

Channel Characteristics and User QoS-Aware Handoff Target Spectrum Selection in Cognitive Radio Networks

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Abstract. In cognitive radio networks (CRNs), in the case that primary users (PUs) reclaim their channels, the secondary users occupying the spectrum of PUs may have to stop their transmission, waiting at current channel or perform spectrum handoff, i.e., switch to other channels. For handoff SUs, designing target spectrum selection schemes is of particular importance for it may affect the transmission performance and user quality of service (QoS) significantly. In this paper, we study spectrum handoff scheme design for a CRN deployed multiple channels. Jointly taking into account the characteristics of handoff candidate channels and user QoS requirements, we propose a channel characteristics and user QoS aware handoff target spectrum selection scheme for handoff SUs. Simulation results demonstrate the effectiveness of the proposed scheme.

1 Introduction

Static spectrum allocation (SSA) policy, in which fixed spectrum is allocated to licensed users, has been employed for a few decades and has served well in the past when the transmission requirement of wireless applications is relatively low [1]. With wireless and radio communications becoming far more widely used, the efficiency and effectiveness of traditional SSA policy have become highly undesired. The consequential effect is that, whereas, the licensed spectrum bands are substantially underutilized, portions of the unlicensed spectrum are becoming overcrowded, leading to the so-called spectrum scarcity problem.

Cognitive radio networks (CRNs) [2, 3] have been identified as the key technology to stress the trade-off between spectrum demand growth and spectrum underutilization by enabling the development of dynamic spectrum access (DSA) mechanisms. In CRNs, unlicensed users, referred to as secondary users (SUs) are equipped with the capability of monitoring spectrum bands occupied by licensed users, i.e., primary users (PUs) and detecting the unused portions or idle periods between successive accesses of PUs, and are allowed to exploit the idle spectrum for data transmission. Through supporting the access of SUs on available spectrum in an opportunistic and dynamic manner, spectrum utilization can be improved significantly.

As PUs have preemptive right over SUs in the licensed band, in the case that the PUs reclaim their channels, the SUs occupying the spectrum of PUs may have to stop their transmission, waiting at current channel or perform spectrum handoff, i.e., switch to other channels. For handoff SUs, designing target spectrum selection schemes is of particular importance for it may affect the transmission performance and user quality of service (QoS) significantly.

Several research works have addressed spectrum handoff problem or handoff target channel selection problem in CRNs. An M/G/1 queuing network model with preemptive resume priority (PRP) is proposed for CRNs, the waiting delay of SUs at the queue is analyzed and the spectrum with the minimum waiting delay is selected as the handoff channel in [4]. The authors in [5] formulate an optimization problem to proactively determine target channel with the objective of minimizing the cumulative delay per connection for new arriving SU while taking into account the channel switching time and the waiting time resulted from the channel obsolescence. Channel handoff agility is considered in [6], where SUs are only allowed to switch to their neighboring channels, a continuous-time Markov model is derived to analyze the forced termination and blocking probabilities of SUs. In [7], the authors propose a probabilistic approach in determining the initial and target channels for a handoff SU in a CRN, and the optimal channel offering the minimum transmission time is chosen as the handoff target channel. In [8] a dynamic channel selection approach is proposed to reduce connection disruption rate in CRNs.

In this paper, we study spectrum handoff scheme design for a CRN deployed multiple channels and consider the handoff performance of the network over a given time period. Jointly taking into account the characteristics of handoff candidate channels including SUs' waiting time for accessing the channel and channels' available transmission time, and user QoS requirements in terms of interrupting delay and transmission data rate, we propose a channel characteristics and user QoS-aware handoff target spectrum selection scheme for handoff SUs.

2 System Model

In this paper, we consider a CRN consisting of one primary base station (PBS), one cognitive base station (CBS), multiple PUs and SUs. We assume that each PU is allocated one of N licensed channel for accessing the PBS while each SU is allowed to access the licensed channel of PUs in an opportunistic manner.

In this paper, a M/G/1 queuing network model is proposed to characterize the spectrum usage between PUs and SUs [4]. To support the higher priority of PUs over SUs, the queue model is partitioned into two sub-queues, i.e., the high priority sub-queue for the PUs and the lower priority sub-queue for the SUs. The key features of the M/G/1 queuing model are described as follows.

- PUs and SUs may arrive at various channels with different rates. In the case that the channels are busy, users will wait in their corresponding sub-queues, i.e., PUs wait in the high priority sub-queues, and SUs wait in the low priority sub-queues till the channels become available.

- Users waiting in the same sub-queue are allowed to access the channels on the basis of first come first served (FCFS) scheduling scheme.
- To reduce the possibility of call drop, higher priority is given to interrupted SUs over new SUs, i.e., SUs with initial service requirement, thus interrupted SUs will be put before new SUs in the low priority sub-queues.

We assume the arrival process of the k th PU follows Poisson process with the arrival rate being $\lambda_k^{(p)}$ and the service time of the k th PU is exponentially distributed with mean $\mu_k^{(p)}$, $k = 1, 2, \dots, N$. In this paper, it is assumed that a cognitive management entity, the cooperative centralized network controller (CCNC) is applied to collect user and network information and conduct spectrum selection scheme for SUs (Fig. 1).

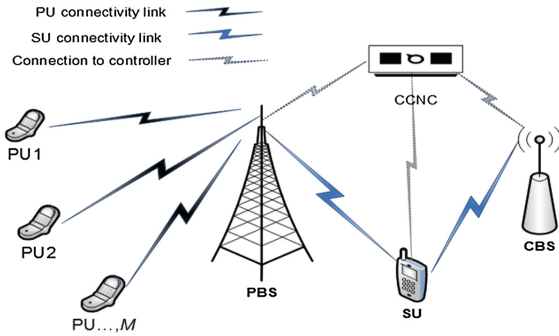


Fig. 1. System model

3 Interruption Delay Constraint and Transmission Time Constraint Formulation

The service of an interrupted SU may pose different QoS requirements on the transmission spectrum. In this paper, we assume each interrupted SU may have different interruption delay and transmission time requirements, which impose constraints on handoff target spectrum. In this section, we formulate the interruption delay constraint and the transmission time constraint of an interrupted SU during a handoff situation.

3.1 Interruption Delay Constraint

In the case that one PU reclaims its allocated channel, the SU occupying the channel should interrupt its transmission, stay at current channel or switch to another channel. For both cases, the interrupted SU cannot resume its data communications until the PUs have completed their transmission, thus resulting in waiting delay. If the interrupted SU chooses to switch to another channel, additional switching delay may occur due to spectrum handoff procedure.

The transmission interruption of an SU resulted from waiting in the channel queue or performing spectrum handoff might be unacceptable for delay sensitive services. Hence, for an interrupted SU, handoff target spectrum should meet certain interruption delay constraint. Denoting T^{\max} as the maximum acceptable interruption delay of the interrupted SU, the k th channel can be selected as the handoff target spectrum of the SU only if it meets the following delay constraint:

$$T_{j,k}^{(I)} \leq T^{\max}, \quad 1 \leq k \leq K. \tag{1}$$

Assume that an interrupted SU with initial source channel j chooses the k th channel as its target channel, the corresponding interruption time can be calculated as:

$$T_{j,k}^{(I)} = T_k^{(w)} + \delta_{j,k} T_{j,k}^{(s)} \tag{2}$$

where $T_{j,k}^{(I)}$, $T_{j,k}^{(w)}$ and $T_{j,k}^{(s)}$ denote the corresponding interruption time, waiting delay and switching delay of the interrupted SU, respectively, and $\delta_{j,k}$ denotes the binary spectrum handoff index, i.e.,

$$\delta_{j,k} = \begin{cases} 0, & \text{if } j = k; \\ 1, & \text{if } j \neq k. \end{cases} \tag{3}$$

In the following subsections, the waiting delay and the switching delay of interrupted SU will be calculated, respectively.

Waiting Delay of an Interrupted SU. In this subsection, the waiting delay of an interrupted SU is analyzed for both staying case and switching case.

a. Staying Case

In the case that an interrupted SU chooses to stay on its current channel, it will be put at the beginning of the sub-queue of the SUs and wait until the PUs in the channel complete their transmissions. Hence, the waiting delay can be expressed as the channel busy time due to the transmission of the PUs. Assuming the k th channel is originally allocated to the k th PU, the waiting delay of the interrupted SU can be calculated as:

$$T_k^{(w)} = E[T_k^{(p)}], \tag{4}$$

where $T_k^{(p)}$ denotes the busy time of the k th channel due to the transmission of the originally allocated PU, $E[z]$ denotes the expectation value of z , $E[T_k^{(p)}]$ can be derived as follows.

Denoting $I_k^{(p)}$ as the idle period of the k th channel due to the transmission of the PU, we obtain:

$$E[I_k^{(p)}] = \frac{1}{\lambda_k^{(p)}}. \tag{5}$$

The utilization factor of the k th channel, denoted by $\rho_k^{(p)}$ can be expressed as:

$$\rho_k^{(p)} = \frac{E[T_k^{(p)}]}{E[T_k^{(p)}] + E[I_k^{(p)}]} = \frac{\lambda_k^{(p)}}{\mu_k^{(p)}}. \tag{6}$$

Combining (4) and (5), we can obtain:

$$T_k^{(w)} = \frac{1}{\mu_k^{(p)} - \lambda_k^{(p)}}. \quad (7)$$

b. Switching Case

In the case that an interrupted SU chooses to switch to another channel, it will be put into the low-priority sub-queue in the target channel and has to wait for the PU or the SU transmitting on the channel to complete its transmission. Furthermore, the interrupted SU also needs to wait for the PUs and the previously interrupted SUs waiting in sub-queues to complete their transmission. Hence, the waiting delay of the interrupted SU can be calculated as the sum of the busy time of the channel due to the transmission of PUs or SUs, and the remaining service time of the channel, i.e.,

$$T_k^{(w)} = \frac{1}{2}E[T_k^{(p)}] + \frac{1}{2}E[T_k^{(s)}] + E[T_k^{(r)}], \quad (8)$$

where $T_k^{(s)}$ denotes the transmission time of an existing SU on the k th channel, and $T_k^{(r)}$ denotes the remaining service time of users on the k th channel. $E[T_k^{(s)}]$ can be calculated as:

$$E[T_k^{(s)}] = \frac{1}{\mu_k^{(s)} - \lambda_k^{(s)}}. \quad (9)$$

$E[T_k^{(r)}]$ in (7) can be calculated as:

$$E[T_k^{(r)}] = \frac{\lambda_n^{(p)}}{(\mu_n^{(p)})^2} + \frac{\lambda_k^{(s)}}{(\mu_k^{(s)})^2}. \quad (10)$$

Switching Delay of an Interrupted SU. In the case that an interrupted SU decides to switch from the j th channel to the k th channel, intra-system or inter-system handoff may occur as the j th channel and the k th channel may belong to the same CRN or different CRNs. For both cases, the SU may conduct the handoff procedure proactively or reactively, resulting in four types of handoff. The corresponding switching delay can be examined, respectively.

a. Proactive and Intra-system Handoff: Denoting $T^{(s,1)}$ as the switching delay of proactive and intra-system handoff, we obtain:

$$T^{(s,1)} = t_{\text{syn}}^{\text{sen}} + t_{\text{sen}} + t_{\text{dec}} + t_{\text{switch}} + t_{\text{syn}}^{\text{tx}}, \quad (11)$$

where $t_{\text{syn}}^{\text{sen}}$ denotes the synchronization time for spectrum sensing, t_{sen} denotes the time period for sensing spectrum resource, t_{dec} denotes the time period for determining a target handoff spectrum, t_{switch} denotes the time required for switching from current channel to the target channel, and $t_{\text{syn}}^{\text{tx}}$ denotes the time required for synchronizing to the transmission slots in the target channel.

b. Proactive and Inter-system Handoff: In the case that a proactive handoff is performed between two heterogeneous CRNs, the reconfiguration of radio frequency (RF) front end is required. Denoting the time required for reconfiguration as t_{recfg} , the resulted switching delay denoted by $T^{(s,2)}$ can be expressed as:

$$T^{(s,2)} = t_{\text{recfg}} + T^{(s,1)}. \quad (12)$$

c. Reactive and Intra-system Handoff: In the case that a reactive handoff is performed inside one CRN, a handoff preparation time, denoted by t_{prep} is required to collect measurement information and determine the handoff spectrum, thus, the resulted switching delay denoted by $T^{(s,3)}$ can be expressed as:

$$T^{(s,3)} = t_{\text{prep}} + T^{(s,1)}. \quad (13)$$

d. Reactive and Inter-system Handoff: In the case that a reactive handoff is performed between two heterogeneous CRNs, both handoff preparation and reconfiguration of RF front end are required. As a result, the switching delay denoted by $T^{(s,4)}$ can be expressed as:

$$T^{(s,4)} = t_{\text{recfg}} + T^{(s,3)}. \quad (14)$$

3.2 Remaining Transmission Time Examination

In the case that the available transmission time on the current channel does not meet the requirement of the SU, there is a possibility of future interruptions. To reduce the number of subsequent spectrum switches, the remaining transmission time, i.e., the transmission time required for the SU to complete its transmission and the available transmission time of candidate spectrum are examined and compared in transmission time constraint.

Denoting L^0 and L^t as the length of original data packets and that of the transmitted packets before interruption, respectively, and L as the length of un-transmitted data packets of the interrupted SU. i.e.,

$$L = L^0 - L^t \quad (15)$$

The expected length of time required by the interrupted SU to complete its remaining transmission on the k th candidate channel, denoted by $T_k^{(t)}$ can be calculated as:

$$T_k^{(t)} = \frac{L}{R_k} \quad (16)$$

where R_k is the data rate on the k th channel and can be expressed as:

$$R_k = B_k \log_2 \left(1 + \frac{P|h_k|^2}{\sigma^2} \right) \quad (17)$$

where B_k is the bandwidth of the k th channel, P denotes the transmit power of the interrupted SU, h_k and σ^2 denote respectively the transmission gain and the noise power of the link from the interrupted SU to its CBS on the k th channel.

Denoting T_k^{av} as the available transmission time useable by the SU on the k th channel, the transmission time constraint can be expressed as:

$$T_k^{(t)} \leq T_k^{(\text{av})}. \quad (18)$$

4 Proposed Handoff Spectrum Selection Scheme

The proposed handoff spectrum selection scheme consists of two functional levels, i.e., interruption delay constraint-based spectrum selection, and available transmission time constraint-based spectrum selection. The detail description of the proposed scheme will be presented in the following subsections.

4.1 Staying on Current Channel

Given that channel switching upon interruption can be costly, we propose a scheme in which, an interrupted SU first considers the possibility of staying on its default channel so as to resume its transmission after the holding time of the interrupting PU provided its current channel meets interruption delay constraint and transmission time constraint. For an interrupted SU with the original channel being j , the interruption delay constraint can be expressed as:

$$T_{j,j}^{(I)} \leq T^{\text{max}} \quad (19)$$

In the case that above constraint meets, we further examine the transmission time constraint on current channel, i.e.,

$$T_j^{(t)} \leq T_j^{\text{av}}. \quad (20)$$

If (20) also holds, the interrupted SU will choose to stay on current channel and resume its transmission after the PU has completed its transmission on current channel.

In the case that constraint in (19) fails to meet, the interrupted SU will examine the characteristics of other channels and consider performing spectrum handoff, as discussed in following subsection. In the case that constraint in (19) meets while constraint in (20) fails to meet, the interrupted SU will jointly examine the characteristics of current channel and other channels, based on which a spectrum selection strategy can be made.

4.2 Interruption Delay Constraint Based Spectrum Selection

In a situation where the current operating channel fails to meet the constraints of the SU, the need to consider switching to a new channel other than the current channel may arise. For the k th channel, the interrupted SU needs to examine interruption delay constraint, i.e., check whether (1) holds. We let M denote the set of candidate channels that meet the interruption delay constraint in (1). According to the value of M , following three cases should be considered.

- Case 1: $M = 0$, meaning no channel meets the interruption delay constraint of the interrupted SU, hence, the handoff fails.
- Case 2: $M = 1$, indicating only one candidate channel meets the interruption delay constraint of the interrupted SU, hence, this channel is selected as the handoff channel of the SU.
- Case 3: $M > 0$, i.e., more than one candidate channel meets the interruption delay constraint of the interrupted SU, the SU will further examine the transmission time constraint of these candidate channels and then select the optimal channel.

4.3 Transmission Time Constraint Based Spectrum Selection

Assume the k th channel meets the interruption delay constraint of the interrupted SU, the SU can then examine the transmission time constraint of the channel according to (18). We let Z denote the number of candidate channels that jointly satisfy user service constraints in (1) and (18), depending on the value of Z , three cases may arise:

- Case 1: $Z = 0$, i.e., no single candidate channel jointly meets the constraints in (1) and (18), thus, the SU will have to perform further spectrum handoff. In this case, we propose a maximum transmission amount based spectrum selection strategy in which the SU selects a channel that can transmit the highest amount of bits within the available transmission time. Therefore, the channel k^* is selected as the target channel which meets:

$$k^* = \arg \max(T_k^{\text{av}} R_k), \quad k = 1, 2, \dots, N. \quad (21)$$

- Case 2: $Z = 1$, indicating only one candidate channel jointly satisfies the constraints in (1) and (18), therefore, the user simply chooses it as handoff target channel.
- Case 3: $Z > 1$, indicating multiple candidate channels jointly satisfy the interruption delay constraint and the transmission time constraint. In this case, we propose a maximum data rate based spectrum selection strategy, i.e., selecting the channel with the best transmission rate as target channel for handoff. Hence the k^* channel is chosen if:

$$k^* = \arg \max(R^k), \quad k = 1, 2, \dots, N. \quad (22)$$

5 Simulation Results

In this section, we examine the performance of the proposed spectrum selection scheme. The simulation experiments are carried out through MATLAB software. In our simulation, we assume 2 to 10 ($M = 2 - 10$) channels each assigned to a licensed user. The simulation time is chosen as a number of time slots with the duration of each time slot being 5.77×10^{-4} s. $\lambda_k^{(p)}$ and $\mu_k^{(p)}$ are chosen as 0.5 and 4, respectively. Table 1 shows other parameters used in our simulation.

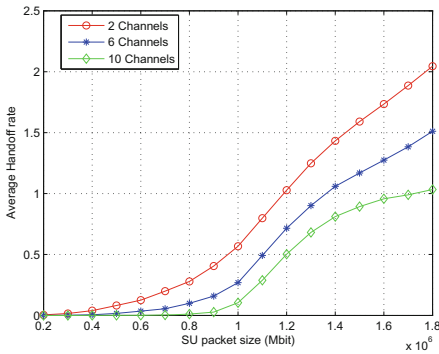
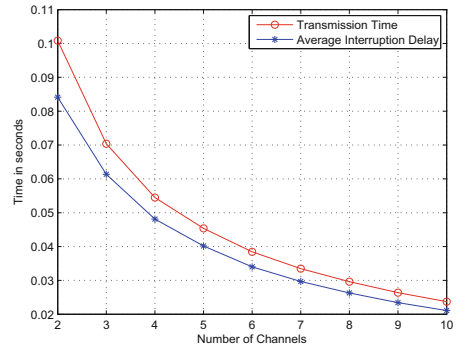
Table 1. Simulation parameters

Parameter	Value
Transmission power of SU	0.6 W
Interruption delay threshold of SU	$9 \cdot 232 \times 10^{-3}$ s
Radius of coverage Network	50 m
Network Bandwidth	2 MHz
Number of slots per channel	512
Packet length of SU	18×10^5 bits
Power of noise	-60 dBm

Averaging over 1000 simulations, the results of our proposed channel selection scheme are shown in the figures below.

Figure 2 shows the average number of handoff versus the packet length of SU. It can be observed that the number of handoff increases as the packet length grows. The reason is that longer transmission time is required for larger number of packets, thus may need multiple handoff. It can also be seen that the rate of handoff reduces with the increase in the number of available channels. This is because when the number of available channel increases, the probability of finding a channel that meets SU constraints becomes high.

Figure 3 shows the transmission time and the mean interruption of SU versus the number of channels. It can be seen that the two performance metrics behave in a similar way, i.e., both decline with the increase in the number of available channels. As the number of candidate channels increases, the probability that a user will find a channel that meets its transmission constraint is relatively high leading to less subsequent interruptions, hence the decline in the interruption delay, which is also reflected in the decreasing of total transmission time.

**Fig. 2.** Average number of handoff versus the packet size of SU**Fig. 3.** Transmission time and average waiting delay versus number of channels

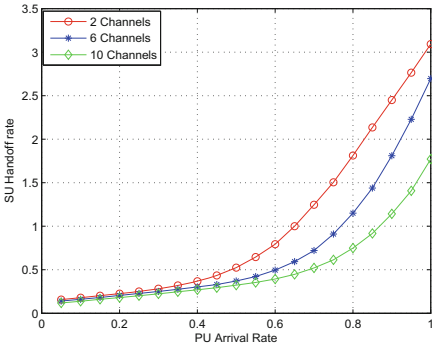


Fig. 4. Average number of handoff versus the arrival rate of PU

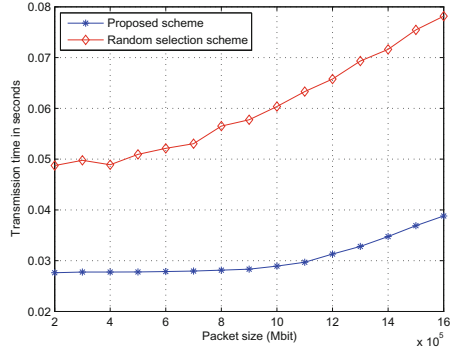


Fig. 5. Transmission time versus the arrival rate of PU

Figure 4 shows the average number of handoff versus the arrival rate of PUs. It can be observed that the average number of handoff increases with the increase in the arrival rate of PUs and the handoff rate reduces with the increase in the number of available channels, this is because when there are multiple channels available, SU can suitably find a target channel that meets its constraints such that the need for further interruptions and switching becomes relatively low, thus keeping handoff rate relatively small.

In Fig 5, we compare the total transmission time in the proposed scheme and a random choice channel selection. Both transmission times decline with increase in the number of available channels, however, it can be seen from that the proposed scheme offers smaller total transmission time in comparison with a random choice channel selection.

6 Conclusions

In this paper, a handoff target spectrum selection with a decision-making mechanism that minimizes the need for multiple handoffs as a means to reduce the total transmission time of an interrupted SU in a CRN is proposed. We examine the interruption delay and the transmission time of an interrupted SU during a handoff situation in both staying and switching scenarios and then jointly considering a SU’s interruption delay threshold, transmission time requirement and channel available time, we present a target spectrum selection scheme consisting of both interruption delay constraint-based spectrum selection and transmission time constraint-based spectrum selection.

Through simulation, we have shown that when an interrupted SU prioritizes staying on the default channel, switching and signaling overhead costs are eliminated thereby reducing the total service time. We have also shown that, when handoff is possible, if the SU considers only channels with relatively minimal interruption delay and, therefore, selects only candidate channels that offer

desired transmission time as target channels, by jointly considering the SU's remaining transmission time and the transmission time available on the candidate channel: the number of future spectrum handoffs is considerably reduced thereby enhancing the performance of the SU.

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