Dynamic spectrum access strategy for cognitive wireless networks based on two channel sensing

Yanliang Li, Dianjun Chen, Luyong Zhang
School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
liyanliang1993@163.com

Abstract A dynamic spectrum access strategy based on two channel sensing is proposed for the spectrum access model in multi-channel multi-user scenarios. The strategy reduces the contention of cognitive users to the channel by sensing the dynamic allocation of spectrum channels. The number of the perceptual access channels is adaptively allocated according to the number of access users, and the collision interference to the authorized channel is reduced. Then based on the above model, a hybrid dynamic spectrum access strategy is proposed, and the Overlay/Underlay hybrid access mode is adopted instead of the original single Overlay access mode. By setting the probability threshold to reduce the perception of the channel with lower credibility, the cognitive user adopts the Underlay access mode shared transmission at a lower transmission rate. The simulation results show that the proposed two dynamic spectrum access strategies can effectively reduce the collision probability and improve the network service quality.

1. Introduction
With the increasing shortage of wireless resources in recent years, how to improve the utilization of spectrum resources through cognitive radio technology is a key concern of all researchers. As two key technologies in cognitive radio networks, research on spectrum sensing and spectrum access has made certain progress and prospects.

In the literature [1-3], the spectrum-aware decision access mechanism is modeled as a partially observable Markov Decision Process (POMDP), and the research on myopia access strategy can reduce the computational complexity of the dynamic spectrum access process to get the best strategy. Literature [4] considers multiple cognitive user contention issues and optimizes the system by coordinating user assignments to perceive different channels. Literature [5] studied the channel allocation problem in multiple cognitive user systems based on the length of cognitive user service requests. Literature [6] [7] maximizes throughput and avoids collision interference by cognitive users based on load balancing intelligent selection of cognitive channels. However, in the case where the cognitive user is unfamiliar with the state of the system environment, there is still a problem of reasonable allocation. In order to solve the problem of fair distribution, the literature [8] allocates cognitive user dynamic access strategies through the control center to improve access efficiency. However, a single channel can only access a single channel independently, which wastes the maximum utilization of spectrum resources to some extent. Therefore, the literature [9] [10] proposed a channel access strategy based on the two channel sensing protocol, which can sense two different channels in the same time slot, ensuring the quality of user service and improving the utilization of spectrum resources. This model only considers maximizing throughput under ideal conditions,
ignoring the problem that the probability of contention collision increases as the user accesses frequently.

In summary, this paper takes spectrum sensing and spectrum access as a whole, and proposes a new spectrum sensing and access mechanism for cognitive radio networks. This paper mainly investigates the impact of continuous sensing two channel and dynamic spectrum allocation mechanism on the whole network system in multi-user multi-channel cognitive radio networks. Through the research on user parameters and network performance, the simulation results are verified.

2. System Model

2.1. Network model

We consider a cognitive radio network scenario based on a well-established device that controls and determines the access requests of cognitive users and assigns policies to them. All networks operate in a synchronous time slot structure. It is assumed that the primary network consists of M non-overlapping grant channels, and the secondary users (SU) can only use these channels in channels that are not used by primary users (PU). There are N secondary users in the range of the base station. If the number of requests from the cognitive users exceeds the number M of authorized channels, only M secondary users in all access requests can be accepted, and other access requests will be accepted. Reject or queue up for access opportunities in the next time slot. In the network model in this paper, the influence of cognitive user queuing is not considered, and the number of channels is assumed to be not less than the number of SUs, that is, $M \geq N$.

2.2. Channel model

It is assumed that each channel in the primary network is identical in terms of bandwidth and fading characteristics. The occupancy state of the channel is modelled independently, and a two-state discrete-time Markov chain model can be used. This channel model has been widely used in the literature [11]. We use the status ON to indicate that the channel is occupied by the PU, and the status OFF indicates that the channel is not occupied by the PU. In addition, we assume that the PU starts transmission only when the time slot starts, and the channel state does not change in the current time slot. For any channel $j$, let $\alpha_j$ denote the transition probability from state ON to state OFF, and $\beta_j$ denote the transition probability from state OFF to state ON. We use $s_j(t)$ to represent the state of channel $j$ at time slot $t$, and then the two-state Markov chain transition probability matrix of channel $j$ can be expressed as:

$$
P_j(s_j(t+1)|s_j(t)) = \begin{pmatrix}
1 - \alpha_j & \alpha_j \\
\beta_j & 1 - \beta_j
\end{pmatrix}
$$

(1)

2.3. Network slot structure

Periodic spectrum monitoring has been widely recognized as an effective way to protect PUs from SU interference. As shown in Fig. 1, defining a slot structure consists of two phases: spectrum sensing and data transmission.

![Fig.1 Network slot structure](image-url)
Assume that the length of each time slot is represented by $T_S$. In the spectrum sensing phase, the duration of sensing a single channel is $\tau_\omega$. We use $i \in (1, 2, ..., N)$ to represent the index of a SU, and the time step is represented by $t (t=1, 2, ...)$. Using $g^1_i(t)$ and $g^2_i(t)$ to represent the 1st-choice channel and the 2nd-choice channel assigned to $SU_i$ in time slot $t$, respectively, then $G_i(t) = (g^1_i(t), g^2_i(t))$ represents the set of candidate channels assigned to $SU_i$. Based on the selection of the $k$th channel, the transmission duration $\tau_\tau$ can be expressed as

$$\tau_\tau = T_S - k \cdot \tau_\omega \quad (k = 1, 2)$$

3. Problem Formulation

Our goal is to find a sub-optimal policy. The primary access model is to sense and select a certain number of channels and dynamically allocate a single or two channel for each SU based on the belief vector. The channel selection problem can be described as a POMDP problem [12] or a robber multi-armed bandit (RMAB) [13] problem. Therefore, a simple myopic perceived access strategy is used instead to reduce the computational complexity. The goal of this strategy is to allocate channels to the SU in the same time slot to increase throughput and reduce collision probability.

We propose a two channel sensing dynamic spectrum access scheme based on Markov chain, which allows the SU sequence to perceive two channels with different priorities. First, we assign a unique first selection channel to the SU. Suppose we use $\xi = [\xi_1, \xi_2, ..., \xi_N]$ to indicate the probability that SU will successfully transmit on the 1st-choice channel. $\eta = [\eta_1, \eta_2, ..., \eta_N]$ is used to indicate the probability that SU is successfully transmitted on the 2nd-choice channel, and then the condition $\eta_j = 1 - \xi_j$ is satisfied for $SU_j$.

3.1. Network state

The vector $S(t) = [s_1(t), s_2(t), ..., s_M(t)]$ is defined as all channel states at time $t$, where $s_j(t) \in \{0, 1\}$. $s_j(t) = 1$ indicates that channel $j$ is busy, and $s_j(t) = 0$ indicates that channel $j$ is idle. Then we define the vector $M(t) = [m_1(t), m_2(t), ..., m_N(t)]$ as the SU state at time $t$, where $m_k(t) \in \{0, 1\}$. $m_k(t) = 1$ means $SU_k$ requests access, $m_k(t) = 0$ means $SU_k$ is idle.

Vector $A(t) = [a_1(t), a_2(t), ..., a_M(t)]$ is defined as the state of user behavior at time $t$, where $a_j(t) \in \{0, 1, 2\}$, $a_j(t) = 1$ indicates that channel $j$ is assigned as the 1st-choice channel, $a_j(t) = 2$ indicates that channel $j$ is assigned as the 2nd-choice channel, and $a_j(t) = 0$ indicates that channel $j$ is not allocated.

3.2. Belief vector

The base station will infer the channel state of the next time period based on past observation history. Thus the choice of the optimal strategy is a sufficient statistic given by the conditional probability that each channel is in the OFF state for all actions and observations in the past. We call this sufficient statistic the belief vector $\Omega(t) = \{\omega_1(t), \omega_2(t), ..., \omega_M(t)\}$, where $\omega_j(t)$ represents the conditional probability that channel $j$ is available at time $t$. In this paper, the system does not consider the priority of SU and the interference to the channel, so the belief vector $\Omega(t)$ is the same for all SUs. The update of the confidence vector depends on the user behaviour $a_j(t)$ and the system channel state $s_j(t)$. At time $t+1$, the confidence vector can be expressed as:

$$\omega_j(t + 1) = \begin{cases} 1 - \beta_j, & \text{if } a_j(t) = 1 \text{ or } 2, s_j(t) = 0 \\ a_j, & \text{if } a_j(t) = 1 \text{ or } 2, s_j(t) = 1 \\ Y(\omega_j(t)), & \text{if } a_j(t) = 0 \end{cases}$$

(3)

The first two cases in Equation (3) respectively indicate whether the channel is allocated as the 1st-choice channel or the 2nd-choice channel, and the conditional probability of the channel being idle is perceived. The last case is that when the channel is not pre-allocated, the channel belief vector of the next time slot cannot be directly judged by the channel state of the previous time slot, so it needs to be iteratively updated according to the belief vector of the previous time slot, as follows:
\[
\gamma(\omega_j(t)) = \omega_j(t) \cdot (1 - \beta_j) + (1 - \omega_j(t)) \cdot \alpha_j
\]  
(4)

For a given belief vector, the solution to its channel allocation problem is as follows. We define
\[ \psi = \{0,1,2\} \] as the channel assignment states, indicating unallocated, assigned as the 1st-choice channel and assigned as the 2nd-choice channel respectively. Then you can define the channel assignment matrix \[ \Phi = [\phi_{ij}]_{M \times N} \]
\[ \phi_{ij} \in \psi \]
\[ \forall i, if \phi_{ij} = 1, then \forall m \neq j, \exists \phi_{im} = 2 or (\sum_{m \neq j}^{M} \phi_{im} = 2) \]  
(5)
\[ \forall i,j, if \phi_{ij} = 1 or 2, then \forall k \neq i and \sum_{k \neq i}^{N} \phi_{kj} = 0 \]  
(6)

\[ \forall i, j, if \phi_{ij} = 1 or 2, then \forall k \neq i and \sum_{k \neq i}^{N} \phi_{kj} = 0 \]  
(7)

The above constraints are respectively indicated
- Equation (5) indicates that there are only three allocation states of the unassigned, 1st-choice channel, and 2nd-choice channel in the channel allocation matrix.
- Equation (6) indicates that when the SU allocates a certain channel as the 1st-choice channel, the other channel can be dynamically allocated as the 2nd-choice channel or remain unallocated.
- Equation (7) indicates the uniqueness of the selected channel. If selected as the first or 2nd-choice channel, it cannot continue to be perceived by other channels.

3.3. Channel sensing and access schemes

According to the network model, we proposed Markov Chain Based Dynamic Assignment of 2nd-Choice Channels (MCDA) scheme. In the time slot \( t \), the first \( n(t) \) channels are preferentially allocated as the 1st-choice channel. The remaining \( M - n(t) \) channels need to satisfy the dynamic allocation principle. If \( M - n(t) \geq n(t) \), the \( n(t) \) channels with the highest residual probability are selected; if \( M - n(t) < n(t) \), then select all remaining channels. The allocation is selected in the reverse order according to the 2nd-choice channel probability such that SU having a small probability of accessing the 1st-choice channel has a greater probability of accessing the 2nd-choice channel until the selected channel is allocated. After the SU sequentially accesses the 1st-choice channel, it selects whether to access the channel according to the perceived collision. If there is no SU successfully accessed, it is determined whether the second channel is allocated to the other channel, and if it exists, the second sensing access is performed. The user whose access fails will wait for the next moment to access.

In the MCDA scheme proposed above, we access all channels through the Overlay mode. When the number of SUs increases or the network is busy, the perceptual access to the full channel will not receive much effect. To solve this problem, combined with the hybrid access mode, Markov Chain Based Mix Dynamic Assignment of 2nd-choice Channels (MCMDA) scheme is proposed, and the probability threshold \( th \) is set in the system model. That is, the belief vector that we get iteratively updated at the beginning of each time slot is compared with the threshold value \( th \). If the belief vector value of channel \( j \) is greater than the threshold \( th \) in the time slot, the channel is classified as Overlay mode access. The channel is selected for allocation by the SU as the first/second sensing channel; and when the belief vector value is less than the threshold \( th \), the channel is classified into the Underlay mode access channel. In this type of channel, the SU does not consider whether the current channel is being occupied by the PU and is shared with the PU at a relatively low transmission rate.

The proposed MCMDA scheme is based on the MCDA scheme, based on which the adjustment changes are made by combining the hybrid access methods, so there is no change in the system network model, system state, confidence vector setting, and objective function. It is mainly adjusted on the distribution rules and the perception-access rules.

We divide the \( M \) channels into two types \( \{B_C, B_S\} \) according to the belief vector, which are respectively represented as channel sets whose belief vector value exceeds the threshold \( th \) and does not exceed, and respectively use \( M_C, M_S \) to represent the set size, that is, satisfy \( |B_C| = M_C, |B_S| = M_S, M_C + M_S = M \). Then, after the confidence vector is updated, let \( L_j(t) \in \{1,0\} \) denote the classification of channel \( j \) at time \( t \):
\[ L_i(t) = \begin{cases} 1, & \omega_j(t) \geq th \\ 0, & \omega_j(t) < th \end{cases} \]  

(8)

According to the relationship between the number of SU users and the number of channels in the current time slot, different allocation rules are sent to the SU. The following uses \( n \) instead of the number of user accesses at time \( t \):

- If \( M_C < n \), it means that the number of available Overlay channels is not enough to be allocated to the accessed SU as the 1st-choice channel, only according to \( \Gamma_0 = [\xi_1, \xi_2, ..., \xi_{M_C}] \). \( \xi_i \) indicates the probability that \( SU_i \) will successfully transmit on the 1st-choice channel. SU is allocated according to probability from large to small.

- If \( n \leq M_C < 2n \), the number of available Overlay channels is sufficient to be allocated to the accessed SU as the 1st-choice channel, but the 2nd-choice channel cannot be allocated for each SU. After allocating the 1st-choice channel according to the belief vector, the remaining \( M_C - n \) channels are used as the 2nd-choice channel set, and are allocated in reverse order according to the \( \Gamma \) vector probability until the channel allocation is completed.

- If \( M_C \geq 2n \), the number of available Overlay channels is sufficient to simultaneously allocate the SU to the access as the 1st-choice channel and the 2nd-choice channel.

3.4. Theoretical analysis

When the SU successfully senses that the channel is idle and accesses it, it can get the return benefit, that is, the system throughput. In this paper we assume that all channel properties and parameters are the same, with the same channel capacity \( C_0 \). Then, in a single time slot, the throughput obtained by channel \( j \) according to user behaviour \( a_j(t) \) and system channel state \( s_j(t) \) can be expressed as follows:

\[ r_j(t) = \begin{cases} \frac{T_S - \tau_S}{T_S} \cdot C_0, & \text{if } a_j(t) = 1, s_j(t) = 0 \\ \frac{T_S - 2\tau_S}{T_S} \cdot C_0, & \text{if } a_j(t) = 2, s_j(t) = 0 \\ E_S, & \text{if access to underlay} \\ 0, & \text{others} \end{cases} \]  

(9)

We can divide all channel sets \( W \) into three sub-sets \( \{W_1, W_2, W_3\} \), \( W_1 \) denotes the channel set assigned as the 1st-choice channel, \( W_2 \) denotes the channel set assigned as the 2nd-choice channel, and \( W_3 \) denotes the allocation A set of channels for the Underlay access mode. Assuming that the
number of SU accesses is \( n(t) \) at time \( t \), the expected throughput of the system on the 1st-choice channel is:

\[
\tau_j^1 = \sum_{i=1}^{n} \phi_{ij} \cdot \omega_j \cdot \frac{T_s - \tau_s}{T_s} \cdot C_0
\]

(10)

Since only part of the SU is assigned the second selection channel, we set \( \delta_{ij} \) to its flag:

\[
\delta_{ij} = \begin{cases} 
1, & \text{if } \phi_{ij} = 2 \\
0, & \text{if } \phi_{ij} \neq 2 
\end{cases}
\]

(11)

The expected throughput of the system on the 2nd-choice channel is:

\[
\tau_j^2 = \sum_{i=1}^{n} \delta_{ij} \cdot \omega_j \cdot \frac{T_s - 2\tau_s}{T_s} \cdot C_0
\]

(12)

The SU that is not assigned the 2nd-choice channel selects the Underlay channel access when the first perceived access fails. Then the expected throughput is:

\[
\tau_j^u = \min \left\{ \sum_{i=1}^{n} \phi_{ij} \cdot (1 - \omega_j), |W_s| \right\} \cdot E_s
\]

(13)

According to the actual situation, the system throughput of each time slot can be expressed as

\[
R_j(t) = \sum_{j \in W_1} \{s_j(t) == 1\} \cdot \frac{T_s - \tau_s}{T_s} \cdot C_0
+ \sum_{j \in W_2} \{s_j(t) == 1\} \cdot \frac{T_s - 2\tau_s}{T_s} \cdot C_0
+ \sum_{j \in W_3} \{s_j(t) == 0 \text{ and } a_j(t) == 1\} \cdot E_s
\]

(14)

In order to compare the performance of users in the cognitive network better, we define the average user throughput as

\[
\bar{R} = \frac{\sum_{t=1}^{T} R_j(t)}{\sum_{t=1}^{T} n(t)}
\]

(15)

4. Performance Analysis

The cognitive radio network has 20 channels, and the traffic pattern arrival and departure parameters \( \alpha \) and \( \beta \) for each channel are randomly generated values that are evenly distributed between 0.1 and 0.9. Similarly, the traffic pattern for each SU is the same as the channel. The results obtained from the average of 1000 simulation experiments were counted, and each test contained 1000 time slots. We assume that all channel characteristics are the same, and the channel capacity is also the same, set to
$C_0 = 1$ Mbps. Moreover, all SUs have the same sensing time for any channel, and the perceptual duration is defined as $1/10$ of the slot length, that is, $\tau_s = 0.1 \cdot T_s$.

For comparison, a Markov chain based channel assignment with single channel sensing (MCASC) scheme and a Markov chain based greedy assignment of 2nd-choice channels (MCGA) scheme are compared with MCDA scheme proposed in this paper. The MCASC scheme only allocates the 1st-choice channel for the accessed SU, and does not allocate the 2nd-choice channel. The MCGA scheme follows the greedy principle for the allocation of the 2nd-choice channel, and multiple SUs can compete for the same channel as the secondary selection. To prove the feasibility of the scheme, we define a Markov chain based single assignment of 2nd-choice channels (MCSA) scheme. Unlike the MCASC scheme, we specify a single channel as the second selection channel.

![Fig.2 Performance comparison with different SU quantity](image)

From the above Fig.2, the comparison of the average throughput and collision probability of different schemes under different SU numbers is obtained. Comparing the MCGA scheme with the MCDA scheme proposed in this paper, we can see from the figure that compared with the MCASC scheme, the average user throughput is considerably improved, and the collision probability is increased. Moreover, as the number of cognitive radio network users increases and the number of access requests increases, the competition of the MCGA scheme in the 2nd-choice channel is obviously the main reason for the increase in collision probability. The MCDA scheme proposed in this paper sacrifices a small amount of throughput, and the collision probability is significantly reduced. The increase in the number of cognitive users can be understood as the increase in the number of access requests and the frequency of access in the network system. Therefore, the average throughput of the two schemes will drop by 3% to 4%. When the number of users does not exceed 15, the system collision probability of MCGA scheme and MCDA scheme increases by 10.28% and 8.17%, respectively. When the number of users exceeds 15, the average percentage of system collision probability of the two schemes is 18.95% and 12.56%, respectively. Based on the experimental results, we can know that when we reduce the contention of the cognitive channel by the cognitive channel, the system collision probability is effectively reduced, and a small part of the throughput is sacrificed in exchange for better system service quality.

Our proposed MCMDA scheme is based on the MCDA scheme, so most of the experimental parameters are the same as the MCDA scheme. The two key experimental parameters of the MCMDA scheme are the probability threshold $th$ and the benefit result $E_B$ after SU accesses the Underlay channel. Here, in order to minimize the interference of SU on the PU, it is assumed in this experiment that $E_B = 0.1 C_0$. The size of the probability threshold $th$ determines the proportion of channel
allocation, and the network performance is analysed by comparing different thresholds. Here, we take simulation experiments with thresholds of 0.25, 0.3, and 0.35, respectively.

![Performance comparison with different threshold](image1)

From the simulation results, we can see that the difference in the probability threshold has a certain degree of influence on the performance indicators. From Fig.3(a), when the threshold is 0.25 and 0.3, the average user throughput of the MCMDA scheme is almost the same as that of the MCDA scheme, and it can almost reach a flat state. From Fig.3(b), the collision probability has a corresponding decline, and with the increase in the number of users, the downward trend is more obvious. When the threshold is 0.4, the number of available first/second selection channels will also decrease. Although the collision probability is more obvious than the MCDA scheme, the system throughput is sacrificed.

Under the premise of user saturation, the collision probability decreased by 4.3%, 6.69% and 10.83%, respectively, while the average user throughput decreased by less than 2% only when the threshold was 0.35. Compared with the above several schemes, it is considered that when the threshold \( \theta = 0.3 \), compared with the other two hybrid access schemes, there will be higher access transmission efficiency to meet the system QoS.

![Performance comparison with different schemes](image2)
Further comparison of the MCMDA scheme proposed in this paper and other scheme, we can conclude from the simulation results that the MCMDA scheme combined with the hybrid access mode can effectively improve the average throughput. Compared with the MCGA scheme, the average throughput and the MCDA scheme are almost the same. In the case that the average throughput gap is negligible, the system collision probability of the MCMDA scheme is more obvious than that of the MCDA scheme, and the network service quality is better.

5. Conclusion

This paper proposes a dynamic spectrum allocation access strategy based on two channel sensing, which considers the low access efficiency caused by traditional single channel sensing and the low quality of network service quality caused by two channel sensing greedy strategy.

An access strategy is designed to dynamically allocate the number of sensing channels according to the number of SU accesses. Then, in combination with the hybrid Overlay/Underlay access mode, different types of channels are distinguished in each time slot by setting a threshold value. The simulation results show that the two schemes can effectively reduce the collision probability of the system and achieve the compromise between system revenue and interference under the premise of sacrificing a small amount of throughput.

References
[1] Zhao Q, Geirhofer S, Tong L, et al. Opportunistic spectrum access via periodic channel sensing[J]. IEEE Transactions on Signal Processing, 2008, 56(2): 785-796.
[2] Q. Zhao, L. Tong, A. Swami, et al. Decentralized cognitive MAC for opportunistic spectrum access in Ad Hoc networks: a POMDP framework[J]. IEEE J. on Sel. Areas Commun., 2007, 25(3): 589-600
[3] Y. Chen, Q. Zhao, A. Swami. Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors[J]. IEEE Trans. Inf. Theory, 2008, 54(5): 2053-2071
[4] Su H, Zhang X. Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks[J]. IEEE Journal on selected areas in communications, 2008, 26(1).
[5] Ren B, Wang D, Cui W, et al. Subchannel allocation algorithm for cognitive systems based on collision probability constraints[J]. Journal of Terahertz Science and Electronics Information. 2013, 11(2): 228-233. (in Chinese)
[6] Wang L C, Wang C W, Adachi F. Load-balancing spectrum decision for cognitive radio networks[J]. IEEE Journal on Selected Areas in Communications, 2011, 29(4): 757-769.
[7] Lai L, El Gamal H, Jiang H, et al. Cognitive medium access: Exploration, exploitation, and competition[J]. IEEE transactions on mobile computing, 2011, 10(2): 239-253.
[8] Tumuluru V K, Wang P, Niyato D. A novel spectrum-scheduling scheme for multichannel cognitive radio network and performance analysis[J]. IEEE Transactions on Vehicular Technology, 2011, 60(4): 1849-1858.
[9] Lai J, Dutkiewicz E, Liu R P, et al. Dynamic spectrum access with two channel sensing in cognitive radio networks[C]//Communications (ICC), 2012 IEEE International Conference on. IEEE, 2012: 1757-1762.
[10] Lai J, Dutkiewicz E, Liu R P, et al. Opportunistic spectrum access with two channel sensing in cognitive radio networks[J]. IEEE transactions on mobile computing, 2015, 14(1): 126-138.
[11] Sansó, Brunilde, Frigon, JeanFrançois, Azarfar A. User-Differentiated Channel Recovery in Multi-Channel Cognitive Radio Networks[C]// Design of Reliable Communication Networks. IEEE, 2013.
[12] Ahmad S H A , Liu M , Javidi T , et al. Optimality of Myopic Sensing in 1 Multi-Channel Opportunistic Access[J]. IEEE Transactions on Information Theory, 2009, 55:4040-4050.
[13] Liu K , Zhao Q , Krishnamachari B . Dynamic multichannel access with imperfect channel state detection.[J]. IEEE Transactions on Signal Processing, 2010, 58(5):2795-2808.