that causes transmission errors. Furthermore, the terminal is always in three states, i.e., the transmission, ICS, or backoff procedure.

Letting $X(t)$ denote the state of the transmit queue at time t , we can obtain:

- the backoff state, $X(t) = \{(i, k) | 0 \leq i \leq m, 0 \leq k \leq W_{i-1}\}$, where i denotes the value of the backoff stage, and k is the value of the backoff counter of the data frame at the head-of-line (HOL);
- The ICS state, $X(t) = \{(-1, \sigma) | \sigma = 0, 1, 2, \dots, D\}$, where $D = DIFS/\delta$, and δ is a time slot length. The state means that the channel is sensed to be idle for the $(D - \sigma) * \delta$ period during the ICS procedure;

Next, we obtain the state transition diagram (Figure 2) of the 2-D Markov chain, which considers all the major factors. The corresponding one-step transition probabilities are as follows (where p_b is the probability that the channel is busy):

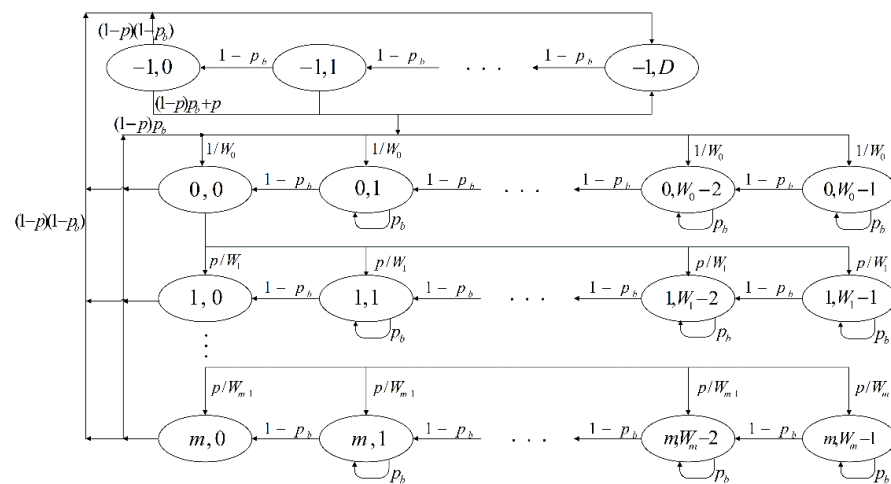


Figure 2. The 2-D Markov chain of IEEE 802.11 operations.

- For $0 \leq i \leq m$, there are the following three state transitions:

if the HOL data frame is successfully transmitted, start the backoff procedure:

$$P(0, k | i, 0) = \frac{(1-p) \times p_b}{W_0}, 0 \leq k \leq W_0 - 1. \quad (1)$$

If the HOL data frame is unsuccessfully transmitted, the frame is retransmitted, resulting in an increase in the backoff stage:

$$P(i, k | i-1, 0) = \frac{p}{W_i}, 0 \leq k \leq W_i - 1. \quad (2)$$

If the HOL data frame is successfully transmitted and the channel is sensed to be idle for a DIFS, the ICS procedure is initiated:

$$P(-1, D | i, 0) = (1-p)(1-p_b) \quad (3)$$

- For the case of $0 \leq \sigma \leq D$ during the ICS procedure:

if the channel is sensed to be idle for a time slot, the counter decreases by one:

$$P(-1, \sigma-1 | -1, \sigma) = (1-p_b) \quad (4)$$

If the channel is sensed to be busy, the backoff procedure is initiated:

$$P(0, k | -1, \sigma) = \frac{p_b}{W_0}, 0 \leq k \leq W_0 - 1. \quad (5)$$

- For the case of $\sigma = 0$ during the ICS procedure:

after the node successfully transmits the previous data frame, it senses that the channel is idle for a DIFS and continues the ICS procedure:

$$P(-1, D | -1, 0) = (1-p)(1-p_b) \quad (6)$$

If the transmitted HOL frame encounters a collision, it enters the 0-backoff stage, or if the channel is sensed to be busy after successfully transmitting the frame:

$$P(0, k | -1, 0) = \frac{p + (1-p)p_b}{W_0}, 0 \leq k \leq W_0 - 1 \quad (7)$$

- In order to represent the backoff counter freezing, for $0 \leq k \leq W_0 - 1$:

the backoff counter freezes when the node senses that the channel is busy:

$$P(i, k|i, k) = p_b, 0 \leq k \leq W_i - 1 \quad (8)$$

If the channel is sensed to be idle, the counter is decremented by one:

$$P(i, k-1|i, k) = 1 - p_b, 1 \leq k \leq W_i - 1 \quad (9)$$

Then, set the probability of the collision during the data frame transmission as p , and denote the steady-state probability distribution of the system $\{b_{i,k}\}$ as follows:

$$\begin{cases} b_{i,k} \triangleq \lim_{t \rightarrow \infty} P\{X(t) = (i, k)\}, & 0 \leq i \leq m, 0 \leq k \leq W_i - 1 \\ b_{-1,\sigma} \triangleq \lim_{t \rightarrow \infty} P\{X(t) = (-1, \sigma)\}, & 0 \leq \sigma \leq D \end{cases}$$

Under the steady-state condition of the system, we have the following steady-state equations:

$$b_{i,0} = p^i b_{0,0}, 0 \leq i \leq m. \quad (10)$$

$$b_{i,k} = \frac{W_i - k}{W_i} \frac{1}{1 - p_b} b_{i,0}, 0 \leq i \leq m, \quad (11)$$

$$b_{i,k} = \frac{p_b + p(1 - p_b)}{(1 - p_b)^D} b_{-1,0} \quad (12)$$

$$b_{-1,\sigma} = \frac{\sigma}{(1 - p_b)^\sigma} b_{-1,0}, 0 \leq \sigma \leq D. \quad (13)$$

From the probability normalization, $\sum_{\sigma=0}^{D_\sigma} b_{-1,\sigma} + \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = 1$, and Equations (10)–(13), we can obtain:

$$b_{-1,0} = \left[\frac{1 - (1 - p_b)^{D+1}}{p_b + (1 - p_b)^D} + \frac{p_b + p(1 - p_b)}{2(1 - p_b)^{D+1}} \left(\frac{1 - (2p)^{m+1}}{1 - 2p} W_0 + \frac{1 - p^{m+1}}{1 - p} \right) \right]^{-1} \quad (14)$$

According to Equations (10)–(14), we obtain the steady-state probability distribution. Define τ as the probability that a node transmits in a time slot, i.e., the steady-state probability when a node is in the backoff stage, i ($0 \leq i \leq m$), and the backoff counter is 0, or the ICS procedure ends. Therefore, it holds that:

$$\tau = b_{-1,0} + \sum_{i=0}^m b_{i,0}.$$

Substituting Equations (10) and (14) into the above equation, we obtain:

$$\begin{aligned} \tau = & \left[\frac{1 - (1 - p_b)^{D+1}}{p_b + (1 - p_b)^D} + \frac{p_b + p(1 - p_b)}{2(1 - p_b)^{D+1}} \left(\frac{1 - (2p)^{m+1}}{1 - 2p} W_0 + \frac{1 - p^{m+1}}{1 - p} \right) \right]^{-1} \\ & \times \left[1 + \frac{p_b + p(1 - p_b)}{(1 - p_b)^D} \right]. \end{aligned} \quad (15)$$

4. Calculation of the Average Idle Time

Based on the above Equation (15), we will calculate the average idle time from the perspective of observer node B, as shown in Figure 3. Note that the value k of the backoff counter decreases in units of 1 when node B detects that the channel is idle, with a probability of $1 - p_b$. The counter is frozen when node B detects that the channel is busy with the probability, p_b , and only when the counter's value is decremented from $W_i - 1$ to 0 will the node successfully transmit with the probability, p_s . When the backoff stage reaches the maximum (or retransmission limit), the data frame still fails to transmit, i.e., $i > m$, and

the frame will be discarded immediately. Therefore, the following correlation probabilities were found:

- The collision probability, p , i.e., the probability that at least one of the remaining $n - 1$ competing nodes at a time slot sends a data frame, can be found as $p = 1 - (1 - \tau)^{n-1}$;
- The probability p_b that the channel is busy, i.e., the probability that at least one node transmits at a time slot, can be found as $p_b = 1 - (1 - \tau)^n$;
- Since the channel has no defects, the total collision probability, p_c , is only related to the busy channel caused by the data frame transmission and data frames' collision, and it can be expressed as $p_c = 1 - (1 - p_b)(1 - p)$;
- The successful transmission probability, p_s , i.e., under the condition that at least one node of the n nodes transmits at a time slot, the probability that exactly one node transmits successfully can be expressed as $p_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}$.

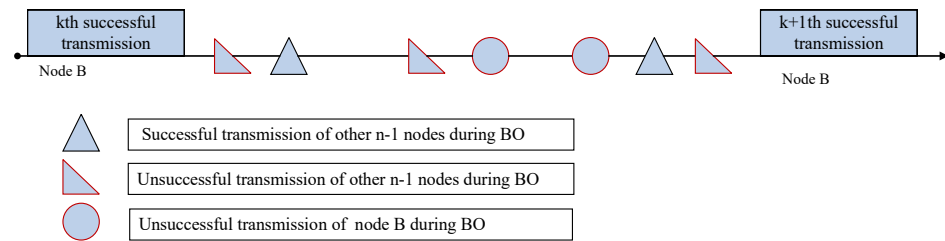


Figure 3. Possible events that occurred between two consecutive successful transmissions for node B.

Based on the above analysis, we note that the time interval between the two consecutive successful transmissions of node B (k -th and $(k + 1)$ -th in Figure 3) may include events, such as failure of sending data frames by node B, the other $n - 1$ nodes successfully send data frames or fail to send data frames when B carries out the backoff procedure, and the channel is idle. Thus, the average idle time, $\overline{BO}$, experienced by node B between two consecutive successful transmissions is defined as the average time that the ICS procedure was performed and the average time that the backoff counter was active during the backoff procedure. From this, it can be determined that the expression of $\overline{BO}$ is:

$$\overline{BO} = \frac{1-p_b}{1-p_c^m} D + p_b \frac{(1-p_b)^{\frac{D}{2}}}{1-p_c^m} \frac{D}{2} x_0 + \frac{1-p_c}{1-p_c^m} (x_0 + x_1) + p_c \frac{1-p_c}{1-p_c^m} (x_1 + x_2) + p_c^2 \frac{1-p_c}{1-p_c^m} (x_1 + x_2 + x_3) + \dots + p_c^{m-1} \frac{1-p_c}{1-p_c^m} (x_1 + x_2 + \dots + x_m). \quad (16)$$

The first term of Equation (16) is the average idle time to complete the ICS procedure, denoted as T_{-1} . The second item is the average idle time that the node may traverse, which performs the backoff procedure after the channel is sensed to be busy during the ICS procedure. Note that $\sigma \in [0, D]$ follows a uniform distribution, with a mean of $D/2$. Therefore, starting from the second term, it describes the average idle time of the backoff procedure, denoted as T_{bt} , where x is a random variable subject to a uniform distribution and is the original length of the backoff counter at each retransmission attempt, and x_i and x_j are independent of each other.

Let the probability generation function (PGF) of $\overline{BO}$ be $G_{\overline{BO}}$, and use the properties of PGF to obtain:

$$G_{\overline{BO}}(z) = G_{T_{-1}}(z) + G_{T_{bt}}(z) = G_{T_{-1}}(z) + \frac{1 - z^{W_0}}{(1 - z)W_0} + \prod_{i=0}^{m-1} \frac{1 - z^{2^i a_i W_0}}{2^i W_0 (1 - z^{a_i})}. \quad (17)$$

where $a_i = p_c^i \frac{1-p_c^{m-i}}{1-p_c^m}$. The above equation will be used to derive our modeling.

5. Service Delay Statistical Model

In this section, the total service delay in 802.11 networks is analyzed to obtain its PGF. We define service delay as the period from the time when the data frame arrives at the HOL of the sending node to the time when it is successfully received by the receiving node. During this period, a node may detect or go through different channel activities, such as whether the node succeeded or failed in sending the data frames and the success or failure of the other $n - 1$ nodes to send data frames and channel leisure [13].

Let T_s , T_{c_j} , T'_{s_j} , T'_{c_j} , and T_{idle} denote the time when node B successfully transmits a data frame, the node B transmission collision time, the time when the other $n - 1$ nodes successfully transmit the data frames, the other $n - 1$ nodes transmission collision times, and the channel's idle duration, respectively. Then, the service delay, T_w , can be expressed as:

$$T_w = T_s + \sum_{j=1}^{n_c} T_{c_j} + \sum_{j=1}^{n'_c} T'_{c_j} + \sum_{j=1}^{n'_s} T'_{s_j} + T_{idle} \quad (18)$$

where n_c , n'_c , and n'_s denote the number of node B retransmissions and the number of collided transmissions and successful transmissions for the other $n - 1$ nodes during $\overline{BO}$, respectively. Regarding them, the following conclusions hold:

Conclusion 1: The number of a node retransmissions, n_c , obeys a truncated geometric distribution. Thus,

$$p(n_c = i) = \frac{p_s(1 - p_s)^i}{1 - (1 - p_s)^{m+1}}, i = 0, \dots, m. \quad (19)$$

Conclusion 2: If the B node has successfully completed its $(r - 1)$ -th transmission and started the backoff procedure, the n nodes are trying to access the channel at this time. The $\overline{BO}$ events and $k - 1$ successful transmissions occur for the remaining $n - 1$ nodes, attempting to access the channel during the node B backoff period. Let the random variable v denote the number of times that the remaining $n - 1$ nodes attempt to send a data frame before node B successfully transmits its $r(=k)$ -th data frame. Then, v obeys the conditional probability distribution:

$$p(v|k) = C_{v-1}^{k-1} p_s^{k-1} (1 - p'_s)^{v-k} \times p_s. \quad (20)$$

$$\text{where } p'_s = \frac{(n-1) \times \tau \times (1-\tau)^{n-2}}{1 - (1-\tau)^{n-1}}.$$

Conclusion 3: Define $n'_c = v - k$, i.e., the number of collisions that occur when the remaining $n - 1$ attempt to send the data frames before the node makes the k -th successful transmission. Then, the conditional probability distribution of n'_c is:

$$p(n'_c|k) = C_{n'_c+k-1}^{k-1} p_s^{k-1} (1 - p'_s)^{n'_c} \times p_s. \quad (21)$$

The following analyzes n'_s . We find that there must be only busy or idle events in the time period between two consecutive transmissions of a node, and the two events occur alternately in the 802.11 DCF protocol. The length of time of each idle or busy event that occurs depends on the size of the transmitted data frame and the opportunity of the node to transmit the data frame, etc., while the average time for idle events to occur is:

$$L_{idle} = \frac{1}{p_b} - 1 = \frac{1 - p_b}{p_b}. \quad (22)$$

Due to channel idle events occurring independently, it obeys the geometric distribution of parameter p_b . Let N represent the number of idle events (counted in a slot time), then:

$$N = \frac{\overline{BO}}{L_{idle}} = \frac{\overline{BO}}{\frac{1}{p_b} - 1} = \frac{\overline{BO} \cdot p_b}{1 - p_b} \quad (23)$$

Furthermore, since the busy or idle state of the channel in the DCF protocol takes place alternately successively over time, it is impossible for the idle or busy to occur twice in succession. Therefore, the number of idle events during $\overline{BO}$ can be approximately equal to the number of busy events (counted in a slot time), M , and namely, $N \cong M$. Since the occurrence of the busy events is caused by the successful transmission of the data frames or data frame transmission collision, M is divided into two parts, namely the number of busy events due to the successful sending of the data frames, n'_s , and the number of busy events due to the data frame transmission conflicts, n'_c . Therefore,

$$\text{Conclusion 4 : } n'_s = Np'_s, \quad n'_c = N \times (1 - p'_s). \quad (24)$$

For the last term, T_{idle} , the idle time in (18), since the backoff counter is frozen when the channel is busy, can be expressed as $\overline{BO}$ minus the number of busy slots, M , i.e., $T_{idle} = \overline{BO} - M = \overline{BO} - N$. In addition, since n_c , n'_c , and n'_s are independent random variables, the PGF of T_w can be obtained by applying z-transformation to Equation (18), as follows:

$$\begin{aligned} E(z^{T_w}) &= E\left(z^{(T_s + \sum_{j=1}^{n_c} T_{c_j} + \sum_{j=1}^{n'_c} T'_{c_j} + \sum_{j=1}^{n'_s} T'_{s_j} + IdleTime)}\right) \\ G_{T_w}(z) &= G_{T_s}(z) E\left(z^{\sum_{j=1}^{n_c} T_{c_j}}\right) E\left(z^{\sum_{j=1}^{n'_c} T'_{c_j}}\right) E\left(z^{\sum_{j=1}^{n'_s} T'_{s_j}}\right) E(z^{IdleTime}). \end{aligned} \quad (25)$$

Combining the above results, using the properties of the conditional PGF [27], we can obtain:

$$E\left(z^{\sum_{j=1}^{n_c} T_{c_j}}\right) = \sum_{i=-1}^m \frac{p_s(1-p_s)^i}{1-(1-p_s)^{m+1}} G_{T_c}(z)^i. \quad (26)$$

$$E\left(z^{\sum_{j=1}^{n'_c} T'_{c_j}}\right) = \sum_{r=1}^{\infty} \sum_{i=-1}^{\infty} p_{n'_s}(i) C_{i+r-1}^{i-1} \times p_s^{i-1} (1-p'_s)^r p_s G_{T'_c}(z)^r \quad (27)$$

$$E\left(z^{\sum_{j=1}^{n'_s} T'_{s_j}}\right) = \sum_{i=-1}^{\infty} p_{n'_s} G_{T'_s}(z)^i. \quad (28)$$

$$E(z^{IdleTime}) = E(z^{\overline{BO}-N}). \quad (29)$$

where $p_{n'_s}(i) = \delta(i - n'_s)$, $n'_s = Np'_s = \frac{\overline{BO} \cdot p_b}{1-p_b} p'_s$.

So far, we obtain a closed expression for the PGF of the service delay T_w by Formulas (25)–(29). Since all the protocol details have been considered in the discussion, the PGF can reasonably describe the service delay behavior of the 802.11 network. Furthermore, we obtain the mean and the variance of T_w by the first-order derivative and second-order derivative, i.e.,

$$E(T_w^i) = \frac{d^i}{dz^i} (G_{T_w}(z))|_{z=1} \Rightarrow \begin{cases} \overline{T_w} = \frac{d}{dz} (G_{T_w}(z))|_{z=1} \\ Var_{T_w} = \frac{d^2}{dz^2} (G_{T_w}(z))|_{z=1} + \overline{T_w}^2 - \overline{T_w}^2. \end{cases} \quad (30)$$

6. Numerical Simulation

In this section, the numerical simulation results are given to verify the validity of the proposed analysis model. As mentioned above, W_{min} , n , m , p_c , T_s , and T_c represent the minimum contention window size, the number of contending nodes, the maximum backoff stage (or retransmission limit), collision probability, and the time when a node successfully transmits a data frame and transmission collision time, respectively. The time when a node successfully transmits a data frame and transmission collision time depends on two transmission modes, i.e., one is the RTC/CTS mode, $T_c = RTS + DIFS + \delta$, $T_s = Data + 3SIFS + DIFS + RTS + CTS + ACK + 4\delta$, and the other is the basic mode,

$T_c = Data + DIFS + \delta$ and $T_s = Data + SIFS + DIFS + ACK + 2\delta$. Using the above parameters, we consider three transmission scenarios (as shown in Table 2), and the parameter settings of each scenario are from [13]. That is, exactly one set of data is taken for each of the three different scenarios set in [13] to achieve the goal of ensuring that the proposed model is valid over a wide range of parameters while also avoiding the complexity of the simulation process.

Table 2. DCF parameters in three different scenarios.

Scenarios	11 Mbit/s 802.11 b	1 Mbit/s 802.11 b	54 Mbit/s 802.11 g
	1	2	3
RTS/CTS	Yes	No	No
MAC (byte)	512	50	1024
n	10	20	20
W_{min}	7	3	15
m	3	3	6
ACK	20	20	20
SIFS	10	10	10
DIFS	50	50	28
Slot (μs)	20	20	9

Figures 4 and 5 show the functional relationship between the average service delay and collision probability, p_c , in all the scenarios, where Figure 4 is in Scenario 1, and Figure 5 is in Scenario 2 and Scenario 3. Obviously, the average service delay of the Nav model in all the scenarios is bigger than that of the analysis model due to missing the lack of the ICS procedure in the Nav model. For the ICS procedure, after the previous data frame is successfully sent, the new data frame can be sent directly after the channel is idle for a DIFS, which further effectively reduces the service delay. Furthermore, the phenomenon in Figure 4 that the average service delay of the analysis model is much smaller than that of the Nav model could indicate that the RTS/CTS mode has advantages over the basic mode.

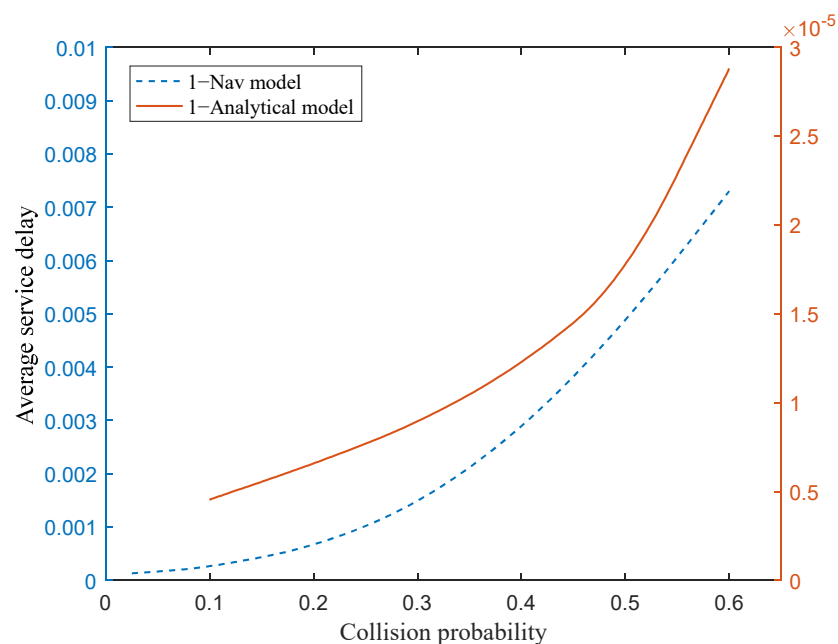


Figure 4. The average service delay with respect to the collision probability in Scenario 1.

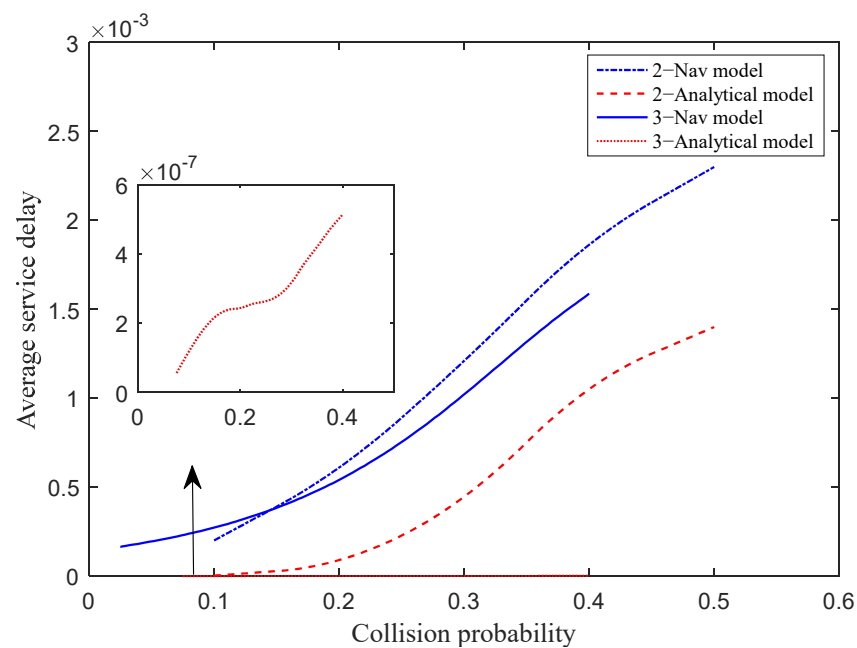


Figure 5. The average service delay with respect to the collision probability in Scenarios 2 and 3.

In Figure 6, we obtain the comparison graphs of the successful transmission probability, p_s , between the analysis model and the Nav model in three scenarios. The following is a brief explanation, with Scenario 2 as an example. We can observe that as the collision probability increases, the successful transmission probability of our model is much larger than that of the Nav model because it comprises the ICS procedure. Indeed, since a DIFS duration is generally much shorter than a random backoff duration, our model saves the bandwidth and improves the transmission efficiency.

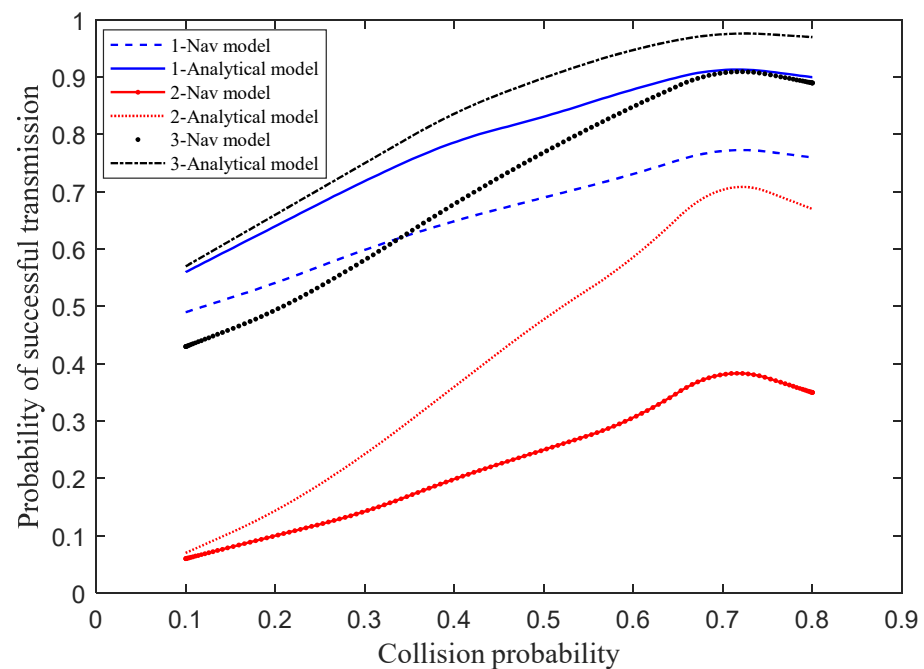


Figure 6. Successful transmission probabilities in all scenarios.

Figure 7 shows the standard deviation of the service delay in terms of the collision probability in all the scenarios. In any scenario, when the collision probability is smaller, the standard deviation of the service delay for the analysis model is smaller than that of

the Nav model. That is because the ICS procedure added to the analysis model saves the transmission delay. When the collision probability reaches a certain value, the standard deviation of the service delay for our model is much larger than that of the Nav model. That is because the duration of the ICS procedure is much smaller than the backoff procedure. Thus, as the collision probability increases, the service delay of the analysis model is bigger as the frequency of entering the backoff procedure increases, and the gap of the service delay standard deviations is larger.

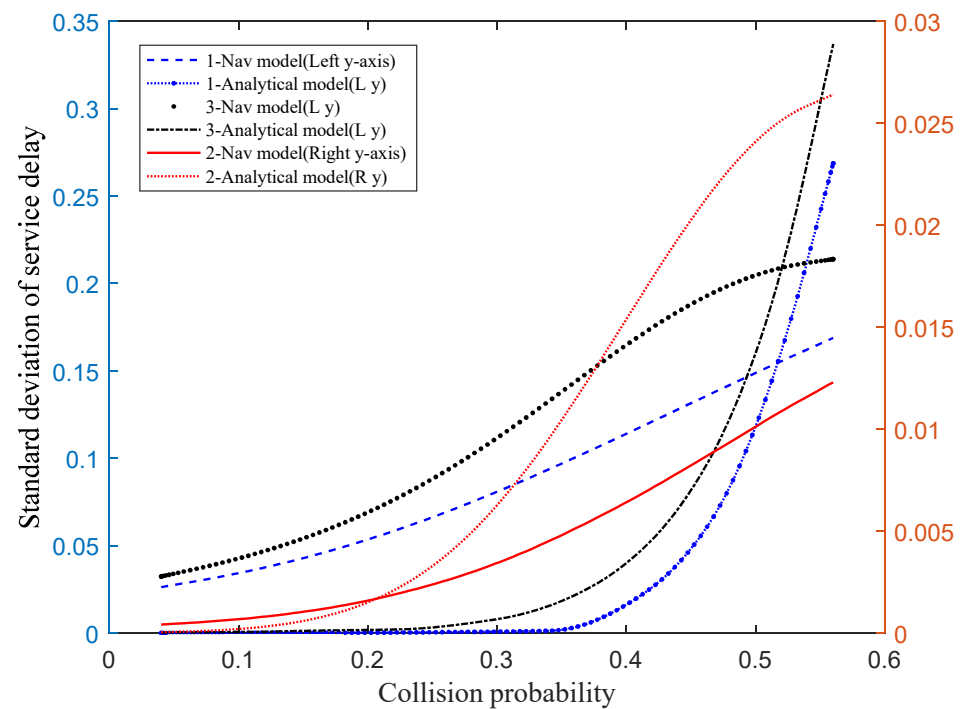


Figure 7. The standard deviation of the service delay in all scenarios.

7. Conclusions

In this paper, by adding the ICS procedure to research the service delay in IEEE 802.11 networks, it is found that our delay evaluation results are significantly better than the traditional evaluation results. The average service delay of the Nav model in all the scenarios is larger than that of the analysis model due to missing the ICS procedure in the Nav model. Since a DIFS duration is generally much shorter than a random backoff duration, our model saves the bandwidth and improves transmission efficiency. Moreover, a comprehensive statistical characterization of the service delay is one of the most useful tools for dealing with Quality of Service (QoS) issues, especially when the network is loaded with numerous emergency traffic. Therefore, our model also applies to 802.11 e networks based on prioritization and will also lay a foundation for subsequent research work, such as dealing with emergency events in public safety networks or traffic flow information in the Internet of Vehicles.

Author Contributions: Q.Y. researched the literature, conceived the study concepts, designed the algorithm, and took charge of the original draft preparation; S.L. improved the mathematical models, provided the systematic research and analysis methodology, edited the manuscript, and the refinement of the paper was completed under the supervision of S.L.; H.L. completed and checked the English grammar; W.C. checked the numerical simulations and formula deducing. All authors have read and agreed to the published version of the manuscript.

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An Efficient Spectrum Management Scheme in 5G Cognitive Radio Ad Hoc Networks

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Abstract—To alleviate the contradiction between the supply and demand of spectrum resources in the large-scale 5G network environment, we propose the minimum remaining idle time channel selection scheme under imperfect spectrum sensing (MRIC-IS) in combination with actual cognitive radio ad hoc networks (CRAHNs) environment. In this scheme, secondary users (SUs) select the available channel with the minimum remaining idle time and catches sensing errors in the form of misdetection and false alarm. By analyzing the resource flow process between primary users (PUs) and SUs in the primary channel and the effect of sensing errors on the resource flow process, we build a two-layer 2-D continuous-time Markov chains (CTMC) and its equilibrium equation system. Then the expressions for the performance measures as spectrum utilization and SUs average throughput are derived after obtaining system steady-state distribution. The numerical simulation results show that this scheme can significantly improve spectrum efficiency and SU average throughput in the fifth generation (5G) cognitive radio ad hoc networks, even under spectrum sensing errors.

Keywords—cognitive radio ad hoc networks (CRAHNs), channel selection, spectrum sensing, misdetection, false alarm

I. INTRODUCTION

At present, while enjoying the benefits brought by gradually large-scale deployment and widespread application of the fifth generation (5G) mobile technology (such as knowledge as a service, surrealistic media of integrated service, etc.) [1], we are also facing the challenge of severe scarcity of spectrum resources brought by the access of massive devices and users [2-3]. Cognitive Radio (CR) technology is one of the most potential technologies to alleviate the contradiction between the supply and demand of 5G spectrum resources. Moreover, combining CR technology with ad hoc networks namely CR ad hoc networks (CRAHNs), can obtain shared spectrum resources to the maximum extent possible [4-5].

In CRAHNs, dynamic spectrum access technology is adopted to realize spectrum sharing, i.e., secondary users (SUs) can access idle primary users (PUs) frequency bands flexibly without harmful interference to PUs [6]. Wireless resources in CRAHNs change dynamically due to PUs activity, so it is crucial to find an intelligent and adaptive channel selection strategy for them. Reference [7] proposed an adaptive spectrum allocation mechanism that accurately estimates the blocking

probability of cells using continuous time Markov chains (CTMC). Reference [8] proposed an active spectrum access method. In the case of perfect spectrum sensing, the SU can intelligently schedule channels and use historical channel activity information to predict future channel availability. However, SUs always consider maximizing their interests and choose the spectrum access with the longest idle time. Based on this, the authors in [9] proposed a best-fit channel selection scheme, i.e., SUs consider available channels that meet their transmission needs. Compared to the channel selection scheme in [8], this scheme further alleviates the impact of spectrum fragmentation through best-fit allocation.

However, in actual network environments, assuming perfect spectrum sensing conditions is not accurate enough to evaluate system performance, which may result in high expectations for spectrum utilization or throughput values. In [10], the authors combined full-duplex technology with CR to propose a cooperative strategy with two full-duplex cognitive base stations without interfering with PUs transmission, and evaluated the effect of this strategy on spectrum utilization under the condition of the Nakagami-m fading channel. Reference [11] proposed the spectrum sharing problem of PUs and SUs access CR network based on discrete-time Markov chain (DTMC) and conducted modeling based on spectrum sensing technology. In the modeling process, false alarms and misdetection probabilities were used to characterize unreliable spectrum sensing. However, the opportunistic approach adopted in [11] limits the ability of SU to utilize unused spectrum.

Inspired by the above research, considering CRAHNs' dynamic characteristics in different dimensions such as location and time, we propose the minimum remaining idle time channel selection under imperfect spectrum sensing (MRIC-IS). In this strategy, SUs choose sufficiently long idle channels that meet their transmission needs instead of the longest idle channels and capture sensing errors in the form of false alarms and misdetection. By analyzing SUs activity states and the resource flow process of the primary channel, we establish a two-layer 2-D continuous-time Markov chain (CTMC) model. Finally, we evaluate the influence of false alarms and misdetection probability on system performance by analyzing spectrum utilization efficiency and throughput. And this proves that the MRIC-IS can effectively solve the spectrum-sharing problem between PUs and SUs in the case of imperfect sensing.

The rest of the paper is organized as follows. Section 2 is the network model, including the primary channel model and SU activity model. Section 3 proposes the minimum remaining idle time channel selection scheme under imperfect spectrum sensing (MRIC-IS). In Section 4, we introduce using Markov methods to establish corresponding analytical models. In Section 5, the effectiveness of the proposed strategy is verified by numerical simulation. Finally, Section 6 concludes the paper.

II. NETWORK MODEL

The CRAHN usually consists of a primary network with spectrum authorization and a decentralized secondary network. Therefore, we consider a network system composed of M primary channels and N SUs.

Due to the primary channel states related to the channel access process of PUs and SUs, we establish the primary channel model and SU activity model respectively, as shown in Fig. 1 and Fig. 2. All PUs and SUs apply the carrier sense multiple access with collision avoidance (CSMA/CA) access scheme.

In the primary channel model, the state "on" represents the PU active period, during which the channel is busy. Naturally, the state "off" represents the non-PU active period, and the non-PU active period includes the SU transmission period (the channel is occupied by the SU) and channel idle time. The state of each channel always alternates between "on" and "off". Since the arrival of PUs and SUs are independent, and all channels are homogeneous, the durations of these two states follow exponential distributions with parameters μ_1 and λ_1 , respectively.

In the SU activity model, there are three states: off, channel sensing and search (CSS) (whose duration is ignored), and transmission. Since the arrival of all SUs in the system is independent of each other, the transmission and "off" durations of SUs follow exponential distributions with parameters μ_2 and λ_2 , respectively. When the SU senses that the channel is idle, it will detect the channel one by one in sequence according to the channel search sequence. If the detected channel meets its transmission conditions, it will change from CSS to transmission state. Otherwise, the SU continue to search for channels one by one. After completing the transmission, the SU switches to the initial state "off". In the CSS process, the channel search sequence is determined by the rules of the channel selection policy, the details of which are described in the next section.

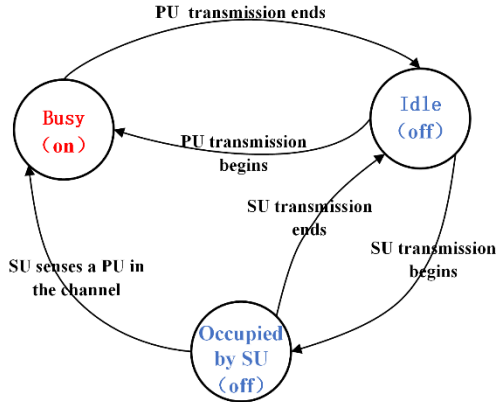


Fig. 1. Primary channel model.

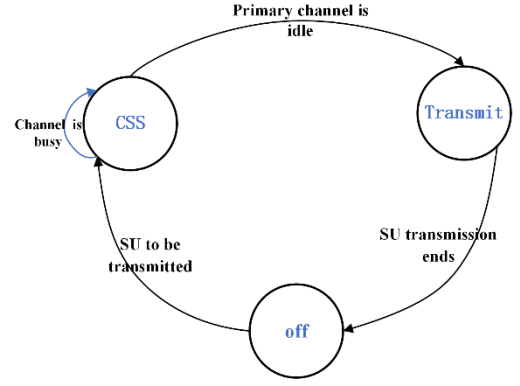


Fig. 2. SU activity model.

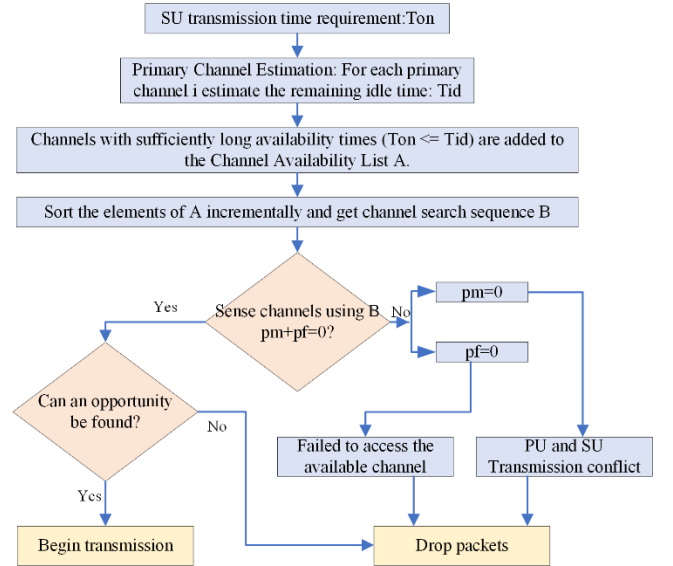


Fig. 3. The MRIC-IS control flow.

III. MINIMUM REMAINING IDLE TIME CHANNEL SELECTION SCHEME UNDER IMPERFECT SPECTRUM SENSING

Considering the actual situation, it is inevitable that SUs will be affected by factors such as the sensitivity of sensing equipment and poor channel conditions when sensing channel states, thereby affecting the reliability of sensing results [11]. Therefore, the possible sensing error events are divided into the following two categories:

(1) Misdetction event: the SU senses the channel being used by the PU as an available channel, which occurs with probability p_m .

(2) False alarm event: the SU senses the available channel as the channel being used by PU, and its probability of occurrence is p_f .

The occurrence of both events will result in the SU being unable to successfully access the channel. Then, the SU perfect sensing result can be expressed in terms of $p_c = 1 - p_m - p_f$, i.e., SU can accurately estimate PU traffic activity patterns. And we assume that SUs cannot share a spectrum at the same time.

So far, we propose the minimum remaining idle time channel selection scheme under imperfect spectrum sensing (MRIC-IS). That is, under imperfect spectrum sensing conditions, the SU selects the channel with the minimum remaining idle time sufficient to complete its transmission. And its control flow chart is shown in Fig. 3. The SU with a transmission request has the self-sensing property of knowing the duration of the next transmission, denoted as T_{on} ; it performs CSS before it sends and estimates the idle duration time of each primary channel, denoted as T_{id} . The elements in channel availability list A are channels that meet condition $T_{on} \leq T_{id}$. By sorting the elements in A in an incremental manner, channel search sequence B can be obtained. The SU senses channels one by one based on channel search sequence B:

- (1) If the sensing is correct and meets its transmission requirements, its packet is transmitted.
- (2) If sensing is correct and no channel in sequence B can meet its transmission requirements (i.e., $B = \emptyset$), its packet transmission attempt fails and is discarded.
- (3) In case of a sensing error, if a false alarm event occurs, the SU is unable to access the available channel, or if a misdetection event occurs, the PU conflicts with the SU transmission. The above event will cause its packet transmission attempt to fail and be dropped.

IV. ANALYTIC MODEL OF PROPOSED CHANNEL SELECTION SCHEM BY MARKOV CHAIN

A. CTMC Model

In this section, to analyze the performance of the MRIC-IS in CRAHNS, the resource flow process between PUs and SUs is transformed into a two-layer 2-D CTMC model.

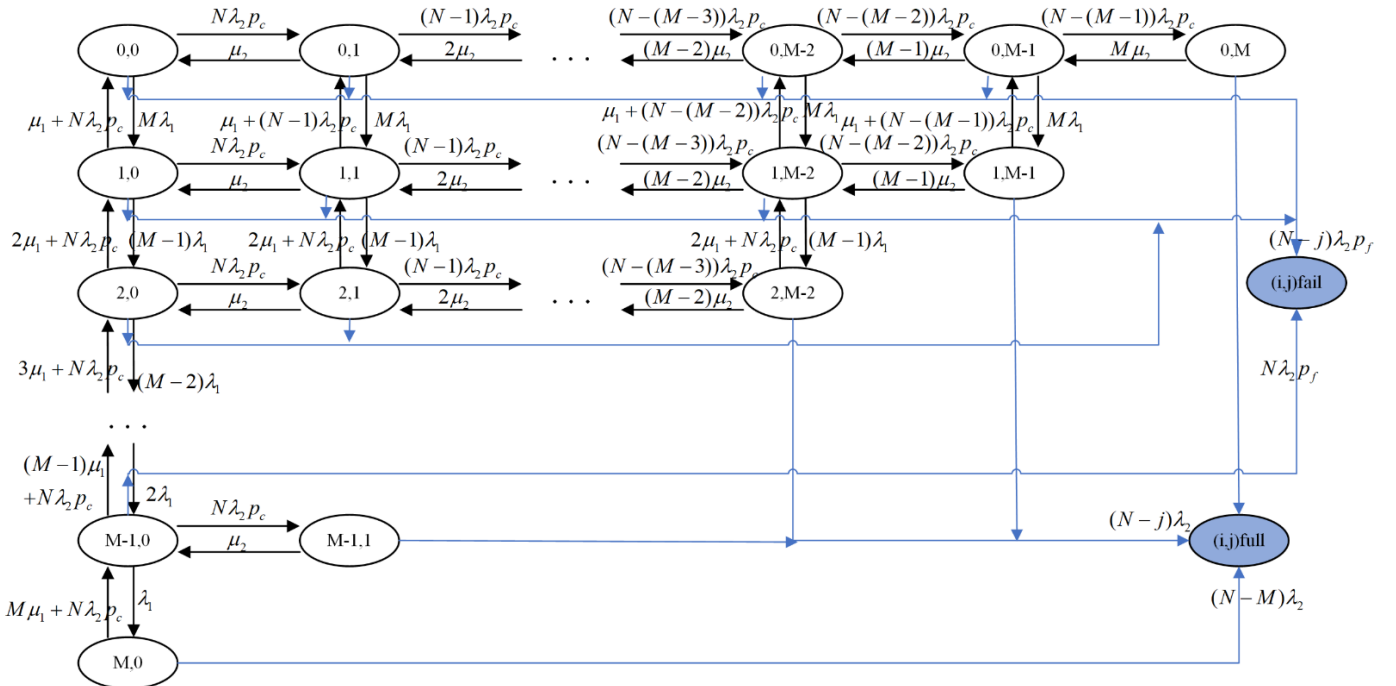


Fig. 4. Dual-layer 2-D continuous-time Markov chains.

Let $X_p(t)$ and $X_s(t)$ be stochastic processes of the number of PUs and SUs being transmitted in the system at time t . At time t , the state of the system is $X(t) = S_{i,j} = \{X_p(t) = i, X_s(t) = j\}$.

Then the state space constituting the 2-D Markov process can be expressed as $S = \{S_{i,j} | 0 \leq i \leq M, 0 \leq i+j \leq M\} = \{S_{0,0}, S_{0,1}, \dots, S_{i,j}, \dots, S_{M,0}\}$, as shown in Fig. 4. where the transition probability from state $S_{i,j}$ to state $S_{k,l}$ is:

$$\begin{cases} (M-i)\lambda_1 & \text{for } k=i+1, i < M, l=j \\ i\mu_1 + p_m\lambda_2 & \text{for } k=i-1, i \geq M, l=j \\ (N-j)\lambda_2 p_c & \text{for } k=i, l=j+1, l < M \\ j\mu_2 & \text{for } k=i, l=j-1, j \geq 1 \\ (N-j)\lambda_2 & \text{for } k=i, l=j_{full}, i+j=M \\ (N-j)\lambda_2 p_f & \text{for } k=i, l=j_{fail}, i+j < M \end{cases}$$

Note that according to the definition of the CTMC, self-transitions can be replaced by $S_{i,j} \rightarrow S_{(i,j)_{fail}}$ and $S_{i,j} \rightarrow S_{(i,j)_{full}}$ [9]. Therefore, the 2-D Markov process is a double-layer 2-D CTMC, where the first layer is a state set composed of elements in the state space S , and the second layer (located in the blue part in Figure 4) is a set of states composed of all cases in which $S_{i,j} \rightarrow S_{(i,j)_{fail}}$ and $S_{i,j} \rightarrow S_{(i,j)_{full}}$ state transitions occur.

B. Performance Metric Based on Equilibrium Equations

Let $\pi_{i,j}$ be the steady-state probability of state $S_{i,j}$, and the equilibrium equations of the CTMC model are as follows:

When $i = 0, i + j < M$,

$$\begin{aligned} & [j\mu_2 + i\mu_1 + (N-j)\lambda_2 p_c + (M-i)\lambda_1]\pi_{i,j} \\ &= (N-j)\lambda_2 p_c \pi_{i,j-1} + (j+1)\mu_2 \pi_{i,j+1} \\ &+ ((i+1)\mu_1 + (N-j)\lambda_2 p_m)\pi_{i+1,j} \end{aligned} \quad (1)$$

When $j = 0, i + j < M$,

$$\begin{aligned} & [i\mu_1 + (N-j)\lambda_2 p_m + (N-j)\lambda_2 p_c + (M-i)\lambda_1]\pi_{i,j} \\ &= (M-(i-1))\lambda_1 \pi_{i-1,j} + (j+1)\mu_2 \pi_{i,j+1} \\ &+ ((i+1)\mu_1 + (N-j)\lambda_2 p_m)\pi_{i+1,j} \end{aligned} \quad (2)$$

When $i \geq 1, j \geq 1, i + j < M$,

$$\begin{aligned} & [j\mu_2 + i\mu_1 + (N-j)\lambda_2 p_m + (N-j)\lambda_2 p_c + (M-i)\lambda_1]\pi_{i,j} \\ &= (N-j)\lambda_2 p_c \pi_{i,j-1} + (M-(i-1))\lambda_1 \pi_{i-1,j} + \\ & (j+1)\mu_2 \pi_{i,j+1} + ((i+1)\mu_1 + (N-j)\lambda_2 p_m)\pi_{i+1,j} \end{aligned} \quad (3)$$

When $i = 0, i + j = M$,

$$j\mu_2 \pi_{i,j} = (N-j)\lambda_2 p_c \pi_{i,j-1} \quad (4)$$

When $j = 0, i + j = M$,

$$\begin{aligned} & [i\mu_1 + (N-j)\lambda_2 p_m]\pi_{i,j} \\ &= (N-j)\lambda_2 p_c \pi_{i,j-1} + (M-(i-1))\lambda_1 \pi_{i-1,j} + (j+1)\mu_2 \pi_{i,j+1} \end{aligned} \quad (5)$$

When $i \geq 0, j \geq 1, i + j = M$,

$$\begin{aligned} & [j\mu_2 + i\mu_1 + (N-j)\lambda_2 p_m + (N-j)\lambda_2 p_c]\pi_{i,j} \\ &= (N-j)\lambda_2 p_c \pi_{i,j-1} + (M-(i-1))\lambda_1 \pi_{i-1,j} \end{aligned} \quad (6)$$

According to the above equations (1)-(6) and the normalization conditions $\sum_{S(i,j) \in S} \pi_{i,j} = 1$, the following transition rate equations can be obtained:

$$\begin{cases} \mathbf{PQ} = 0 \\ \mathbf{Pe} = 1 \end{cases} \quad (7)$$

where $\mathbf{P} = [\pi_{S(i,j)}]_{(M+1)^2} = [\pi_{i,j}]_{(M+1)^2}$, $\mathbf{Q}$ is the transition rate matrix, and $\mathbf{e}$ is a column vector with all elements being 1. The linear equations (7) can be solved by the Gauss-Seidel method to obtain the steady-state probability distribution [12].

Based on the steady-state distribution obtained by Equation (7), the average number of SUs transmitting in the network can be obtained as follows:

$$N_{SU} = \sum_{\forall S(i,j) \in S} j \cdot \pi_{i,j} \quad (8)$$

According to Equation (8) and the basic definition of throughput, the average SU throughput can be written as:

$$\Gamma = \frac{N_{SU}}{N} = \frac{\sum_{\forall S(i,j) \in S} j \cdot \pi_{i,j}}{N} \quad (9)$$

The channel idle probability (i.e., channel availability) being

$$p_{id} = \frac{\mu_1}{\lambda_1 + \mu_1}, \text{ thus the spectrum utilization rate can be defined}$$

as the ratio of the average number of available channels for transmitting SUs to the total available channels of all M primary channels:

$$\Psi = \frac{N_{SU}}{Mp_{id}} = \frac{\sum_{\forall S(i,j) \in S} j \cdot \pi_{i,j}}{Mp_{id}} \quad (10)$$

V. NUMERICAL RESULTS

To verify the effectiveness of our channel scheme in alleviating spectrum scarcity and the impact of imperfect spectrum sensing on system performance, the relevant parameters set as follows during the numerical simulation process: $M=8, N=16, \lambda_1 = 0.5, \mu_1 = 2, \lambda_2 = \mu_2 = 1$. And select three different values for p_m and p_f , respectively, $p_m = 0, p_f = 0$ (perfect spectrum sensing); $p_m = 0, p_f = 0.05$; $p_m = 0.05, p_f = 0$. At the same time, we compare MRIC-IS with opportunistic access schemes in [11].

As shown in Fig. 5, the spectrum utilization of the MRIC-IS increases as the SU traffic load continues to increase. As the probability of misdetection p_m or false alarm p_f increases, the spectrum utilization under imperfect spectrum sensing is slightly lower than that under perfect spectrum sensing. That is due to the spectrum waste caused by the occurrence of false detection events that will cause the originally active channel to become an idle channel and the occurrence of false alarm events that will cause the available channel to remain idle.

As shown in Fig. 6, as the SU traffic load continues to increase, the average SU throughput of the MRIC-IS decreases. This phenomenon is caused by the limited number of primary channels and finite spectrum opportunities. Similarly, the average SU throughput under imperfect spectrum sensing is slightly lower than that under perfect spectral sensing due to the occurrence of sensing error events. In addition, we observe that when the spectrum sensing error rate is 5%, the spectrum utilization and the average SU throughput of the proposed scheme are slightly lower than the perfect spectrum sensing case by 0%-4.4% as the SU traffic increases, which is sufficient to show that the proposed scheme can effectively alleviate the conflicting spectrum supply and demand even under the influence of sensing errors.

In addition, observation of the above experimental results reveals that MRIC-IS consistently outperforms the opportunistic access scheme, further demonstrating the effectiveness and superiority of the MRIC-IS scheme.

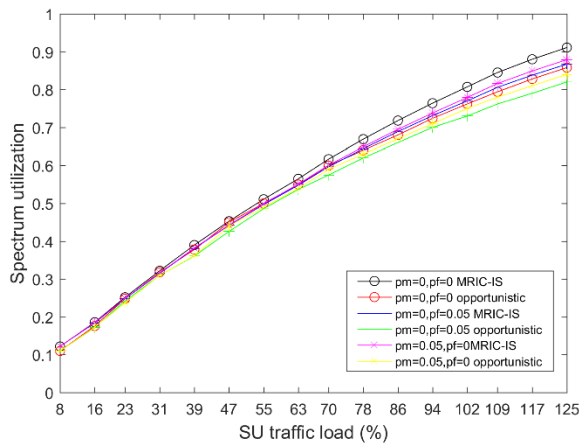


Fig. 5. Spectrum utilization under increasing numbers of SUs.

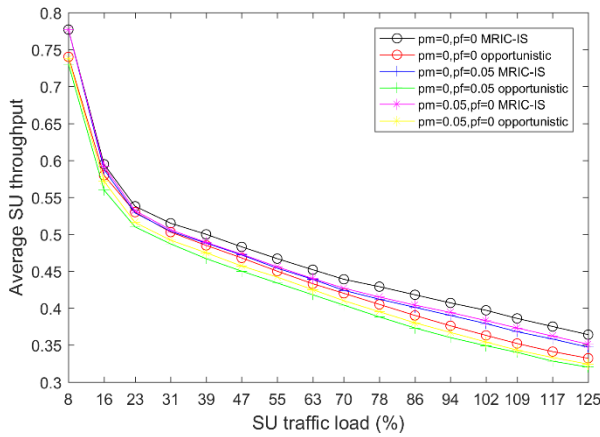


Fig. 6. Average SU throughput under increasing numbers of SUs.

VI. CONCLUSION

In this paper, to find the channel access scheme applicable to the actual 5G CRAHNS, we propose the minimum remaining idle time channel selection scheme under imperfect spectrum sensing. In this scheme, the SU can actively access the spectrum through spectrum sensing technologies, selecting a sufficiently long idle channel that meets its transmission requirements instead of the longest idle channel. By analysing the impact of false alarms and misdetection on the flow process of SUs resources, we establish a double-layer 2-D CTMC model. During the numerical simulation, we evaluate the impact of false alarms and misdetection on system performance. The results show that this scheme not can improve the accuracy of

evaluating system performance but also effectively alleviate the effects of spectrum fragmentation, thereby improving spectrum utilization and the average SU throughput.

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