Access Point Selection for WLANs with Cognitive Radio: A Restless Bandit Approach

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***Abstract*—In conventional WLANs, stations (STAs) select access points (APs) using the existing scheme based on the current quality of links. However, some novel improved architectures of WLANs are proposed with cognitive radio (CR) to negotiate spectrum usage, where the existing AP selection scheme might not be suitable for it. Thus in this paper, a new optimal AP Selection based on Restless Bandits (APSRB) scheme with the "indexability" property is proposed for WLANs with CR to maximize the throughput and to minimize the energy consumption. The AP selection problem is firstly established as a restless bandit problem, which is solved by the primal-dual index heuristic algorithm based on the first order relaxation with low complexity to yield APSRB scheme. Additionally, the APSRB scheme is divided into offline computation and online selection, where main work will be finished in former one so as to decrease the complexity further. Finally, extensive simulation results illustrate the significant performance improvement of the APSRB scheme compared to the existing one in different scenarios.**

***Index Terms*—WLANs, cognitive radio, access point selection, restless bandits.**

I. INTRODUCTION

Wireless local area networks (WLANs), as an effective and flexible wireless access method, has been widely deployed in offices, homes and public places, where the stations (STAs) can have high-speed access to the Internet at low cost via access points (APs). IEEE 802.11 WLANs share the industrial, scientific and medical (ISM) band with other devices such as microwave ovens, cordless phones, and Bluetooth and ZigBee devices to communicate with AP [1]. When a STA intends to access the Internet, there might be several potential APs nearby. The STA needs to select the most appropriate AP according to various criteria such as the radio environment. Accordingly, study of AP selection schemes is of interest.

A lot of work has been done on AP selection in WLANs. [2] presents an AP selection strategy for the association procedure in large-scale WLANs. The proposal considers the different node topologies among candidate Basic Service Sets (BSSs), considering the effects of hidden terminals due to their significant adverse impact on throughput. In [3], the authors present an AP selection strategy in the office environment covered by a WLAN and define a quality-of-service (QoS) based information element that is advertised by APs. On this basis, voice stations are able to select the AP which is associated with a less number of voice stations so as to achieve a lower call blocking probability. In [4], the authors propose an AP selection mechanism, called High-Rate First Association in order to achieve load balancing and the efficient use of radio resource. [5] proposes two effective AP selection algorithms which estimate the AP traffic load by observing and estimating the IEEE 802.11 frame delays and use the results to determine which AP to use. [6] proposes an AP selection scheme to achieve overall load balancing and optimum resource utilization in the network. In [7], the authors address the joint problem of AP selection and channel assignment with the objective to satisfy a given user load vector with the minimum number of channels. To sum up, most of the previous studies let STAs select APs based on the current traffic load and link quality.

Since the ISM-band devices are operated independently, it is difficult for traditional WLANs to negotiate the radio frequency (RF) spectrum usage with them. Thus, some novel improved architectures of WLANs are proposed with Cognitive Radio (CR) to cope with this problem [8][9][10]. As WLANs with CR can sense the RF environment more effectively than conventional WLANs, the existing AP selection schemes might be improved. Accordingly, in this paper, we formulate the AP selection problem for WLANs with CR as a restless bandit problem, which is solved by the primal-dual index heuristic algorithm based on the first order relaxation. This yields the proposed AP Selection based on Restless Bandits (APSRB) scheme. The distinct features of this scheme are as follows.

- APSRB has an indexability property that dramatically reduces computations and simplifies its implementation. A STA simply selects among the potential APs one that has with lowest index.
- The objectives of APSRB are not only to maximize the throughput of each STA, but also to minimize energy consumption during the transmissions.
- APSRB not only considers the current reward, but also takes long-term reward into account.
- APSRB works in a distributed manner. There is no need for AP or WLAN controller to control the selection of all the STAs. Each STA selects its AP independently. Thus the proposed scheme is distributed and scalable.

- According to extensive simulation results, APSRB significantly improves the performances of throughput and energy consumption, compared to the existing AP selection methods in different scenarios.

The rest of this paper is organized as follows. Section II introduces the system model and the AP selection problem. This problem is formulated as a restless bandit problem and solved in Section III. Section IV details the process of APSRB. Extensive simulation results are provided in Section V to compare the performance of APSRB with existing methods, and Section VI concludes this study.

II. System Model

This section reviews the throughput model based on distributed coordination function (DCF), and describes the AP selection problem in WLANs with CR.

A. Throughput of DCF Protocol

Since DCF based on carrier-sensed multiple access with collision avoidance (CSMA/CA) is the basic access protocol supported by all 802.11 compliant devices, we consider that STAs access APs using DCF. DCF has been modelled in [11] to derive the throughput. It is assumed that there are K STAs sharing a channel. In a fully loaded system the probability τ that a STA attempts a transmission in a time slot can be deduced by the following equations

$$\tau = \frac{2\left(1-2p\right)}{\left(1-2p\right)\left(W+1\right)+pW\left(1-\left(2p\right)^{K}\right)} \tag{1}$$

$$p = 1-\left(1-\tau\right)^{K-1} \tag{2}$$

where W is the minimum contention window and p is the probability of collision. Thus the throughput of the k-th STA can be represented as

$$R_k = QL_k = \frac{\tau\left(1-\tau\right)^{K-1}L_k}{\sigma P_{\text{idle}}+T_s P_{\text{succ}}+T_c\left(1-P_{\text{idle}}-P_{\text{succ}}\right)} \tag{3}$$

where σ is the slot duration, T_s is the duration of a successful transmission and T_c is the duration of a collision, $P_{\text{idle}} = \left(1-\tau\right)^{K}$ and $P_{\text{succ}} = K\tau\left(1-\tau\right)^{K-1}$. L_k is the frame payload size of the k-th STA in bits. Obviously, Q is a function of K, which can be denoted as $Q\left(K\right)$.

B. AP Selection Problem

In this paper, we suppose that an extended service set (ESS) consists of several APs with CR function. Every AP select one channel according to the existing channel assignment scheme such as the theory regarding graph coloring or regulation of the least congested channel search (LCCS)[12]. Compared with the conventional AP, each AP with CR has additional intelligence to collect the state information of itself and to estimate the state transition probabilities based on historical observations [8][10].

When a STA intends to access this ESS, we assume that it has N available APs, which are denoted as $\mathbf{N} = \{1,2,\cdots N\}$. The service duration is divided into T equal-length epochs, and we assume T is large enough to be considered as infinite. At the beginning of the each epoch, every AP sends its state to this STA through the beacon broadcast. In the residual time of each epoch, according to these states, the STA independently selects the most appropriate M APs to transmit the data. If the STA is conventional, it can utilizes only one channel simultaneously, namely $M = 1$. If the novel STA is designed to use more than one channel (or AP) synchronously and APs work corporatively with each other, we will set that $M > 1$. Thus the AP selection problem in the uplink is how the STA selects the M APs from $\mathbf{N}$ according to their states in each epoch, in order to optimize some given objectives. The state of AP we consider includes

- The quantity of serviced STAs in each AP.
- The interference from ISM devices to each AP.
- The channel gain between this STA and each AP.

The objectives are

- To maximize the throughput of this STA.
- To minimize energy consumption during the transmission.

In this AP selection problem, each STA distributedly selects its APs not only considering the current states of them, but also taking into account the transition probability of each state, which is suitable to be established as a restless bandit problem that provides a powerful modeling framework in clinical trials, aircraft surveillance, worker scheduling and so on [13]. The problem formulation will be discussed in the following section.

III. Restless Bandit Formulation

In this section, the AP selection problem mentioned above is modeled as a restless bandit problem. And then the primal-dual index heuristic algorithm is used to solve this problem.

A. Action of Each AP

We assume $a_n\left(t\right)$ to be the action of the n-th AP in the t-th epoch, where $n \in \mathbf{N} = \{1,2,\cdots N\}$, $t \in \mathbf{T} = \{1,2,\cdots T\}$ and $a_n\left(t\right) \in \mathbf{A} = \{0,1\}$. $a_n\left(t\right) = 1$ means that the n-th AP is active (or selected) in the t-th epoch, while $a_n\left(t\right) = 0$ means that it is passive (or not selected). Thus the actions of APs need to satisfy the following equation

$$\sum_{n=1}^{N} a_n\left(t\right) = M \tag{4}$$

B. State and Transition Probability

The state of the n-th AP includes quantity of STAs, ISM interference and channel gain.

During the t-th epoch, the quantity of STAs in the n-th AP is defined as $\xi_n\left(t\right) \in \mathbf{C}_n = \{0,1,\cdots,C_{\max}^n\}$, where $C_{\max}^n$ is the maximum number of STAs according to the history information. Thus, $\xi_n\left(t\right)$ is modeled as a stochastic variable, evolving according to a finite-state Markov chain. The state transition probability matrix with action a can be represented as $\mathrm{O}_n^a(t) = \left[o_{g_n h_n}^a(t)\right]_{C_{\max}^n \times C_{\max}^n}$, where

$$o_{g_n h_n}^a(t) = \Pr\left\{\xi_n(t+1) = h_n \middle| \xi_n(t) = g_n, a_n(t) = a\right\} \tag{5}$$

and $g_n, h_n \in \mathbf{C}_n,\ a \in A$. $\mathrm{O}_n^a(t)$ can be obtained by the history information of record. If the traffic is modeled as Poisson process, it can also be calculated with the continuous time Markov chain (CTMC).

The interference from other ISM-band devices to AP can be modeled as a Markov chain by dividing the continuous interference state into discrete levels for simplification [14]. We assume the interference of the n-th AP in the t-th epoch to be a stochastic variable $\eta_n(t)$ evolving according to a finite-state Markov chain, which is characterized by a set of states $\mathbf{D}_n = \{d_1, d_2, \cdots, d_D\}$, where D is the quantity of available interference state levels. The number of discrete levels is not specified. A less-discrete level number may reduce the complexity, whereas a larger quantity may enhance the accuracy. Thus, the transition probability matrix of the state with action a can be represented as $\Psi_n^a(t) = \left[\psi_{x_n y_n}^a(t)\right]_{D\times D}$, where

$$\psi_{x_n y_n}^a(t) = \Pr\left\{\eta_n(t+1) = y_n \middle| \eta_n(t) = x_n, a_n(t) = a\right\} \tag{6}$$

and $x_n, y_n \in \mathbf{D}_n,\ a \in A$. The values in the interference state transition probability matrix can be obtained by the history information of sensing in CR.

Block fading channel will be considered in this paper, which is also modeled as a Markov chain by dividing the continuous interference state into discrete levels for simplification. We denote the channel gain as $\varsigma_n(t)$, where the states are assumed to be $\mathbf{E}_n = \{e_1, e_2, \cdots, e_E\}$. Thus, the transition probability matrix can be represented as $\Phi_n(t) = [\varphi_{i_n j_n}(t)]_{E\times E}$, where

$$\varphi_{i_n j_n}(t) = \Pr\left\{\varsigma_n(t+1) = j_n \middle| \varsigma_n(t) = i_n\right\} \tag{7}$$

and $i_n, j_n \in \mathbf{E}_n$. For Rayleigh fading channels, $\varphi_{i_n j_n}(t)$ can be approximated as [15]

$$\varphi_{i_n j_n}(t) \approx \begin{cases} \dfrac{\sqrt{\frac{2\pi\Gamma_{i_n}}{\Gamma}}\mathrm{e}^{\left(-\frac{\Gamma_{i_n}}{\Gamma}\right)}T_P}{\mathrm{e}^{\left(-\frac{\Gamma_{j_n}}{\Gamma}\right)}-\mathrm{e}^{\left(-\frac{\Gamma_{i_n}}{\Gamma}\right)}} \text{ if} \begin{cases} i_n = j_n + 1, \\ 1 \le j_n \le E-1 \end{cases} \\ \dfrac{\sqrt{\frac{2\pi\Gamma_{j_n}}{\Gamma}}\mathrm{e}^{\left(-\frac{\Gamma_{j_n}}{\Gamma}\right)}T_P}{\mathrm{e}^{\left(-\frac{\Gamma_{j_n}}{\Gamma}\right)}-\mathrm{e}^{\left(-\frac{\Gamma_{i_n}}{\Gamma}\right)}} \text{ if} \begin{cases} i_n = j_n - 1, \\ 2 \le j_n \le E \end{cases} \end{cases} \tag{8}$$

where Γ_{i_n} and Γ_{j_n} are the SNR corresponding to the state i_n and j_n, $\overline{\Gamma}$ is the expected SNR and T_p is the packet duration.

Thus, the state of the n-th AP can be model as $\omega_n(t) = [\xi_n(t), \eta_n(t), \varsigma_n(t)]$, where $\omega_n(t) \in \Omega$. And its transition probability matrix can be shown as

$$\Pi_n^a(t) = \left[\left(o_{g_n h_n}^a(t), \psi_{x_n y_n}^a(t), \varphi_{i_n j_n}(t)\right)\right]_{L\times L} \tag{9}$$

where $L = C \times D \times E$.

C. System Reward

The system rewards in this paper are to maximize the throughput and to minimize the energy consumed. The frame payload must be beyond a threshold $\bar{L}$ to satisfy the request of the minimum throughput, according to the quality of service (QoS) demands. Namely,

$$L_n = B_n T_s \log_2\left(1 + \frac{\varsigma_n(t) P_n}{\eta_n(t) + N_0}\right) \ge \bar{L} \tag{10}$$

where B_n is the bandwidth of the channel in n-th AP, P_n is the transmission power and N_0 is the power spectrum density of Additive White Gaussian Noise (AWGN). And the minimum transmission power can be deduced as

$$P_{\min}^n = \frac{1}{\varsigma_n(t)}\left(\eta_n(t) + N_0\right)\left(2^{\frac{\bar{L}}{B_n T_s}} - 1\right) \tag{11}$$

Thus, the system reward consists of throughput and energy consumption, which can be represented by

$$\begin{cases} R_{\omega_n}^1 = \tau_1 Q\left(\xi_n(t)\right)\bar{L} - \tau_2 T_s P_{\min}^n \\ R_{\omega_n}^0 = 0 \end{cases} \tag{12}$$

where $\omega_n(t) \in \Omega$, τ_1 and τ_2 are the weights of throughput and energy consumption, and $\tau_1 + \tau_2 = 1$.

D. Problem Formulation

The set of admissible policies is denote as Z. The scheduling policy $\zeta \in \mathrm{Z}$ is $[a_n(t)]_{T\times N}$, where the element $a_n(t)$ represents the action taken by the n-th AP in the t-th epoch. The time discount factor for the rewards is set to be β, where $0 < \beta < 1$. Accordingly, the AP selection problem is to find an optimal scheduling policy that maximizes the total expected discount reward over an infinite horizon, which can be represented as

$$\begin{aligned} &\max_{\zeta\in\mathrm{Z}} E_\zeta\left[\sum_{t=1}^{T}\left(\sum_{n=1}^{N} R_{i_n}^{a_n(t)}(t)\right)\beta^t\right], \\ &\text{s.t.} \\ &\sum_{n=1}^{N} a_n(t) = M, \\ &\pi_{i_n j_n}^a(t) = \Pr\left\{\omega_n(t+1) = j_n \middle| \omega_n(t) = i_n, a_n(t) = a\right\} \end{aligned} \tag{13}$$

where $i_n, j_n \in \Omega$. This problem is a representative restless bandit problem, which will be solved in the following subsection.

E. The Primal-Dual Index Heuristic Algorithm

The restless bandit problem mentioned above can be solved by the primal-dual index heuristic algorithm based on the first order relaxation, which has been demonstrated to have less complexity and very close performance compared to the optimal one [16].

The primal-dual index heuristic algorithm first deduces the first-order relaxation of the restless bandit problem and its corresponding dual problem, where details can be found in [16]. As both primary and dual problems are linear program problem, they can be solved by the classical algorithm such as simplex search method. We denote $\left\{\bar{\chi}_{i_n}^{a_n}\right\}$ and $\left\{\bar{\lambda}_{i_n}, \bar{\lambda}\right\}$ as the optimal solution of primal and dual problems respectively. Therefore, the corresponding optimal reduced cost coefficients can be represented as

$$\bar{\gamma}_{i_n}^0 = \bar{\lambda}_{i_n} - \beta \sum_{j_n \in \Omega} \pi_{i_n j_n}^0 \bar{\lambda}_{j_n} - R_{i_n}^0, \tag{14}$$

$$\bar{\gamma}_{i_n}^1 = \bar{\lambda}_{i_n} - \beta \sum_{j_n \in \Omega} \pi_{i_n j_n}^1 \bar{\lambda}_{j_n} + \bar{\lambda} - R_{i_n}^1, \tag{15}$$

where $\bar{\gamma}_{i_n}^0, \bar{\gamma}_{i_n}^1 \geq 0$. $\bar{\gamma}_{i_n}^0$ and $\bar{\gamma}_{i_n}^1$ mean the rates of decrease in the objective value of the primal problem per unit increase in the value of the variable $\chi_{i_n}^0$ and $\chi_{i_n}^1$ respectively. Here we define δ_{i_n} as the index for the n-th AP when it is in state $i_n \in \Omega$, which is shown as

$$\delta_{i_n} = \bar{\gamma}_{i_n}^1 - \bar{\gamma}_{i_n}^0 \tag{16}$$

Accordingly, in each epoch, the STA calculates the indices of all the APs according to their states. And the M APs that have the smallest indices are set active or selected. The details of this APSRB scheme will be explicated in the next section.

IV. Process of APSRB Scheme

In this section, we first introduce the steps of APSRB scheme. And then communication overhead and computational complexity of this scheme are analyzed.

A. The Steps of the APSRB Scheme

The steps of this scheme are divided into offline computation and online selection. In the offline stage:

Step 1: Based on the history information of sensing in CR, each AP estimates its transition probability Π_n^a and the reward $R_{\omega_n}^a$, where $\omega_n \in \Omega$ and $a \in A$, and send them to the STA through the beacon broadcast.

Step 2: The STA offline calculates the indices of all the states according to the approach mentioned in section III, and stores them in the indices table.

In the online stage:

Step 3: At the beginning of each epoch, every available AP estimates the state of itself and transmits the state information to STA through the beacon broadcast.

Step 4: According to these states, the STA lookups the indices table to find out the corresponding index. The M APs that have the smallest indices are selected for this STA.

B. Analysis of Overhead and Complexity

The communication overhead is the necessary information exchange between AP and STA. In APSRB scheme, the overhead are divided into two parts. One is the information for indices table in offline stage, which occurs only one time at the beginning of transmission. The other is the state information of the available APs for the STA in each epoch, which can be encoded into sequence. Therefore, communication overhead in this scheme is light compared with the data transmission.

The process of selection is divided into offline computation and online selection. The indices table can be computed and stored in the offline stage. What the STA needs to do online is just to lookup the table, which causes little burden of calculation. Accordingly, the computation complexity of the APSRB scheme is not high.

V. Simulation Results and Analysis

In this section, extensive simulation results are illustrated to compare the performance between the APSRB scheme and the existing scheme, where the existing scheme selects AP based on the current quality of links.

The parameters in the simulations are chosen based on the ones widely adopted as follows [8] [11] [16]. There are 12 APs to cover a 200-by-200 m^2 service area. STAs are uniformly placed in this area. All the wireless channels in the simulations are assumed to be Rayleigh fading without inter symbol interference. Direct sequence spread spectrum (DSSS) is adopted in the physical layer. Thus, W is 32 and σ is 20us according to corresponding standard. Both T_s and T_c are assumed to be 944us. The bandwidth of the channel B_n is assumed to be 20 MHz. β is set to be 0.8 and τ_1 and τ_2 are set to be 0.5. Background Noise N_0 is assumed to be -117 dBm.

A. Improvement of Throughput

In Fig. 1, we run the simulation for 5000 seconds and set $N = 6$. From this figure, the average throughput of the APSRB scheme improved significantly compared to the existing one. When $M = 1$, the average throughput of STAs is around 3.4 Mbps in the existing scheme while it is around 4.4 Mbps in the APSRB scheme. Additionally, the improvement of the APSRB scheme is also over 1 Mbps when $M = 2$. The APSRB scheme not only considers more factors regarding the throughput than existing scheme such as load, interference in ISM band and radio environment, but also considers states of the factors and the transition probabilities of them, while existing scheme only takes the current state of link into account. That is why the throughput of the proposed scheme is higher than the existing one.

Fig. 2 compares the throughput performance between the APSRB scheme and the existing scheme in different N. Form this picture, we can found out that the APSRB scheme is superior to the existing one in different M and N, which ought to be ascribed to the same reason as Fig. 1. Additionally, with the increment of N, the rate of throughput rise in proposed scheme is higher than the existing one, which should be ascribe to the fact that the proposed scheme optimize the long-term reward according to the transition probability and larger value of N provides bigger room of selection.

B. Improvement of Energy Consumption

In Fig.3, the performances of energy consumption between the APSRB scheme and the existing scheme are revealed. In these simulations, we set N to be 6, and use normalized initial energy. According to the results in this picture, the energy of the existing scheme run out earlier than the proposed scheme in different M. In each epoch, the proposed scheme selects AP that cost less energy according to the radio environment, while the existing scheme does not consider the energy consumption, which is responsible for this phenomenon.

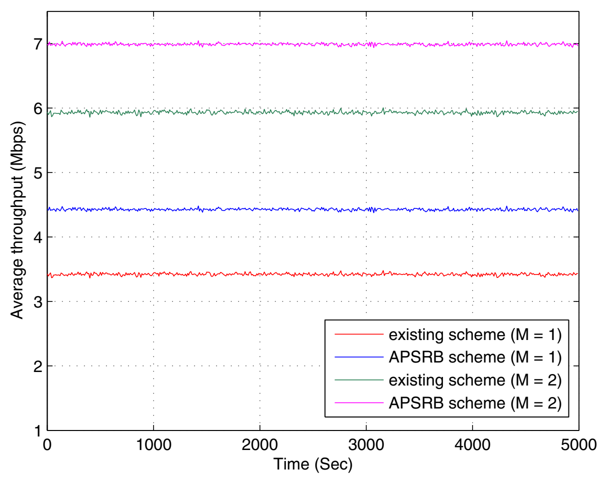

Fig. 1. The throughput performance improvement ($N = 6$)

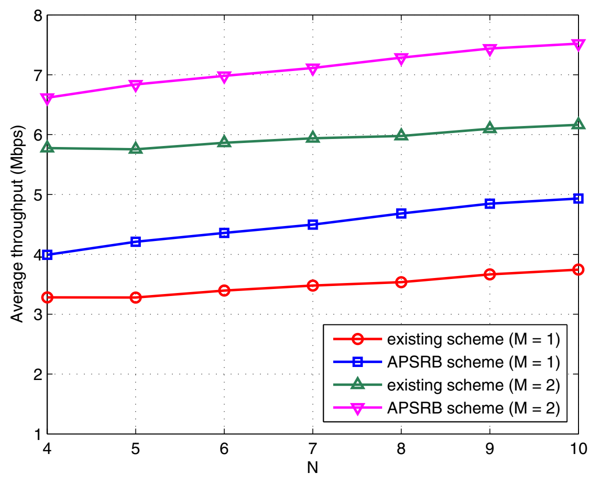

Fig. 2. The average throughput with different available APs

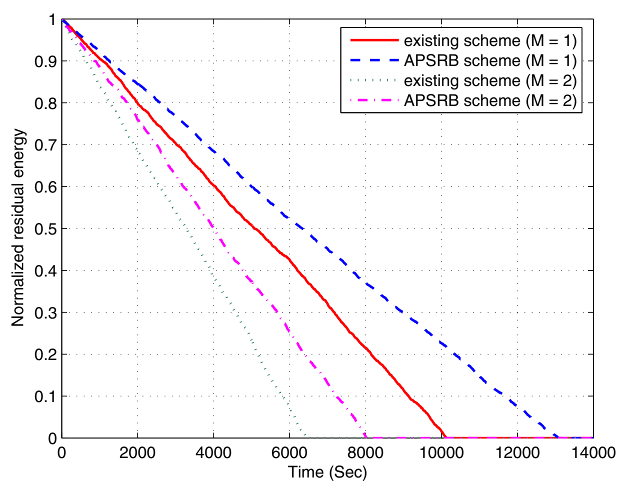

Fig. 3. Energy consumption of different AP selection schemes ($N = 6$)

VI. Conclusions

In this paper, we focused on the AP selection problem for WLANs with CR. We first modeled the AP selection problem as a restless bandit problem, which is solved by the primal-dual index heuristic algorithm based on the first order relaxation to form the APSRB scheme. In addition, the proposed scheme is divided into offline computation and online allocation, where main work will be finished in former one so as to decrease the complexity. Finally, extensive simulation results illustrated the significant performance improvement of APSRB scheme compared to the existing one in different scenarios.

Acknowledgment

This paper is jointly sponsored by National Natural Science Foundation under Grand 60832009, Beijing Municipal Natural Science Foundation under Grand 4102044, and National Youth Science Foundation under Grand 61001115.

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