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Traffic sensitive spectrum access scheme for cognitive radio networks①

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Abstract

A traffic sensitive spectrum access scheme is proposed to satisfy the traffic load requirement of secondary users (SUs). In the proposed design, SU only accesses available channels which can meet the traffic demand. To achieve this, the expected transmission time (ETT) of the SU is calculated first based on the delivery ratio. Then, the channel idle time is estimated based on the activity of primary users (PUs). Therefore, available channels with estimated idle time longer than ETT could be chosen. With high probability, the SU can finish transmission on these channels without disruption, thereby satisfying the traffic load demand of the SU. Finally, our method is extended to the multi-channel scenario where each SU can access multiple channels simultaneously. Performance analysis shows that our method satisfies the requirement of SUs while effectively improving the throughput.

Key words: opportunistic spectrum access, expected transmission time, cognitive radio network

0 Introduction

Due to the fixed spectrum management, there is significant temporal and spatial variation in the usage of the allocated spectrum, which differs from 15% to 85%[1]. The extremely unbalanced spectrum utilization results in a spectrum scarcity problem. Allowing SUs access licensed frequency bands as long as they do not introduce severe interference to PUs[2-4], cognitive radio (CR) is an effective method to alleviate the frequency scarcity problem. Therefore, the CR network can take the advantage of dynamic spectrum access and utilize the spectrum diversity over wide spectrum.

In the prior opportunistic spectrum access schemes, an SU occupies a channel as soon as it senses it idle. Hence, if the idle time cannot accommodate the traffic load of the SU, the PU will appear during the transmission. Then, the SU has to switch to other bands to continue its transmission. Due to the delay cost in detecting new channels, spectrum efficiency will be lowered and the throughput may be reduced. Since more and more traffic load sensitive applications, such as streaming media and high bandwidth content distribution will be supported, it is necessary to design new spectrum access schemes to realize QoS provisioning for SUs.

In this paper, a traffic sensitive spectrum access scheme is proposed in order to meet the traffic load requirement of SUs and improve the spectrum efficiency. In our scheme, ETT is introduced as a constraint on channel selection and computed according to the channel bandwidth and delivery ratio. In addition, the channel idle time is estimated based on the activity of the PUs. Thereafter, channels with idle time longer than ETT will be selected. SUs can transmit the packets within the transmission duration, thereby satisfying the traffic load demands. Finally, we extend our method to the multi-channel scenario where each SU can access multiple channels simultaneously. Note that different set of channels could be used by each SU, which makes the spectrum allocation problem significantly difficult along with the rate requirement of the SU. The multi-channel selection problem is formulated as a constrained optimization problem. With the solution, the traffic load of SUs will be satisfied and the spectrum efficiency can also be improved.

The rest of the paper is organized as follows. Section 1 provides a brief overview of existing solutions to spectrum access. Section 2 presents a network model.

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Our proposed spectrum access model is introduced in Section 3. In Section 4, the performance of our proposed model is analyzed. Finally, we conclude the paper in Section 5.

1 Related work

Spectrum allocation is one of the key technologies in CR networks[5]. A poor spectrum allocation scheme assigns an idle channel with low bandwidth to a secondary user who requires high bandwidth, resulting in degraded network performance. On the contrary, assigning a wide band to a secondary user who requires low data rate causes the underutilization of bandwidth. Many approaches have been proposed to address spectrum allocation in CR networks[6-10]. In Refs[6,7], a Markovian model is proposed to predict the spectrum availability under the assumption of slotted primary and secondary networks. Taking into account an unslotted primary network, the authors proposed a learning-based approach to maintain and use belief vectors for channel access[8]. In Ref. [9], proactive channel sensing and switching techniques were proposed to minimize the disruptions to PUs and maintain the reliable communications of SUs. In Ref. [10], a spectrum matching algorithm was discussed to decrease the spectrum handover probability. However, these approaches do not consider the traffic load constraints. Differently, in our scheme, only the available channels that satisfy the traffic load requirement of SUs are selected.

2 Network model

The cognitive ad hoc network is considered in which SUs coexist with PUs. The spectrum consists of M channels, each with bandwidth $B_i (i = 1, \cdots, M)$. To exploit and access local spectrum opportunities without causing interference to PUs, SU should be equipped with configurable transceiver and capable of sensing and learning the communication environment. As shown in Fig. 1, a time-slotted system is assumed to be adopted for SUs. A slot can be divided into two parts, sensing time and transmission time. All of the channels can be sensed by the N SUs. One or more channels can be accessed by each SU simultaneously. In this model, each channel alternates between two modes, IDLE (the channel is not occupied by PUs) and BUSY (the channel is occupied). The state of channels are given by $[S_1, \cdots, S_M]$, where $S_i \in \{0(BUSY), 1(IDLE)\}$.

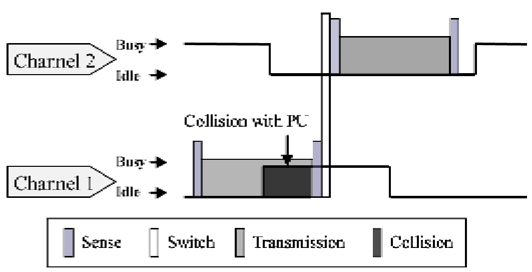

Fig. 1 Collision with PU

3 Opportunistic spectrum access scheme

In this section, we design a novel spectrum access scheme to satisfy the traffic load of SUs. Fig. 2 illustrates the components of the scheme. The proposed scheme consists of spectrum sensing and spectrum scheduling. In the spectrum sensing part, SU senses all the channels and acquires the status information. In the spectrum scheduling module, ETT is calculated according to the traffic load of the SU. Then, the idle time of all available channels can be estimated according to the distribution of PU activity. So, the appropriate channels with channel idle time longer than ETT are chosen for transmission. We also formulate the multi-channel selection problem as a constrained optimization. By solving this constrained optimization problem, the traffic of the SU can be proportionally distributed on different channels.

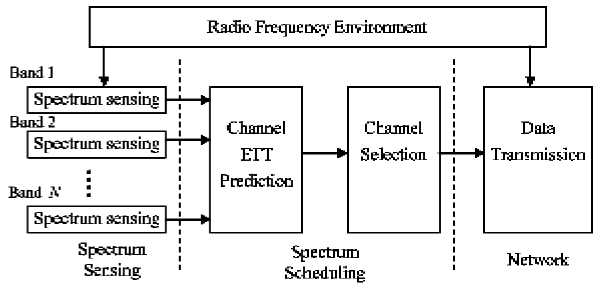

Fig. 2 Spectrum access scheme

3.1 Channel ETT prediction

In order to capture the dynamic nature of CR networks, each band could be characterized by various parameters such as bandwidth and delivery ratio. Here, the delivery ratio is defined as the probability of a successful transmission. These channel characteristics are important factors in deciding the expected transmission count (ETX)[11,12]. ETX is calculated with the forward and reverse delivery ratio of the link. The forward delivery ratio d_f is the measured probability that a data packet successfully arrives at the receiver. Likewise, the reverse delivery ratio d_r refers to the probability that the ACK (acknowledgement) packet is successfully received. Thus, the probability that a packet is successfully received and acknowledged is $d_f \cdot d_r$. A sender will retransmit a packet that is not successfully acknowledged. Because each transmission attempt can be considered as a Bernoulli trial, ETX can be written as

$$ETX = \frac{1}{d_f \cdot d_r} \tag{1}$$

The delivery ratios d_f and d_r can be measured using probe packets. First, we broadcast probes of fixed size in every period. Then, we count the successfully received probes at the receiving node. d_f can be derived from

$$d_f = \frac{count(t-w, t)}{w/\tau} \tag{2}$$

where $count(t-w, t)$ is the number of probes received during window w, w/τ is the number of probes that should be received. Similarly, the reverse delivery ratio d_r can be computed at the sender.

ETT can be computed according to the transmission requirement of the SU using the following

$$ETT = \gamma \cdot ETX \frac{R}{B \cdot \log_2(1 + SINR)} \tag{3}$$

where R is the traffic load requirement, B is the bandwidth of the channel. As current channel capacity cannot reach the Shannon capacity, $\gamma (\gamma \geqslant 1.0)$ is used to model the actual capacity.

3.2 Channel selection

Let $G(y)$ denote the probability that the channel idle time is less than y. This means that the PU appears on the channel before the SU's transmission is over. The probability is computed by the SU as

$$G(y) = \int_0^y g(t)\mathrm{d}t \tag{4}$$

where $g(t)$ denote the channel idle time distribution.

In this case, the SU's transmission will interfere with the PU's transmission. $G(y)$ is actually the probability that collision happens between the PU and the SU. As mentioned in the above subsection, we can predict the expected transmission time of each SU by Eq. (3). Here, we assume ETT as the upper bound of the channel idle time so that Eq. (4) can also be written as

$$G = \int_0^{ETT} g(t)\mathrm{d}t \tag{5}$$

So, the SU can access a channel from the available channel set where the following constraint is satisfied

$$\pi = 1 - G > \delta \tag{6}$$

where π denotes the probability that the channel idle time meets the traffic load of the SU, δ is the given permissibility threshold of channel access.

For prediction of the channel idle time, the most commonly used models are uniform distribution[13], exponential distribution[7] and the distribution estimated from the history of spectrum usage data[14]. Without loss of generality, we assume the channel idle time is exponentially distributed. The length of the IDLE period is characterized by a random variable. The duration of the IDLE period is independent and identically distributed (i. i. d.). For each channel, the duration of idle period t follows an exponential distribution with mean $1/\lambda$

$$g(t) = \begin{cases} \lambda e^{-\lambda t} & t \geqslant 0 \\ 0 & t < 0 \end{cases} \tag{7}$$

So, we can get

$$G = \int_0^{ETT} \lambda e^{-\lambda t}\mathrm{d}t = 1 - e^{-\lambda ETT} \tag{8}$$

Thus, the constraint in Eq. (6) can be expressed as

$$\pi = e^{-\lambda ETT} > \delta \tag{9}$$

3.3 Multi-channel selection

In this part, we consider the scenario where each SU is capable of using multiple channels simultaneously. In this case, the traffic load can be distributed over different channels. Since different set of channels could be used by an SU, it is difficult to find an optimal channel set under the constraint of traffic load requirement of the SU. To solve this problem, we formulate the multi-channel selection process as a constrained optimization so that the number of spectrum switching is minimized while the spectrum utilization is maximized.

Since each SU may use several channels simultaneously to meet the requirement, we denote the traffic load assigned on the allocated channel i as R_i and the expected transmission time as ETT_i. As mentioned in the above subsection, the collision occurs when the idle time of each channel i is less than ETT_i. Therefore, the collision happens when

$$T_{idle}^i < ETT_i \tag{10}$$

where T_{idle}^i is the idle time of channel i.

We also assume the idle time of the PUs on channel i is exponentially distributed with parameter λ_i. So, the probability of collision is

$$G_i = P(T_{idle}^i < ETT_i) = \int_0^{ETT_i} \lambda_i e^{-\lambda_i t}\mathrm{d}t = 1 - e^{-\lambda_i ETT_i} \tag{11}$$

Considering the traffic load requirement of SU, the channel selection process is formulated as a constrained optimization problem as follows

$$\min\left(\sum_{i=1}^{M} S_i \cdot B_i\right)$$
$$s.t.$$
$$P(T_{idle}^{i} \geqslant ETT_i) = 1 - G_i = \pi_i > \delta \qquad (12)$$
$$\sum_{i \in A} R_i = R$$
$$\sum_{i=1}^{M} S_i \cdot B_i \cdot ETT_i \geqslant R$$

where S_i is the status of channel i. π_i is the probability that the rate requirement can be satisfied on channel i, δ is the given permissibility threshold ($1 > \delta > 0$), A is the set of selected channels.

In Eq. (12), the objective function is to minimize the assigned channel bandwidth. The first constraint means the probability that the channel could carry the traffic load assigned on the channel should exceed a certain limit δ. The second constraint shows that the traffic load requirement R is proportionally allocated to each selected channel i. The last constraint denotes that the total capacity of the selected channels should be no less than the SU's requirement. The optimal channel allocation can be acquired by solving this optimization problem.

4 Performance analysis

In this section, the performance of the proposed spectrum access scheme will be investigated. We study two scenarios, the single channel scenario where each SU can only access one channel and the multi-channel scenario where each SU can access multiple channels simultaneously. The simulation parameters are given in Table 1.

Table 1 Simulation parameters

Parameter	Value
d_f	0.98
d_r	0.98
$SINR$	10dB
γ	1.05
Number of Channels	[1 ~ 16]
Channel Bandwidth	[0.5 ~ 3.0] Mbps
R	[1 ~ 10] Mb
δ	[0.6 ~ 0.9]
λ	[0.2 ~ 0.8]
Number of Flows	[1 ~ 16]

4.1 Single channel scenario

Here, a practical scenario is proposed where nodes and multiple flows corresponding to multiple pairs of secondary can be scheduled on different channels. In this section we mainly investigate the saturation throughput and the probability of PU collision.

4.1.1 Saturation throughput

Assume that the number of the available channels is j with probability

$$P^j = C_M^j \pi^j (1 - \pi)^{M-j} \qquad (13)$$

So, the expected flow is

$$E(F) = \sum_{j=0}^{M} min(j, F) P^j \qquad (14)$$

Then, the saturation throughput can be written as

$$C = T_x / T \cdot E(F) \cdot R \qquad (15)$$

where T_x is the transmission time, $T_x = T - MT_s$ and T_s is the sensing time for each channel.

Fig. 3 shows the saturation throughput with respect to the number of channels. Set $T_s = 0.01T$ and $\lambda = 0.5$. It is observed that the throughput increases first as the number of flows grows. Then, the throughput converges when the number of flows exceeds the number of channels. As a comparison, the method outperforms the random algorithm which selects channels randomly under the same conditions, and the number of flows has no effect on the throughput in the case of $M = 1$. In addition, the throughput increases quickly as the number of channels grows.

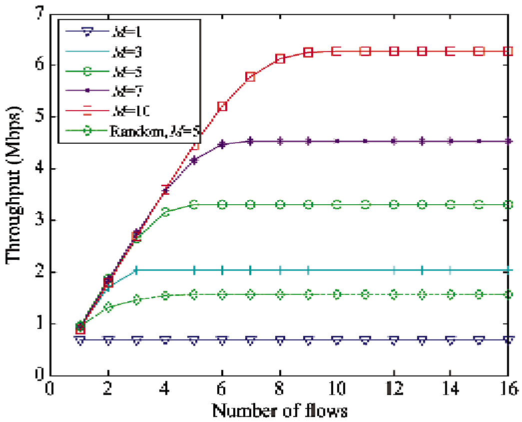

Fig. 3 Throughput vs. number of flows with different number of channels

Fig. 4 shows the saturation throughput with respect to different λ. Set $M = 6$. As λ decreases, PU becomes less active, thereby increasing the throughput. Similar to Fig. 3, our method is also better than the random one.

4.1.2 Probability of PU collision

Assume that there are j channels in the available channel set. For each available channel, the probability of being selected by a flow is

$$P_s = \begin{cases} F/j & F < j \\ 1 & F \geqslant j \end{cases} \qquad (16)$$

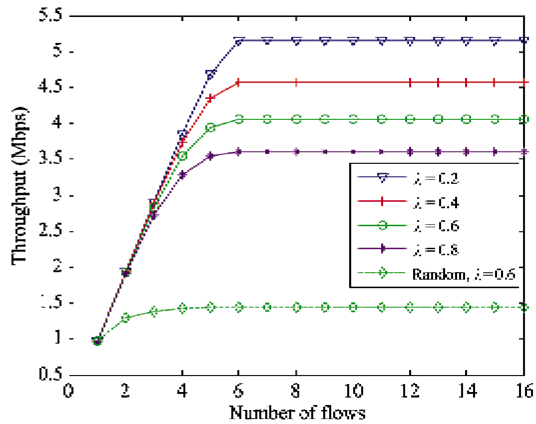

Fig. 4 Throughput vs. Number of flows with different λ

Therefore, given the sensing error probability at each node P_e, the collision probability is

$$P_c = (1 - \pi) P_e \sum_{j=1}^{M} (P^j P_s) \quad (17)$$

Fig. 5 illustrates the effect of the number of flows on PU collision. As the number of flows increases, the probability of PU collision rises and then converges. The probability increases as λ rises as well. That means more collisions will happen when the channel idle time decreases. Similarly, in Fig. 6, the PU collision probability also increases according to the number of channels first. However, the probability will decrease when the number of channels exceeds the number of flows. This phenomenon happens because the probability of collision on each channel will be reduced with the increase of the number of channels in the latter case. In Fig. 5 and Fig. 6, the collision probability of the proposed method is lower than that of random algorithm.

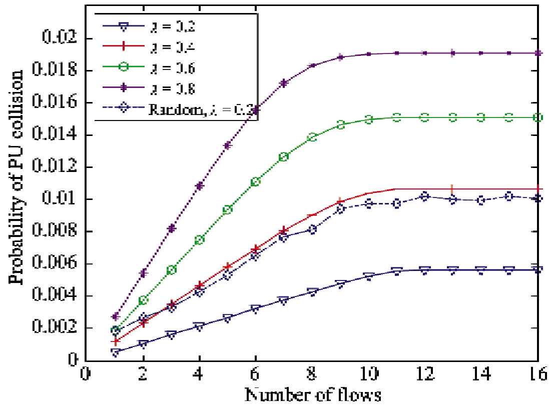

Fig. 5 Probability of PU collision vs. Number of flows

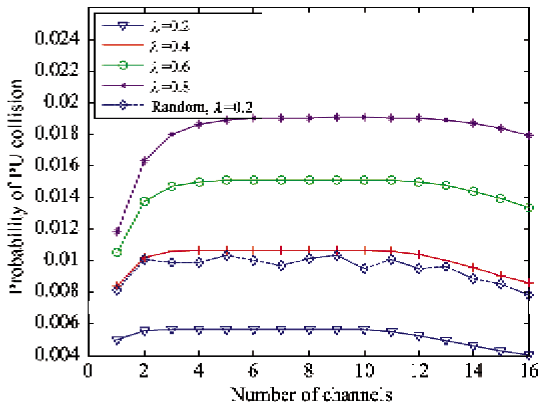

Fig. 6 Probability of PU collision vs. Number of channels

4.2 Multi-channel scenario

In the multi-channel scenario, the performance is investigated in terms of the number of channel switches, spectrum utilization ratio and average throughput of the SUs. The method is compared with the single channel-based method and other multi-channel access methods.

4.2.1 Number of channel switches

The improvement of the proposed scheme is shown with respect to the number of channel switches. For the single channel access case, the random approach is used. As a comparison, three multi-channel approaches are adopted, greedy, random and our proposed algorithm. The greedy algorithm is a naive approach in which an SU chooses channels with the maximum ETT for transmission. From Fig. 7, as the cumulative traffic load of SU rises, the number of channel switches in the single channel scheme is greatly increased. By contrast, the number of switches is reduced by up to 90% in the multi-channel scheme. Additionally, our optimization algorithm outperforms the other two multi-channel algorithms as the traffic rises. Our approach can drastically reduce channel switches, thus significantly improving the network throughput.

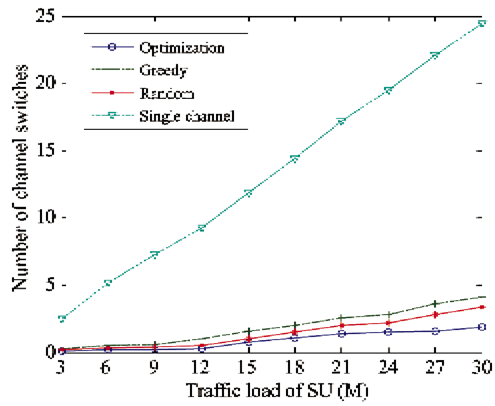

Fig. 7 Number of channel switches vs. Cumulative traffic load of SU

4.2.2 Spectrum utilization ratio

The system performance is evaluated in terms of average spectrum utilization ratio. It is defined as

$$\rho = \frac{\sum_{j \in A} R_j}{\sum_{i=1}^{M} S_i B_i ETT_i} \quad (18)$$

where A is the set of selected channels.

Fig. 8 shows the average spectrum utilization ratio of the three multi-channel approaches when the traffic load is uniformly distributed over[1-10]. It is observed that the spectrum utilization increases as the traffic load grows for all the three algorithms. Simulation result shows that the proposed approach improves the spectrum utilization ratio by up to 43% and 24% respectively compared to the greedy algorithm and the random algorithm. It is clear that the spectrum utilization ratio of the optimization algorithm is superior to the others, especially when the traffic load is moderate. Additionally, the performance gap of the spectrum utilization among these algorithms shrinks as the traffic load increases. The underlying reason is that the allocated channels are constantly occupied when the traffic load is high.

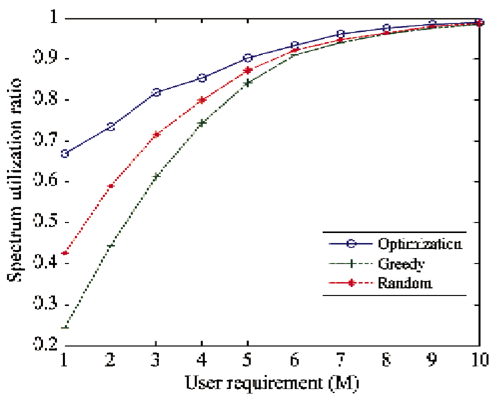

Fig. 8 Spectrum utilization ratio vs. Traffic load of SU

4.2.3 Average throughput

The average throughput of three approaches are compared with respect to δ. For the multi-channel upper bound approach, the instant channel availability is assumed to be known. Therefore its performance serves as the upper bound of the throughput that the multi-channel approach could achieve.

Fig. 9 demonstrates that the throughput of our optimal approach is close to that of multi-channel upper bound, and outperforms that of the single channel approach significantly. Obviously, the throughput heavily depends on the choice of δ. As expected, a small δ leads to significantly improved throughput, while the throughput decreases quickly as δ increases. That is because the number of available channels becomes less when the permissibility threshold is high. In Fig. 9, when δ is 0.6, the average throughput of multi-channel approaches 2.1Mbps which outperforms the single channel case by 400%. This result shows that parameter δ plays an important role in system performance.

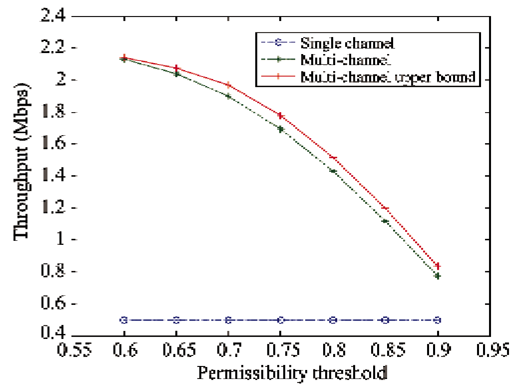

Fig. 9 Effect of increasing permissibility threshold δ

5 Conclusions

Spectrum access is an important issue in cognitive radio networks. Traditional spectrum access is based on the scheme that an SU occupies a channel once it senses the channel idle without considering the traffic load requirement. Therefore, transmission disruption happens if the channel idle time cannot satisfy the traffic load which also leads to lower throughput.

A novel spectrum access scheme is proposed based on the expected transmission time and estimated channel idle time. In our scheme, the ETT is calculated according to the traffic loads of SUs and the channel idle time is estimated considering the distribution of PU activity. So, the appropriate channels with channel idle time longer than ETT are chosen for transmission. In addition, we also address the multi-channel selection problem by formulating it as a constrained optimization problem. Performance analysis shows that the proposed scheme could effectively improve the throughput while realizing QoS provisioning for SUs.

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