Advanced Dynamic Channel Access Strategy in Spectrum Sharing 5G Systems

Siyu Lin, Linghe Kong (corresponding author), Qian Gao, Muhammad Khurram Khan, Zhangdui Zhong, Xi Jin, and Peng Zeng

Abstract

5G wireless communications aim at providing higher data rates, spectral efficiency, and energy efficiency than 4G. To achieve this target, the spectrum resource with low utilization is emptied out for 5G refarming. The refarmed spectrum is of effective propagation nature; however, it leads to extensive competition between PTOs and DTOs. To mitigate such competition, dynamic spectrum sharing should be realized. For this purpose, a spectrum sharing framework of a 5G system is designed in this article, in which the public users and dedicated users can access the sharing spectrum dynamically. In the framework, to ensure the QoE of the secondary users in a spectrum sharing system, the DTO in this case, an advanced dynamic channel access strategy is proposed. The spectrum sharing system states are modeled as a finite state Markov chain, and are used to analyze the system state transition model. Based on the analysis results, the optimal dynamic channel access strategy with minimum queuing time for DTO is derived by a Markov decision process. Extensive simulations show that the proposed dynamic channel access strategy can achieve the optimal queuing time.

Introduction

The continuous increase of mobile data traffic drives the emergence of fifth generation (5G) wireless communications. The traffic growth of mobile communications comes not only from the public telecommunication users but also from dedicated telecommunication users of vertical industries, including public safety, rail transportation, vehicular communications, and so on [1, 2]. To meet the explosive traffic growth and provide better quality of experience (QoE), the Third Generation Partnership Project (3GPP) organization is working on collecting user requirements for dedicated telecommunication systems and technique realizations in 5G, where spectrum sharing is a necessary option [1].

5G planning aims at higher system throughput, spectrum utilization, energy efficiency, and cost efficiency than conventional networks [3]. To achieve the above key performance metrics, more spectrum resource is exploited for 5G [4]. According to the 5G vision, the potential spectrum bands can be divided into two parts: the bands below 6 GHz and the ones above. Because most spectrum resource above 6 GHz is not allocated, abundant and continuous bandwidth (e.g., > 500 MHz) is easily found for 5G [4, 5]. On the contrary, the band below 6 GHz, which has been allocated to a variety of 2G, 3G and 4G systems, is extremely crowded, and that spectrum resource is suitable for providing wide area coverage and outdoor-indoor coverage. With the development of the mobile communications, 2G and 3G systems are coming to an end, and part of the allocated spectrum resource below 6 GHz will be refarmed to a 5G system for providing seamless coverage with high data rate. Due to the effective propagation nature of these spectrum resource, the dedicated telecommunication operators (DTOs) compete with the public telecommunication operators (PTOs) to win the refarmed spectrum.

The traffic characteristics of public telecommunication systems and dedicated telecommunication systems are inconsistent in time and space; therefore, an opportunity is provided so that the refarmed spectrum can be shared spatially and temporally to meet their traffic demands simultaneously. In such a way, the spectrum sharing can achieve better quality of experience (QoE) for multiple vertical industry customers. Spectrum sharing is an effective approach to implement dynamic spectrum management.

Advanced spectrum sharing schemes have been investigated in cognitive radio and TV white space to improve spectrum utilization. H. Bogucha *et al.* adopted the enhanced multicarrier technologies to realize the dynamic spectrum aggregation [6]; meanwhile, the associated interference was limited via power control. To maximize average sum rate (ASR) of secondary users (SUs), an optimal spectrum access and power control algorithm was designed for 5G [7].

But the associated interference can be limited at the expense of QoE of secondary users, so several QoE-driven channel allocation schemes were proposed. For instance, a dynamic spectrum allocation scheme based on user QoE expectations was proposed to provide seamless multimedia service and improve QoE [8]. To enhance the QoE of 5G, public-private spectrum sharing and dynamic spectrum leasing were

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proposed to improve the spectrum utilization and QoE of the user [7, 9]. Considering the heterogeneous network scenario, the cooperation between macro base stations (BSs) and micro BSs can further increase both spectral and energy efficiency [10, 11]. A new paradigm of integrated spectrum and energy harvesting in 5G wireless networks was proposed [12, 13], in which the secondary user can harvest energy for data transmission if the channel is occupied, and thus the energy efficiency of the system can be further improved. The QoE of secondary users in a spectrum sharing system can be enhanced though interference management and traffic scheduling. However, there has been no rigorous study in the literature on how to guarantee the QoE for a secondary user in a spectrum sharing system via dynamic spectrum access, which is the main focus of this article.

In this article, we first design a spectrum sharing framework of 5G system for PTOs and DTOs, in which the PTO and DTO are considered as the primary user (PU) and secondary user (SU), respectively. In this framework, three key design techniques are discussed. To provide the guaranteed QoE for DTOs in spectrum sharing systems, we design a dynamic channel access strategy, in which the traffic load and channel state information of the PTO and DTO are obtained from an environment learning process. Next, traffic load is modeled as multiple virtual queues, and the spectrum sharing system states are modeled as a finite state Markov chain, which are used to analyze the system state transition model. Minimizing average queuing time of SUs is taken as an example of a QoE objective of a DTO. Considering the queuing analysis results, the optimal dynamic channel access strategy is derived by the Markov decision process (MDP). Simulation results show that the proposed dynamic channel access strategy can achieve the optimal queuing time. The MDP-based dynamic channel access strategy is also appropriate for other QoE objectives, such as minimizing average packet drop rates.

Design of 5G Spectrum Sharing

To realize spectrum sharing, radio resource and mobility management is required across homogeneous and inhomogeneous spectrum. In such a way, spectrum utilization and adaptation is enhanced at the expense of system complexity and cost. The ideal LTE-based 5G spectrum sharing system architecture [9] is shown in Fig. 1, where any user can access their own licensed spectrum or the refarmed spectrum. The proposed system has three principal members:

- An enhanced mobility management entity (MME) is the main modified off=the-shelf entity in the LTE core network. The enhanced MME is responsible for control and management of spectrum sharing cells [9].
- The radio access network consists of central base stations (CBSs) and base stations (BSs) for PTOs and DTOs, respectively. The BSs of the PTOs and DTOs can only process the service requests of their own users. The CBS performs service request processing and dynamic spectrum access management of PTO users and DTO users in all spectrum bands, and the CBS has the ability for traffic status and channel state information cognition of the PTO and DTO.

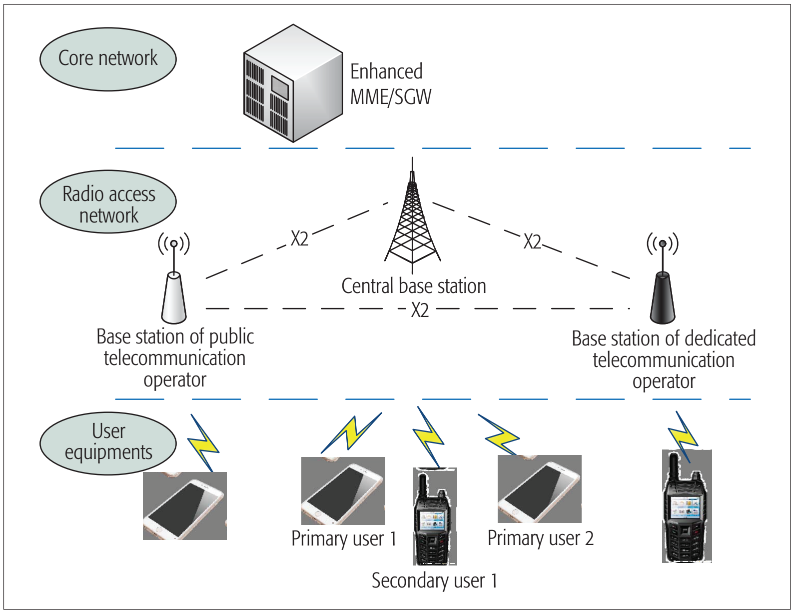

FIGURE 1. LTE-based 5G spectrum sharing system architecture.

- User equipments of the PTO and DTO can access their own licensed spectrum and the refarmed spectrum. There are two types of services of DTO users: mission-critical services (MCS) and non-mission-critical services (NMS) are considered. MCS can be synchronous video transmission and multimedia dispatching communications, NMS can be file transfer. MCS packets are considered to have higher priority than the NMS for transmission. The PTO traffic is not further classified.

The proposed system cannot work with only the abstract framework. Next, we discuss three key technologies and designs in this system.

Spectrum Leasing in the Refarmed Spectrum

From the economic perspective, spectrum leasing is a good solution to solve the competition problem between the PTO and DTO with the benefit of spectrum utilization improvement and infrastructure investment reduction. In this work, we consider that the PTO and DTO have their own licensed spectrum, and the PTO leases its refarmed spectrum to the DTO in exchange for technical cooperation or telecommunication infrastructure sharing (towers, BS buildings, etc.).

The spectrum band of the PTO is divided into $M \in \mathbb{Z}+$ frequency channels. Out of these M channels, $N \in \mathbb{Z}+$ channels come from the spectrum refarming of 2G and 3G systems. The PTO leases all the refarmed $N \in \mathbb{Z}+$ channels to the DTO, as shown in Fig. 2. The leased spectrum is fixed during the time of observation. The users of the PTO are considered as the PUs, who can access the licensed spectrum band of the PTO and the refarmed spectrum. The users of the DTO are considered as the SUs, who can access its own licensed spectrum band and the leased channels from the PTO. Because the PUs and SUs exclusively access their unleased spectrum, next we focus on the dynamic spectrum management of the leased spectrum.

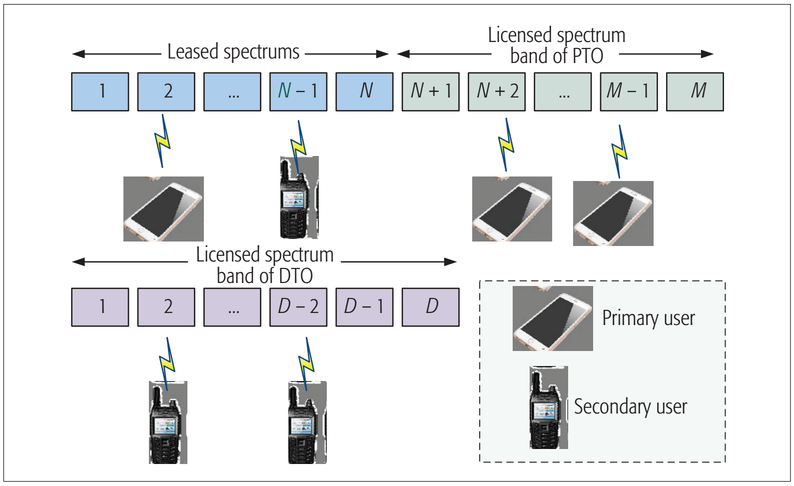

FIGURE 2. Spectrum allocation of PTO and DTO.

Dynamic Channel Access in the Refarmed Spectrum

The dynamic channel access strategy is used to allocate channel for the PUs and SUs according to their traffic and channel information. The dynamic spectrum access procedure is introduced first; then the access strategy of the spectrum sharing system is proposed.

The spectrum sharing system is considered as a time-slotted system. The PUs and SUs send their own service requests to the CBS when they have service packets for transmission in each slot. The CBS allocates the appropriate channels to the PUs and SUs according to spectrum occupation and channel information. The above signaling procedure is completed in the logical control channels. After that, the PUs and SUs start to implement the spectrum sensing in each slot for packet transmission, which is shown in Fig. 3a.

During the dynamic access management program execution, the CBS maintains three virtual finite queues for each channel to buffer the packets that cannot be immediately served, which are illustrated in Fig. 3b. The virtual buffers belong to a functional module of the CBS, which is used for queuing management and computing queue length according to the packet load of the requested services. For the leased spectrum, the packet arrival rate of PUs, MCS, and NMS are denoted as λ_p, λ_{mc} and λ_{nm}. For each channel, three virtual finite queues consist of one PU packet queue, a high-priority queue for MC packets, and a low-priority queue for NMC packets. The queue length of the three virtual queues for channel n in the time slot t are denoted as $q_{p,n}(t)$, $q_{mc,n}(t)$, and $q_{nm,n}(t)$. The buffer sizes of the three virtual queues of channel n are $L_{p,n}$, $L_{mc,n}$, and $L_{nm,n}$. All the queues in the system adopt a first come, first served (FCFS) protocol. The dynamic access decisions (i.e., the allocated transmission channel of packets of the PU, MCS, and NMS) are determined by CBS according to the above information.

Next, the basic dynamic channel access strategy of sharing spectrum is explained according to two user events: PU packets arrival and SU packets arrival. The detailed channel access strategy for the MCS and NMS is designed in the following sections.

When a new PU packet arrives, it is allocated the idle channel in its licensed spectrum first. If all the channels in the licensed spectrum are occupied, the PU packet is allocated to the leased channels; then it waits in the virtual buffer. The PU packets can be served by the allocated channel with high priority; if the allocated channel is occupied, the PU packets should wait to be served in the virtual queues.

When a new SU packet (either MCS or NMS) arrives, it will also access its own licensed spectrum with higher priority than the leased spectrum. If all channels in the licensed spectrum are occupied, the SU packet can access the leased channel allocated by the CBS; then it waits in the virtual queue of the allocated channel. The MCS packets can be served when the PU virtual queue of the allocated channel is empty. The NMS packets cannot be served unless the MCS queue and PU queue are empty.

Spectrum Mobility

Spectrum mobility management is used to switch channels of PUs and SUs in time to guarantee the utilization of the spectrum sharing system. The designed spectrum mobility management strategy is explained according to the packet departure events.

If a PU packet departs the licensed spectrum of the PU, one waiting PU packet in the leased spectrum switches to access the licensed spectrum immediately, which means that the PU accesses its licensed spectrum with priority. If an SU packet departs the licensed spectrum of the SU, one waiting SU packet in the leased spectrum switches to the vacant channel in the licensed spectrum immediately.

The key point of the dynamic access strategy is how to allocate the channel for the SUs according to the channel and queuing information. Next, the queuing models of PU packets and SU packets are modeled as a finite state Markov chain (FSMC). Based on the FSMC analysis, the channel allocation problem of the SU is formulated as a Markov decision process problem according to the QoE requirements of SUs.

Queuing Model of Dynamic Channel Access

In this work, the queuing time of packets is considered as the QoE objective of an SU, so the optimal dynamic channel access strategy is to minimize the average queuing time of SU packets. Due to that, the PUs can access the leased spectrum with priority; the queuing time of SU packets is influenced by the queuing states of PU virtual buffers. The queuing models of PU packets and SU packets are developed first; then the optimal dynamic channel access strategy for SUs can be designed based on the queuing analysis results.

The arrival processes of the PU packets, MCS packets, and NMS packets are assumed to follow independently and identically distributed (i.i.d) Bernoulli processes in each time slot, with parameters λ_p, λ_m, and λ_{nm}. Let μ_p, μ_m, and μ_{nm} denote the service rates of the PU packets, MCS packets, and NMS packets, respectively, which are assumed to follow geometric distributions. Due to the fact that PUs and SUs access their own licensed spectrum in advance, the service

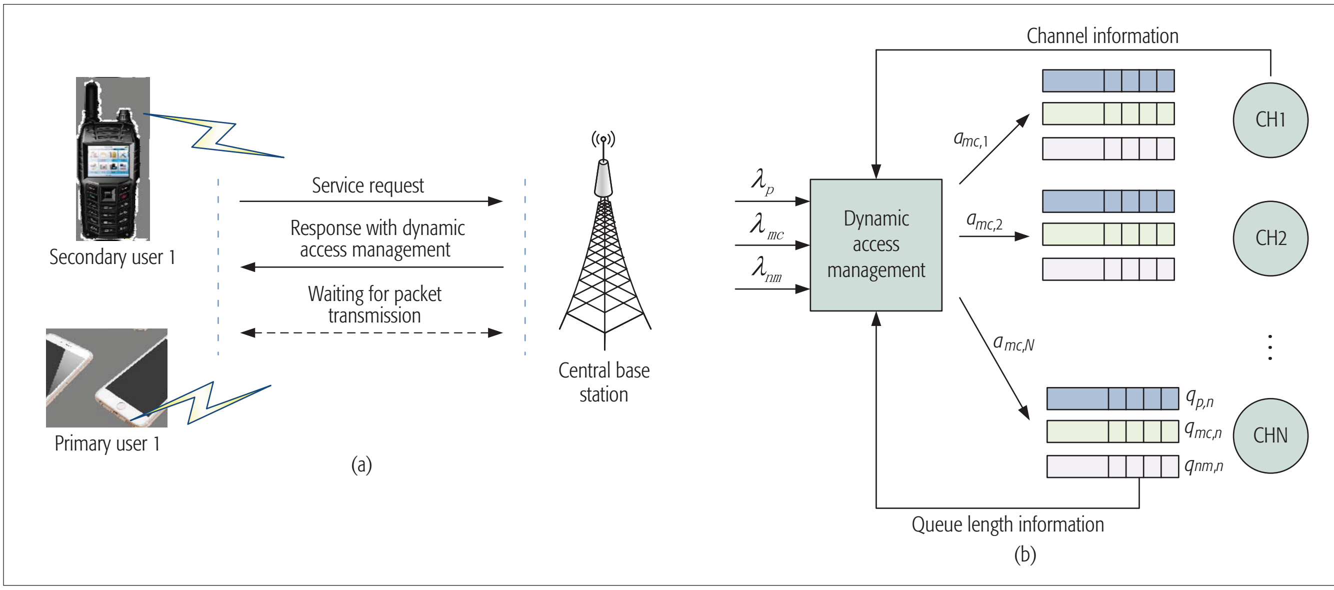

FIGURE 3. Dynamic channel access strategy in leasing spectrum: a) channel access procedure; b) queuing model for the leased spectrum.

arrival rates of PUs and SUs in the leased spectrum are the probability that the licensed spectrum is completely occupied.

Queuing Model for the PU

The behaviors of PU activity are described by two models: the PU queuing model and the channel service model for the PU. The PU queuing model is used to describe the queue state of the PU packets in each channel; whether the channel is occupied by PU packets is described by the channel service model.

The queue state of PU buffer in channel n at the tth slot $q_{p,n}(t)$ follows a Markov chain with state space $(l, 0 \le l \le L_{p,n})$, and the queue state transition model is shown in Fig. 4a. There are the following four cases. If the buffer is empty and one PU packet arrives, the queue state transits to 1; otherwise, the channel state keeps unchanged. If the buffer is full, no PU packet arrives, and one packet is served at this slot, the queue state transits to $q_{p,n}(t + 1) = L_p - 1$, else the channel state stays unchanged. If the queue state is $q_{p,n}(t) = l$, no PU packet, arrives and one packets is served at this slot, the queue state transits to $q_p(n) = l - 1$; if one PU packet arrives and no packet is served in this slot, the queue state transits to $q_p(n) = l + 1$; otherwise, the queue state keeps unchanged.

According to the PU queuing model, the channel service state model for a PU can be derived as shown in Fig. 4b. The channel service states $C_n(t)$ are modeled as an ON/OFF model, where ON denotes the idle channel and OFF otherwise. If the channel service state is ON and the queue state is 0, and also there is no PU packet arrival, the channel keeps the state ON and OFF otherwise; if the current channel service state is OFF and the queue state is 1, and also there is no packet arrival and the packet is served, the channel state is changed to ON and OFF otherwise.

The state steady probability matrices and transition probability matrices of the above models can be solved by basic queue theory.

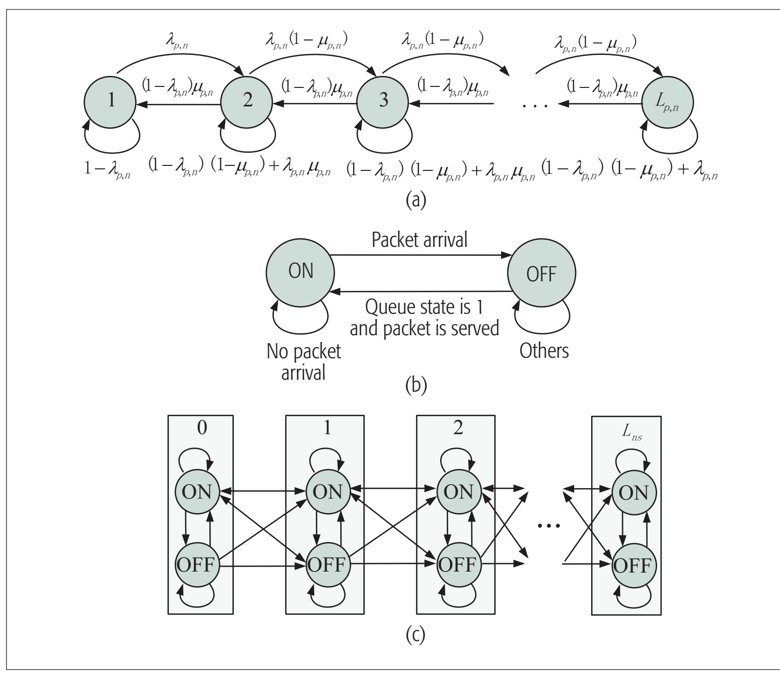

FIGURE 4. Queuing model for a PU and the NMS of an SU in leasing spectrum: a) queue state transition model for PU queues; b) channel service state transition model for PU; c) queue state transition model for MCS of SU queues.

Queuing Model for MCS of the SU

Because MCS packets have higher priority than NMS packets for transmission, the impacts of NMS packet transmission on the MCS packets can be ignored. For the queuing model for MCS of an SU, only the channel service state for the PU should be considered for the analysis on the dynamic access strategies of MCS. Thus, the pair of MCS queue state and service state for the PU $(q_{mc,n}(t), C_n(t))$ is used to describe the overall system state for the MCS packets at the tth time slot, which can construct an argument FSMC. The MCS queue state space is $(0 \le q_{mc,n}(t) \le L_{ns})$, the service state space for the PU can be ON or OFF

Case index	Activity	$q_{mc,n}(t) \rightarrow q_{mc,n}(t+1)$	$C_n(t) \rightarrow C_n(t+1)$
1	No MCS packet arrival	$0 \rightarrow 0$	ON/OFF → ON/OFF
2	One MCS packet arrival	$0 \rightarrow 1$	ON/OFF → ON/OFF
3	No MCS packet arrival and one MCS packet is served	$l_{mc} \rightarrow l_{mc} - 1$	ON → ON/OFF
4	One MCS arrival and no packet is served One MCS packet arrival	$l_{mc} \rightarrow l_{mc} + 1$ $l_{mc} \rightarrow l_{mc} + 1$	ON → ON/OFF OFF → ON/OFF
5	No MCS packet arrival No MCS packet arrival and no MCS packet is served One MCS packet arrival and one MCS packet is served	$l_{mc} \rightarrow l_{mc}$ $l_{mc} \rightarrow l_{mc}$ $l_{mc} \rightarrow l_{mc}$	OFF → ON/OFF ON → ON/OFF ON → ON/OFF

TABLE 1. Queuing state transition model for MCS of SU.

in each MCS queue state. The state transition model of the FSMC of MCS is shown in Fig. 4c. In terms of the queue state transition of the NMS of channel n in the tth slot, the transition model can be divided into five cases as shown in Table 1.

Case 1: In this case, there is no MCS packet arrival; then the channel state keeps at $q_{mc,n}(t + 1) = 0$; meanwhile, the channel service state transition for the PU depends on the PU queue state, which has been explained in the channel service model of the PU.

Case 2: In this case, one NMS packet arrives; then the channel state transits to $q_{mc,n}(t + 1) = 1$. This case does not impact the channel service model of the PU.

Case 3: In this case, one MCS packet is served, and no packet arrives. It means that the $S_n(t)$ cannot remain in the OFF state because the channel should be used to serve NMS packet. As shown in Fig. 4c, the state pair (l, OFF) could not transit to (l-1,ON) or (l-1,OFF).

Case 4: In this case, if one MCS packet arrives and no packet is served, the channel service state transits from ON to ON or OFF; if one MCS packet arrives, the channel service state transits from OFF to ON or OFF.

Case 5: In this case, if no MCS packet arrives and the PU packet is served, the channel service state transits from OFF to ON or OFF; if no MCS packet arrives and no MCS packet is served, or one packet arrives and one packet is served, the channel serve state transits from ON to ON or OFF.

However, due to the buffer size being limited, the transition model of the full buffer case is not analyzed in the above five cases. If the packet arrival and departure is the same as in case 3, the queue length transits to $q_{mc,n}(t + 1) = L_{mc} - 1$; otherwise, the system state stays in full state.

Queuing Model for NMS of the SU

Comparing the PU and MCS of the SU, the NMS packets have the lowest transmission priority. For the queuing model for NMS of the SU and the channel service state for the PU, the queue state of the PU and NMS should be considered when we analyze the dynamic access strategy for NMS transmission. The pair of MCS queue state and service state for the PU ($q_{nm,n}$, $q_{mc,n}(t)$,$C_n(t)$) is used to describe the overall system state for the NMS packets at the tth time slot, which can construct an argument FSMC. However, the access strategy of NMS is not the key point in this work, and also the QoE of NMS does not need to be guaranteed, so the state transition model of the FSMC of NMS is ignored.

Markov Decision Problem Formulation

The QoE of MCS is determined by the PU behaviors and the dynamic channel access strategy. To achieve the QoE requirements of MCS, such as minimizing the average queuing time for MCS, the optimal dynamic channel access strategy is derived according to the system transition model analysis results.

The channel access strategy is considered as the MCS access actions; the system state of MCS and the state transition model have been analyzed in the previous section. The average queuing time of MCS packets can be considered as the immediate reward obtained after an action is taken. Then we can formulate the optimal channel selection strategy as an MDP problem to derive the optimal channel access strategy [14].

The state space of the system is $S(t) = (q_{mc,n}(t), C(t))$. The MCS access actions are denoted as $A = a_{mc,1}, a_{mc,2}, \cdots, a_{mc,N}$, where $a_{mc,n} = 1$ means that the channel n is allocated to the MCS packet; otherwise $a_{mc,n} = 0$. According to the analysis results of system transition model, the transition probability function from state s to the state s', after the action a is taken, is presented as $P(s, \pi(a), s')$, where π denotes the mapping function from a state to an action. The goal of the MDP is to find a channel access strategy to minimize the average queuing time for MCS, which is formulated as an infinite time horizon MDP problem:

$$\min \liminf_{T \to \infty} \frac{1}{T} \mathbb{E}_{\pi,s}\left[\sum_{t=1}^{T} R\left(s_t' \mid s_t, \pi(a_t)\right)\right]. \quad (1)$$

Here, $\mathbb{E}[.]$ is the expectation function, $R(s'_t \mid s_t$, and $\pi(a_t))$ is the queuing time cost per state transition.

Similarly, if the QoE of NMS of the SU is considered as the objective of the channel access strategy, it can also be formulated as the MDP problem based on the system transition model. To derive the optimal dynamic channel access strategy that satisfies the above objective function, there are many solution methods. The value iteration method is the most efficiently and widely used method to solve an infinite time horizon discounted MDP [15].

Performance Evaluation

In this section, simulation results are provided to evaluate the performance of the proposed dynamic channel access strategy.

In the spectrum sharing system, three channels are configured in the refarmed spectrum. The default arrival rate of PU, MCS, and NMS are set as $\lambda_p = 0.55$, $\lambda_{mc} = 0.7$, and $\lambda_{nm} = 0.2$, respectively. The service rate for the PU, MCS, and NMS at channels 1, 2, and 3 are set as $\mu_{p,1} = 0.4$, $\mu_{p,2} = 0.35$, $\mu_{p,3} = 0.3$, $\mu_{mc,1} = 0.45$, $\mu_{mc,2} = 0.4$, and $\mu_{mc,3} = 0.35$, and $\mu_{nm,1} = 0.25$, $\mu_{nm,2} = 0.35$, and $\mu_{nm,3} = 0.2$, respectively. The shortest queue channel access strategy is selected as the baseline, in

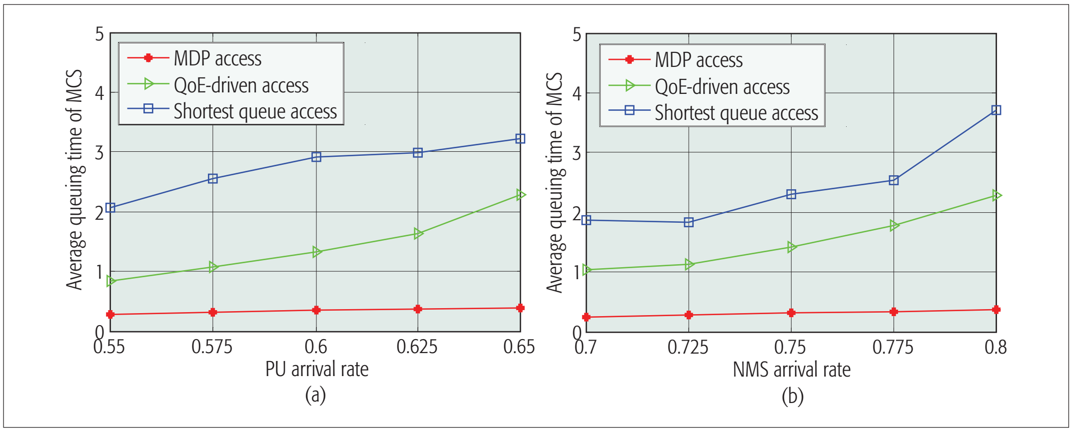

FIGURE 5. Average queuing time of MCS in leasing spectrum: a) queuing time vs. PU arrival rate; b) queuing time vs. MCS of SU arrival rate.

which the CBS always allocate the channel with the shortest total queue length of PU and MCS to MCS packet. Also, a QoE-driven dynamic channel access strategy [8] is selected for performance comparison.

The effects of PU arrival rate on the average queuing time of MCS under different access strategies are investigated. It is shown in Fig. 5a that the average queuing time of MCS is increased when the PU arrival rate varies from 0.55 to 0.65. This is because the PU packets occupy more time for their packet transmission. We can see that the average queuing time of the proposed strategy outperforms the shortest queue length strategy and QoE-driven access strategy. This is because the shortest queue length strategy is a greedy strategy, which ignores the randomness of channel service rate. Due to the QoE-driven access strategy trying to reduce the spectrum handoff probabilities, the channels are fairly allocated to different services; thus, the average queuing time of MCS cannot be guaranteed. For the proposed dynamic channel access strategy, it allocates channels according to the variation of the channel state and channel service state; hence, the channel allocation action is the optimal one for the required QoE objective. With the increase of PU arrival rate, the queuing time of MCS of baselines increases from 2.05 and 0.87 slots to 3.13 and 2.23 slots, respectively, while the queuing time of the proposed scheme slightly increases from 0.27 slots to 0.36 slots.

The effects of MCS arrival rate on the average queuing time of MCS under different access strategies are also investigated. It is shown in Fig. 5b that the average queuing time of MCS is increased when the MCS arrival rate varies from 0.7 to 0.8. With the increase of MCS arrival rate, the queuing time of MCS of baselines increases from 1.86 and 1.03 slots to 2.27 slots and 3.81 slots, respectively, while the queuing time of the proposed scheme slightly increases from 0.27 slots to 0.33 slots. Therefore, we can see that there is little increase rate with increased packet arrival rate of PUs and SUs in our proposed dynamic channel access strategy.

Conclusion and Future Research Challenge

In this article, we focus on the dynamic channel access problem between two operators in refarmed spectrum of a 5G system. A dynamic spectrum sharing system is first designed for PTO and DTO; then three key techniques are discussed. To derive the optimal dynamic channel access strategy, an FSMC model is developed to describe the spectrum sharing system state transition. The FSMC model can assist in deriving the optimal dynamic channel access strategy with minimized queuing time of SUs. The optimal dynamic channel access strategy is formulated as an MDP problem to obtain the optimal solution.

Low-latency communications are the typical scenario of 5G systems. However, the spectrum handoff cannot be avoided to introduce extra handoff delay in a spectrum sharing system. Therefore, reducing the spectrum handoff probability and delay is a hot topic in spectrum mobility. Besides that, implementing the dynamic spectrum management requires learning the radio environment, such as learning the traffic patterns of primary users and interference levels. The learning efficiency determines the implementation performance of dynamic spectrum management. Therefore, improving the learning efficiency is also a challenge of practical spectrum sharing 5G systems.

To derive the optimal dynamic channel access strategy, an FSMC model is developed to describe the spectrum sharing system state transition. The FSMC model can assist in derivingthe optimal dynamic channel access strategy with minimized queuing time of SUs. The optimal dynamic channel access strategy is formulated as an MDP problem to obtain the optimal solution.

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Implementing the dynamic spectrum management requires learning the radio environment, such as learning traffic pattern of primary users and interference levels. The learning efficiency determines the implementing performance of dynamic spectrum management. Therefore, improving the learning efficiency is also a challenge of practical spectrum sharing 5G systems.

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