A Novel Energy Saving Strategy with N-Policy Sleep Mode in Cognitive Radio Networks

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Abstract

Energy consumption is significant even when the base station is idle in traditional cognitive radio networks. Taking into account both the energy saving in the base station and the latency of the secondary user packets, we propose an energy saving strategy with N-policy sleep mode in this paper. From the perspective of an overlay structure, we establish a two-dimensional continuous-time Markov chain model to capture the stochastic behavior of the proposed strategy. The stable condition of the system is obtained accordingly. Using the method of matrix geometric solution method, we derive the performance measures, such as energy saving rate of system and average latency of secondary user packets. Moreover, we provide simulation statistics as well as analysis results to verify the effectiveness of the proposed strategy and the accuracy of the performance estimation. Finally, we present an artificial bee colony algorithm to optimize the sleep parameter in the proposed strategy.

Keywords: Artificial bee colony algorithm, Cognitive radio networks, N-policy, Overlay, Sleep mode

1 Introduction

Cognitive radio network (CRN), which can effectively realize dynamic spectrum access, has been proposed as a promising technology to solve the spectrum scarcity problem. Recently, CRN has become one of the most important topics and have triggered a significant amount of research [1-2]. With the worldwide growth of the number of mobile terminals and the request for higher data rates, energy consumption on the base station (BS) in CRNs increases tremendously at a staggering rate [3-4]. In this paper, we focus on the energy saving strategy in CRNs with the constraint of response performance.

Existing works of CRN focus on two transmission modes, namely underlay and overlay, respectively [5].

For the underlay CRN, the secondary user (SU) packets share the licensed spectrum assigned to the primary user (PU) packets under a tolerable interference level at any time. On the basis that SU receivers below a predefined threshold harvest the ambient radio frequency energy, Louis et al. derived the analytical expression of average energy harvesting [6]. Considering that the channel state information is not often accurate in practical systems, Wang et al. investigated the robust energy efficiency maximization problem and adopted the worst-case optimization approach to ensure the quality of service (QoS) of PUs [7].

For the overlay CRN, SU packets can access the licensed spectrum only when it is not occupied by PU packets. Combining QoS-aware flow control, routing selection, channel and power allocation, Teng et al. proposed an energy efficiency heuristic algorithm for cross-layer optimization [8]. By exploiting limited automatic repeat request feedback from the secondary destination, Chao et al. showed that the energy consumption of the secondary system can be effectively reduced [9]. With the constraint of link maintenance probability, Wu et al. designed the optimal time length of channel sensing sequence to obtain the maximum energy efficiency [10]. To achieve the optimal performance tradeoff between individual fairness and network energy efficiency, Yang et al. proposed a general cooperative game-theoretical scheme [11].

From the literatures mentioned above, we see that in most studies relating to energy saving, the BS is supposed to be awake even though the system is idle.

In some networks, such as IEEE 802.16e network, cellular networks and so on, BS is set to sleep state to reduce energy consumption when BS is idle. In [12], Chen et al. investigated the topology architecture, namely random cluster head and sub-cluster head with sleep mode (RCHSCHSM). They developed a sleep

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mode for sensor nodes based on correlations among sensor data within cub-clusters in RCHSCHSM. In [13], Zhao et al. designed a BS sleeping protocol in software-defined radio access networks and presented an implementation proposal with a threshold-based algorithm. In [14], considering power consumption, area spectral efficiency, coverage and overlap, Prabhu et al. carried out a multi-objective optimization framework for energy saving in an OFDMA based cellular networks. In these literatures, sleep mode is demonstrated to be a straightforward and valid way to save energy in wireless networks. However, the sleep mode has not widely applied in CRN.

For the purpose of reducing energy consumption on BS in the overlay CRN, in this paper, we propose an energy saving strategy with N-policy sleep mode. N-policy is proposed to decrease the response time of SU packets. With the queueing theory [15-17] widely used in performance evaluation of communication networks, we establish a priority stochastic model with N-policy vacation to capture the proposed strategy. In order to balance the tradeoff between the energy saving rate of the system and the average latency of SU packets, we give an artificial bee colony algorithm to optimize the sleep parameter.

The remainder of the paper is organized as follows. In Section 2, we propose a novel energy saving strategy and build a two-dimensional continuous-time Markov chain model [18-19]. In Section 3, after discussing the stable condition of the system, we derive the steady-state probability distribution of the system model. With statistical experiments, we estimate the system performance in Section 4. In Section 5, we optimize the sleep parameter with an artificial bee colony algorithm. Finally, conclusions are drawn in Section 6.

2 System Model

In this section, we propose a novel energy saving strategy with N-policy sleep mode, and then establish a Markov chain model accordingly.

2.1 Energy Saving Strategy with N-Policy Sleep Mode

In conventional CRNs, BS keeps awake even though neither PU packets nor SU packets need to be transmitted, thus a great deal of energy is wasted. Aiming to reduce the energy consumption in BS, we propose a novel energy saving strategy with N-policy sleep mode. Moreover, we consider only one licensed spectrum in overlay CRNs. We note that PU packets have preemptive priority to SU packets, we assume that the transmission of PU packets is not affected by SU packets' behavior [20]. Considering the response performance of SU packets, we assume that when the number of SU packets reaches N $(N=1,2,\cdots)$, we call N as threshold, the sleep period will be terminated ahead of time, i.e., the BS will enter awake state from sleep state, all the accumulated packets will be transmitted one by one.

According to the stochastic behavior of PU packets and SU packets, as well as the working principle of a sleep timer and N-policy, BS will be switched among sleep state, awake state and listening state. Figure 1 illustrates the state transition of BS in the novel energy saving strategy.

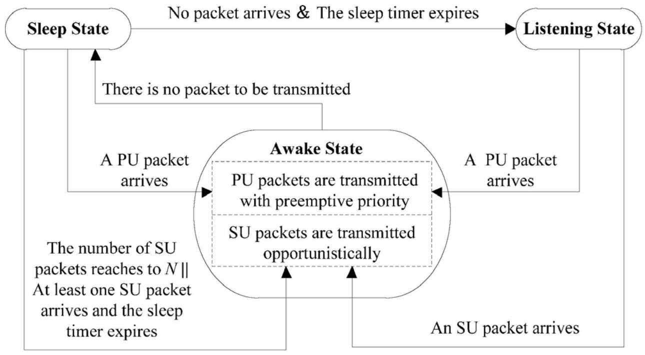


Figure 1. The State Transition of BS

In Figure 1, there are some issues to be highlighted as follows:

(1) In this proposed strategy, what is noteworthy is that a buffer with infinite capacity is provided for SU packets and no buffer is prepared for PU packets. If the licensed spectrum is being occupied when SU packets arrive at the system, those newly arriving SU packets will queue in the buffer following first in first out (FIFO) discipline and wait for future transmission. When all the packets are transmitted, i.e., there is no any packet in the system, BS will be switched to sleep state.

(2) The sleep timer will be started once BS is switched to sleep state. Moreover, we assume that the time length of the sleep timer is a random value given as a system parameter. As is shown in Figure 1, if there is a PU packet arrival or the number of SU packets reaches the threshold N, the sleep timer will be terminated immediately and BS will be switched to awake state. When there is no packet arrival during the sleep period, BS will be switched to listening state when the sleep timer expires.

(3) BS can be switched to listening state only from sleep state. In listening state, BS will listen to the licensed spectrum continuously until any packet arrives at the system, then BS will be switched to awake state.

(4) In awake state, the licensed spectrum can be occupied by a PU packet or an SU packet. PU packets are transmitted with the preemptive priority, while SU packets can only access the licensed spectrum opportunistically. The transmission procedure of those two types of packets is described here.

Transmission of a PU packet. Once a PU packet occupies the licensed spectrum, the transmission of this

PU packet will be definitely completed. During the transmission procedure of this PU packet, if another PU packet arrives at the system, this newly arriving PU packet will be blocked, since no buffer is prepared for PU packets.

Transmission of an SU packet. If an SU packet occupies the licensed spectrum, the transmission of this SU packet is possible to be interrupted by arriving PU packets. During the transmission procedure of an SU packet, if there is a PU packet arrival, the newly arriving PU packet will interrupt the transmission of this SU packet, and this interrupted SU packet will be discarded. As long as there is no PU packet arrival, the transmission of this SU packet will be completed.

It is clear that in this novel energy saving strategy with N-policy sleep mode, not only the energy consumption can be reduced, but also the transmission procedure of PU packets and the response performance of SU packets can be guaranteed.

2.2 Markov Chain Model

Considering the continuous-time structure, we assume that the arrivals of SU packets and PU packets follow Poisson processes with parameters λ_{su} $(\lambda_{su} > 0)$ and λ_{pu} $(\lambda_{pu} > 0)$ respectively, and the transmission times of an SU packet and a PU packet follow exponential distributions with parameters μ_{su} $(\mu_{su} > 0)$ and μ_{pu} $(\mu_{pu} > 0)$ respectively. Specifically speaking, the arriving intervals and transmission times for both of SU and PU packets are independent, identically distributed (i.i.d) random variables. In addition, we assume the time length ξ of the sleep timer to follow exponential distribution with parameter θ $(\theta > 0)$. It is obvious that the average time length $E[\xi]$ of the sleep timer is $\frac{1}{\theta}$.

We define the total number of SU packets in the system as the system level, the BS state combining with the spectrum condition as the system stage. Let $X(t) = i$ $(i \geq 0)$ be system level at the time instant t, and $Y(t) = j$ $(j = 0,1,2,3)$ be the system stage at the instant t. For the system stage, $j = 0$ represents BS is sleep; $j = 1$ represents BS is awake and a PU packet is being transmitted on the licensed spectrum; $j = 2$ represents BS is awake and an SU packet is being transmitted on the licensed spectrum; $j = 3$ represents BS is idle, that is BS is in listening state. $\{X(t),\ Y(t),\ t \geq 0\}$ constitutes a two-dimensional Markov chain. The state space for this Markov chain is given as follows:

$$\Omega = \{(i, j) : i \geq 0, j = 0,1,2,3\}$$

Let $\pi_{i,j}$ be the steady-state distribution of the two-dimensional Markov chain. $\pi_{i,j}$ is given as follows:

$$\pi_{i,j} = \lim_{t \to \infty} P\{X(t) = i, Y(t) = j\}, i = 0,1,2\ldots, j = 0,1,2,3.$$

2.3 System Stable Condition

The necessary and sufficient condition for the system to be stable is that the traffic intensity ρ of the system is less than 1.

From the perspective of PU packets, the traffic intensity ρ_{pu} of PU packets is the probability that the licensed spectrum is being occupied by a PU packet.

We notice that the steady-distribution of PU packets can be obtained from an ON/OFF model [21]. When a PU packet is being transmitted, we say the licensed spectrum is in ON state, otherwise, we say the licensed spectrum is in OFF state. The probability π_{on} that the licensed spectrum being in ON state is just the traffic intensity ρ_{pu} of PU packets. So ρ_{pu} can be given as follows:

$$\rho_{pu} = \frac{\lambda_{pu}}{\mu_{pu} + \lambda_{pu}} \tag{1}$$

The traffic intensity ρ_{su} of SU packets is the probability that the licensed spectrum is being occupied by an SU packet. Let T be the arriving interval of PU packets, S be the transmission time of an SU packet without interruption. Let P_I be the probability that the transmission of an SU packet is interrupted by the arrival of a PU packet. P_I is then given as follows:

$$P_I = P\{T < S\} = \int_0^{\infty} \int_0^{x} \lambda_{pu} e^{-\lambda_{pu} y} dy \mu_{su} e^{-\mu_{su} x} dx = \frac{\lambda_{pu}}{\mu_{su} + \lambda_{pu}} \tag{2}$$

From the perspective of the traffic intensity ρ_{su} of SU packets, P_I can also be given as follows:

$$P_I = \rho_{su} \frac{\lambda_{pu}}{\lambda_{su}} \tag{3}$$

From Eqs. (2) and (3), the traffic intensity ρ_{su} of SU packets can be given as follows:

$$\rho_{su} = \frac{\lambda_{su}}{\mu_{su} + \lambda_{pu}} \tag{4}$$

Combining the traffic intensity ρ_{pu} of PU packets given in Eq. (1) and the traffic intensity ρ_{su} of SU packets given in Eq. (4), we can obtain the traffic intensity ρ of the system as $\rho = \rho_{pu} + \rho_{su}$. When the traffic intensity ρ of the system is less than 1, the system will reach a steady state. So the system stable condition is

$$\frac{\lambda_{pu}}{\mu_{pu}+\lambda_{pu}}+\frac{\lambda_{su}}{\mu_{su}+\lambda_{pu}}<1 \quad \textbf{(5)}$$

3 System Analysis

We define $\mathbf{Q}$ as one step state transition rate matrix of the $\{X(t),Y(t),t\geq 0\}$, and $\mathbf{Q}(u,v)$ as the one step transition rate sub-matrix from the system level u to v. Considering there are four stages, namely 0,1,2,3, in the system, it is easy to find that each sub-matrix $\mathbf{Q}(u,v)$ is with order 4×4 structure.

According to the changes of system level, we deal with each sub-matrix $\mathbf{Q}(u,v)$ in detail.

(1) If $v=u$, it means the number of SU packets in the system is fixed via one step transition.

For the case of $u=0$, the possible transitions from different original system stages are given here.

The initial system stage $j=0$**.** If there is no packet arrival and the sleep timer does not expire, the BS will keep at the sleep state, i.e., the system stage will be fixed at $j=0$; If there is a PU packet arrival, the BS will wake up immediately to serve the PU packet, i.e., the system stage will change to $j=1$; If the sleep timer expires, the BS will wake up to serve the SU packet, i.e., the system stage will change to $j=2$.

The initial system stage $j=1$**.** If the transmission of the PU packet occupying the licensed spectrum is completed, the BS will go to sleep to save energy, i.e., the system stage will change to $j=0$; If the transmission of the PU packet occupying the licensed spectrum is not completed yet, the BS will serve the PU packet continuously, i.e., the system stage will be fixed at $j=1$.

The initial system stage $j=3$**.** If there is a PU packet arrival, the BS will serve the PU packet immediately, i.e., the system stage will change to $j=1$; If there is no packet arrival, the BS will keep idle, i.e., the system stage will be fixed at $j=3$.

We denote $\mathbf{Q}(0,0)$ by $\mathbf{A}_0$. Based on the stochastic behavior discussed above, $\mathbf{A}_0$ is then given as follows:

$$\mathbf{A}_0=\begin{bmatrix}-\lambda_{su}-\lambda_{pu}-\theta & \lambda_{pu} & 0 & \theta\\ \mu_{pu} & -\lambda_{su}-\mu_{pu} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & \lambda_{pu} & 0 & -\lambda_{su}-\lambda_{pu}\end{bmatrix} \quad \textbf{(6)}$$

For the case of $0<u<N$, we denote $\mathbf{Q}(u,u)$ by $\mathbf{A}_1$. Since there is at least one SU packet in the system, there are two different stage changes: When the sleep timer expires, the BS will wake up to serve the SU packet, i.e., the system stage will change to $j=2$ from $j=0$; When the transmission of the PU packet occupying the licensed spectrum is completed, the BS will serve the SU packets waiting in the buffer, i.e., the system stage will change to $j=2$ from $j=1$. For the initial stage $j=2$, if the transmission of the SU packet occupying the licensed spectrum is not completed yet and there is no PU packet arrival, the BS will continuously serve the SU packets one by one, i.e. the system stage will be fixed at $j=2$. When the system level is greater than 0, the BS cannot be idle, i.e., the system stage cannot be $j=3$, that is, if there is at least one packet in the system, BS cannot be in listening state.

$\mathbf{A}_1$ is given as follows:

$$\mathbf{A}_1=\begin{bmatrix}-\lambda_{su}-\lambda_{pu}-\theta & \lambda_{pu} & \theta & 0\\ 0 & -\lambda_{su}-\mu_{pu} & \mu_{pu} & 0\\ 0 & 0 & -\lambda_{su}-\lambda_{pu}-\mu_{su} & 0\\ 0 & 0 & 0 & 0\end{bmatrix} \quad \textbf{(7)}$$

For the case of $u\geq N$, we denote $\mathbf{Q}(u,u),\ u\geq N$ by $\mathbf{A}$. Once the number of SU packets arriving at the system reaches threshold *N* during sleep state, BS will be switched to awake state immediately. That is to say, when the system level $u\geq N$, the system stage $j=0$ does not exist.

$\mathbf{A}$ is given as follows:

$$\mathbf{A}=\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & -\lambda_{su}-\mu_{pu} & \mu_{pu} & 0\\ 0 & 0 & -\lambda_{su}-\lambda_{pu}-\mu_{su} & 0\\ 0 & 0 & 0 & 0\end{bmatrix} \quad \textbf{(8)}$$

(2) If $v=u-1$, it means that during one step transition, an SU packet departs from the system, so the initial system stage can only be $j=2$. We discuss the sub-matrix $\mathbf{Q}(u,u-1)$ according to the departure scenario of an SU packet.

If the transmission of the SU packet occupying the licensed spectrum is completed successfully, the system stage will change to $j=0$ or be fixed at $j=2$. For the case of the initial system level being equal to 1, BS will go to sleep and the system stage will change to $j=0$ from $j=2$ after an SU packet leaves the system. For the case of the initial system level being greater than 1, the system stage can only be fixed at $j=2$ after an SU packet leaves the system.

If the transmission of the SU packet occupying the licensed spectrum is interrupted by a newly arriving PU packet, the system stage will change to $j=1$ from $j=2$.

We denote $\mathbf{Q}(1,0)$ by $\mathbf{B}_1$ and $\mathbf{Q}(u,u-1),\ u>1$ by $\mathbf{B}$ respectively. $\mathbf{B}_1$ and $\mathbf{B}$ are then given as follows:

$$\mathbf{B}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mu_{su} & \lambda_{pu} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \lambda_{pu} & \mu_{su} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{10}$$

(3) If $v = u + 1$, it means that during one step transition, an SU packet arrives at the system. Based on the initial number of SU packets in the system, we discuss the sub-matrix $\mathbf{Q}(u, u+1)$.

For the case of $u = 0$, that is to say, there is no SU packet in the initial state. During the one step transition, there is an arrival of SU packet. This arrival occurs when BS is in sleep state, listening state, or awake state with a PU packet being transmitted on the licensed spectrum.

When BS is in sleep state. Considering that the threshold $N = 1$, once one SU packet arrives at the system, the sleep timer will be terminated immediately and this SU packet will be transmitted directly. Accordingly, the system stage will change to $j = 2$ from $j = 0$. Relatively, for the case of the threshold $N > 1$, if the sleep timer does not expire, even though an SU packet arrives at the system, the BS will keep in sleep state, i.e., the system stage will be fixed at $j = 0$.

When BS is in listening state. As soon as an SU packet arrives at the system, the BS will serve the SU packet immediately, i.e., the system stage will change to $j = 2$ from $j = 3$.

When BS is in awake state with a PU packet being transmitted on the licensed spectrum. The newly arriving SU packet has no effect on the transmission of the PU packet occupying the spectrum. Thus, the system stage will be fixed at $j = 1$.

We denote $\mathbf{Q}(0,1)$ for threshold $N = 1$ by $\mathbf{C}_0$ and $\mathbf{Q}(0,1)$ for threshold $N > 1$ by $\mathbf{C}_1$ respectively. $\mathbf{C}_0$ and $\mathbf{C}_1$ are then given as follows:

$$\mathbf{C}_0 = \lambda_{su} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{11}$$

$$\mathbf{C}_1 = \lambda_{su} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{12}$$

For the case of $0 < u < N - 1$, we denote $\mathbf{Q}(u, u+1)$ for $0 < u < N - 1$ by $\mathbf{C}_2$. Since there is at least one SU packet in the system, BS will not be in listening state, an SU packet arrival may occur when another SU packet is being transmitted. Accordingly, the system stage will be fixed at $j = 2$.

$\mathbf{C}_2$ is given as follows:

$$\mathbf{C}_2 = \lambda_{su} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{13}$$

For the case of $u = N - 1$, we denote $\mathbf{Q}(u, u+1)$, $u = N - 1$ by $\mathbf{C}_3$. Considering that the number of SU packets in the system after one step transition, the stage changes for the initial system stage $j = 0$ in $\mathbf{C}_2$ and that in $\mathbf{C}_3$ are different. When $u = N - 1$, once an SU packet arrives at the system, the number of SU packet will reach *N*, the BS will wake up, i.e., the system stage will change to $j = 2$ from $j = 0$.

$\mathbf{C}_3$ is given as follows:

$$\mathbf{C}_3 = \lambda_{su} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{14}$$

For the case of $u \geq N$, we denote $\mathbf{Q}(u, u+1)$, $u \geq N$ by $\mathbf{C}$. The difference between $\mathbf{C}$ and $\mathbf{C}_3$ is that the initial system stage $j = 0$ does not exist in $\mathbf{C}$.

$\mathbf{C}$ is given as follows:

$$\mathbf{C} = \lambda_{su} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{15}$$

Based on Eqs. (5)-(14), we illustrate the structure of the one step state transition rate $\mathbf{Q}$ for different thresholds *N*.

For $N = 1$, $\mathbf{Q}$ is given as follows:

$$\mathbf{Q} = \left[\begin{array}{ccccc} \mathbf{A}_0 & \mathbf{C}_0 & & & \\ \mathbf{B}_1 & \mathbf{A} & \mathbf{C} & & \\ \hdashline & \mathbf{B} & \mathbf{A} & \mathbf{C} & \\ & & \ddots & \ddots & \ddots \end{array} \right] \tag{16}$$

For $N = 2$, $\mathbf{Q}$ is given as follows:

$$\mathbf{Q} = \left[\begin{array}{ccccc} \mathbf{A}_0 & \mathbf{C}_1 & & & \\ \mathbf{B}_1 & \mathbf{A}_1 & \mathbf{C}_3 & & \\ \hdashline & \mathbf{B} & \mathbf{A} & \mathbf{C} & \\ & & \ddots & \ddots & \ddots \end{array} \right] \tag{17}$$

For $N \geq 3$, $\mathbf{Q}$ is given as follows:

$$\mathbf{Q}=\begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ N-2 \\ N-1 \\ N \\ \vdots \end{array}\left[\begin{array}{ccccccccc} \mathbf{A}_0 & \mathbf{C}_1 & & & & & & & \\ \mathbf{B}_1 & \mathbf{A}_1 & \mathbf{C}_2 & & & & & & \\ & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_2 & & & & & \\ & & \ddots & \ddots & \ddots & & & & \\ & & & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_2 & & & \\ & & & & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_3 & & \\ \hline & & & & & \mathbf{B} & \mathbf{A} & \mathbf{C} & \\ & & & & & & \ddots & \ddots & \ddots \end{array}\right] \quad (18)$$

From the structure of $\mathbf{Q}$, we find that $\mathbf{Q}$ is a blocked three-diagonal matrix and the system state transition occurs only in adjacent levels. So the stochastic process $\{X(t),\ Y(t),\ t \geq 0\}$ is a type of quasi-birth-and-death (QBD) process.

Let $\mathbf{\Pi}_i$ be the stationary probability distribution for the system being at level i, $i \geq 0$. $\mathbf{\Pi}_i$ can be given as follows:

$$\mathbf{\Pi}_i = (\pi_{i,0},\ \pi_{i,1},\ \pi_{i,2},\ \pi_{i,3}) \quad (19)$$

The steady-state probability distribution $\mathbf{\Pi}$ of the system is composed of $\mathbf{\Pi}_i$, $i = 0,\ 1,\ 2, \cdots$. $\mathbf{\Pi}$ is then given as follows:

$$\mathbf{\Pi} = (\mathbf{\Pi}_0,\ \mathbf{\Pi}_1,\ \mathbf{\Pi}_2, \cdots) \quad (20)$$

From Eqs. (16)-(18), we find that for threshold $N = 1$, the rows of the one step state transition rate $\mathbf{Q}$ are repeating after the third row; for threshold $N > 1$, the rows of the one step state transition rate $\mathbf{Q}$ are repeating after the $(N+1)$ throw. For the QBD process, we can obtain $\mathbf{\Pi}$ by using the matrix geometric solution method [22]. The steady-state distribution satisfies:

$$\begin{cases} (\mathbf{\Pi}_0,\ \mathbf{\Pi}_1,\ \mathbf{\Pi}_2, \cdots,\ \mathbf{\Pi}_N) B[\mathbf{R}] = 0 \\ \mathbf{\Pi}_0 \mathbf{e} + \mathbf{\Pi}_1 \mathbf{e} + \cdots + \mathbf{\Pi}_N (\mathbf{I} - \mathbf{R})^{-1} \mathbf{e} = 1 \\ \mathbf{\Pi}_i = \mathbf{\Pi}_N \mathbf{R}^{i-N},\ i > N \end{cases} \quad (21)$$

where $\mathbf{e}$ is a column vector of ones.

Matrix $\mathbf{R}$ is the minimum non-negative solution of the matrix equation $\mathbf{R}^2\mathbf{B} + \mathbf{R}\mathbf{A} + \mathbf{C} = \mathbf{0}$. By using an iteration method, we can approximate the solution of matrix $\mathbf{R}$. Additionally, the spectral radius of $\mathbf{R}$ is less than 1.

$B[\mathbf{R}]$ is a block matrix with order $(4N+4) \times (4N+4)$ structure.

For $N = 1$, $B[\mathbf{R}]$ is given as follows:

$$B[\mathbf{R}] = \begin{bmatrix} \mathbf{A}_0 & \mathbf{C}_0 \\ \mathbf{B}_1 & \mathbf{A} + \mathbf{R}\mathbf{B} \end{bmatrix} \quad (22)$$

For $N = 2$, $B[\mathbf{R}]$ is given as follows:

$$B[\mathbf{R}] = \begin{bmatrix} \mathbf{A}_0 & \mathbf{C}_1 & \\ \mathbf{B}_1 & \mathbf{A}_1 & \mathbf{C}_3 \\ & \mathbf{B} & \mathbf{A} + \mathbf{R}\mathbf{B} \end{bmatrix} \quad (23)$$

For $N \geq 3$, $B[\mathbf{R}]$ is given as follows:

$$B[\mathbf{R}] = \begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ N-2 \\ N-1 \\ N \end{array}\left[\begin{array}{ccccccc} \mathbf{A}_0 & \mathbf{C}_1 & & & & & \\ \mathbf{B}_1 & \mathbf{A}_1 & \mathbf{C}_2 & & & & \\ & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_2 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_2 & \\ & & & & \mathbf{B} & \mathbf{A}_1 & \mathbf{C}_3 \\ & & & & & \mathbf{B} & \mathbf{A} + \mathbf{R}\mathbf{B} \end{array}\right] \quad (24)$$

Combining Eqs. (21)-(24), the steady-state probability distribution $\mathbf{\Pi}$ can be obtained accordingly.

4 Performance Measures and Numerical Results

In this section, we derive the expressions for the performance measures in terms of the energy saving rate and the average latency of SU packets, then we provide numerical results with analysis and simulation to evaluate the system performance.

4.1 Performance Measures

We define the energy saving rate ζ as the energy conservation in BS per unit time. In the proposed energy saving strategy, there are three kinds of states, namely, sleep state, listening state and awake state. Since some devices are turned off when BS is sleeping, energy can be conserved during sleep state. However, when BS returns to awake state or listening state from sleep state, additional energy will be consumed to activate the closed devices. Let f_1 be the energy conservation per unit time when BS is in sleep state. Let f_2 be the energy consumption for each switching procedure from sleep state to either awake state or listening state. ζ is then given as follows:

$$\zeta = f_1 \sum_{i=0}^{\infty} \pi_{i,0} - f_2 \left(\sum_{i=0}^{N-1} \pi_{i,0} (\lambda_{pu} + \theta) + \pi_{N-1,0} \times \lambda_{su} \right) \quad (25)$$

We define the latency of an SU packet as the time duration from the instant this SU packet arrives at the system to the instant this SU packet is transmitted successfully. The average latency of SU packets reflects the experience quality of users with successful packet transmission.

The average latency of SU packets is the sum of average waiting time of SU packets queueing in the buffer and the average transmission time of SU packets without interruption from PU packets. Based on the model analysis results, we derive the average number of SU packets waiting in the buffer at steady state as $\sum_{i=1}^{\infty}(i(\pi_{i,0}+\pi_{i,1})+(i-1)\pi_{i,2})$. By using Little's formula [23-24], the average waiting time of SU packets is $\frac{1}{\lambda_{su}}\sum_{i=1}^{\infty}(i(\pi_{i,0}+\pi_{i,1})+(i-1)\pi_{i,2})$. On the other hand, for the SU packets transmitted successfully, the average transmission time is $1/\mu_{su}$. So, the average latency ω of SU packets is given as follows:

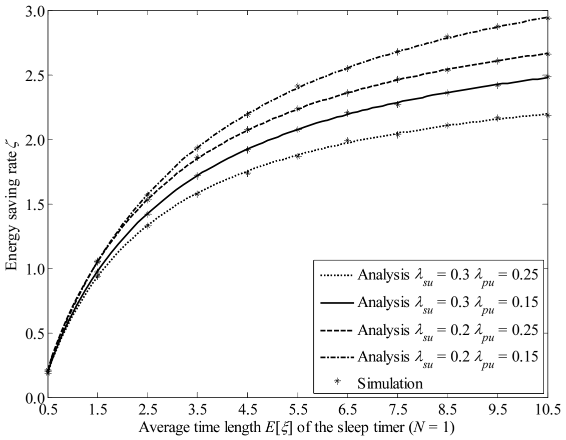
$$\omega=\frac{\sum_{i=1}^{\infty}(i(\pi_{i,0}+\pi_{i,1})+(i-1)\pi_{i,2})}{\lambda_{su}}+\frac{1}{\mu_{su}} \qquad \textbf{(26)}$$

4.2 Numerical Results

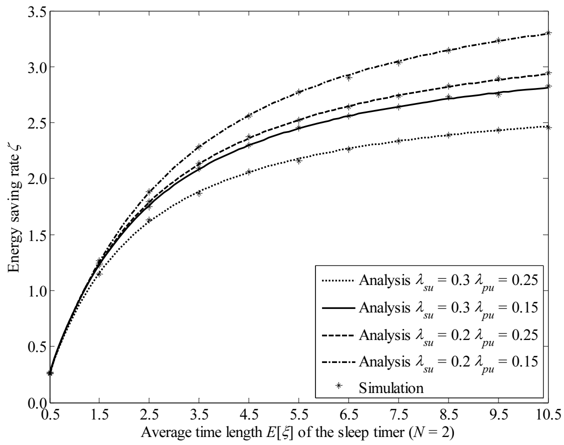
In order to estimate the influences of the arrival rate of SU packets, the arrival rate of PU packets, the threshold N and the average time length of the sleep timer on the system performance, we provide numerical results with analysis and simulation. Referencing to [25], we set the transmission rate of PU packets as $\mu_{pu}=0.7$ and the transmission rate of SU packets as $\mu_{su}=0.8$ in numerical experiments. Referencing to [26], we set the energy conservation per unit time when BS in sleep state as $f_1=7$ mJ and the energy consumption for each switching procedure as $f_2=2$ mJ, respectively.

All the numerical experiments were run in Matlab platform 7.10 on Intel (R) Core (TM)2 Duo CPU E7500 @2.93GHz 2.93GHz, 3.50GB (Microsoft Windows XP Professional Operating System).

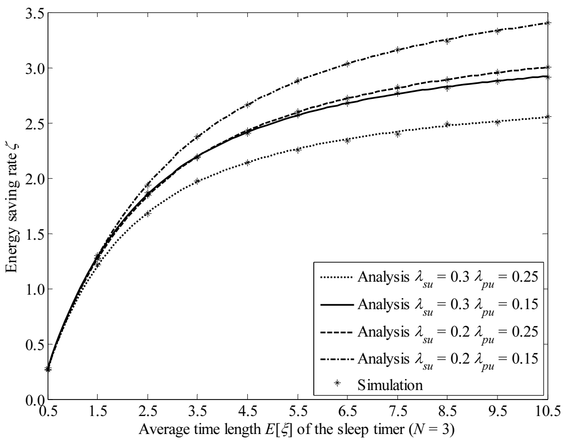
Figure 2 shows the variation of energy saving rate versus to different thresholds with N-policy and without N-policy.



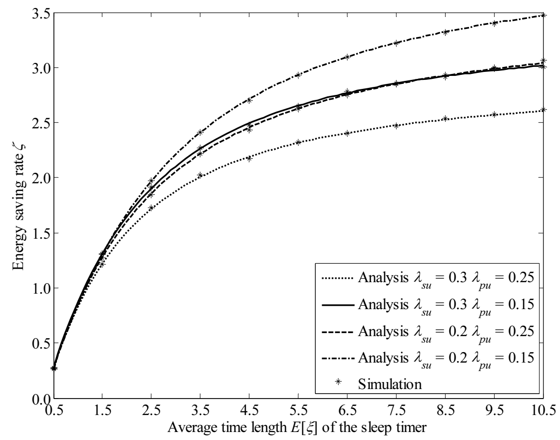
(a) $N=1$



(b) $N=2$



(c) $N=3$



(d) Without N-policy

Figure 2. Variation for the energy saving rate ζ

In Figure 2, we find that the energy saving rate ζ increases along with the increase in the average time length $E[\xi]$ of the sleep timer. When other parameters such as the threshold N, the arrival rates of SU packets and PU packets are given, the larger the average time length of the sleep timer is, the bigger the probability of BS being in sleep state is. So the energy saving rate becomes greater.

We also observe that for the same average time length $E[\xi]$ of the sleep timer, when the arrival rate λ_{pu} of PU packets and the arrival rate λ_{su} of SU packets are given, as the threshold increases, the energy saving rate ζ will increase accordingly. The reason is that the larger the threshold is, the less likely is that the sleep timer is terminated in advance due to the number of SU packets in the system reaches threshold N, the BS will be in sleep state for a longer time, that will result in an increase in the energy saving rate.

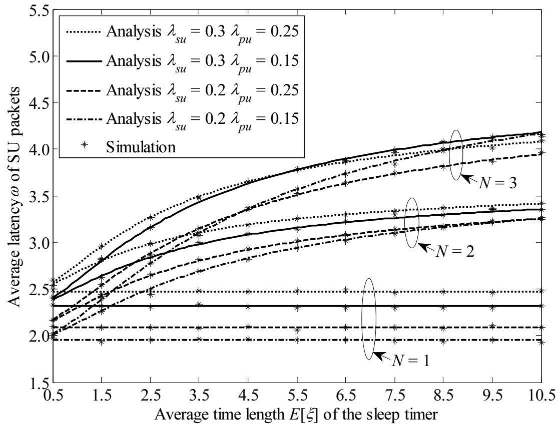
Moreover, we notice that for the same average time length $E[\xi]$ of the sleep timer, the same threshold and the same arrival rate λ_{su} of SU packets, as the arrival rate λ_{pu} of PU packets increases, the energy saving rate ζ will decrease. There are two reasons lead to this tendency. One reason is that the higher the arrival rate of PU packet is, the more likely is that the sleep timer will be terminated in advance due to the arrival of an PU packet, the shorter the BS will be in sleep state, then the lower the energy saving rate will be. The other reason is that the more frequently the PU packets arrive at the system, the less likely is that the BS will go to sleep, so the lower the energy saving rate will be.

Additionally, we also notice that for the same average time length $E[\xi]$ of the sleep timer, the same threshold N and the same arrival rate λ_{pu} of PU packets, as the arrival rate λ_{su} of SU packets increases, the energy saving rate ζ will decrease. The reason is similar to the explanation for illustrating why the energy saving rate decreases along with the increase in the arrival rate of PU packets. We won't explore it in this article.

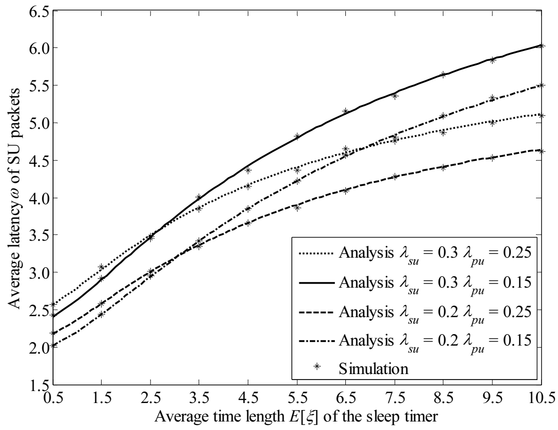
Comparing Figure 2(d) with Figures 2(a)-2 (c), we note that the energy saving rate in our proposed strategy is bit less than that without N-policy. This shortage could be covered by adjusting the sleep parameter properly.

Figure 3 shows the variation of the average latency of SU packets versus to different thresholds with N-policy and without N-policy.

From Figure 3(a), we find that the average latency ω of SU packets increases along with the increase in the average time length $E[\xi]$ of the sleep timer except for the threshold $N = 1$. When the threshold $N = 1$, the transmission of an SU packet is dependent of the sleep timer, i.e., the proposed energy saving strategy is degenerated as a conventional spectrum allocation strategy without sleep mode. When the threshold $N > 1$, the larger the average time length of the sleep timer is, the longer the BS stays in sleep state, so the average latency of SU packets will be greater.



(a) With N-policy



(b) Without N-policy

Figure 3. Variation for the average latency ω of SU packets

In Figure 3(a), we also find that for the same average time length $E[\xi]$ of the sleep timer, when the arrival rate λ_{pu} of PU packets and the arrival rate λ_{su} of SU packets are given, the average latency ω of SU packets will increase with the increase in the threshold N. The reason is that the higher the threshold is, the less likely is that the sleep timer will be terminated in advance due to the number of SU packets in the system reaches the threshold, the longer the BS stays in sleep state, that results in a greater average latency of SU packets.

Moreover, we observe that for the same average time length $E[\xi]$ of the sleep timer, when the threshold $N(N > 1)$ and the arrival rate λ_{pu} of PU packets are given, the higher the arrival rate λ_{su} of SU packets is, the greater the average latency ω of SU packets will be. It is because the more frequently the SU packets arrive at the system, the greater the average number of SU packets queueing in the buffer is, that results in an increase in the average latency of SU packets.

On the other hand, for the same threshold $N(N>1)$ and the same arrival rate λ_{su} of SU packets, when the average time length $E[\xi]$ of the sleep timer is shorter, the average latency ω of SU packets will increase with the increase in the arrival rate λ_{pu} of PU packets. In contrast to this finding, when the average time length of the sleep timer is larger, the average latency ω of SU packets will decrease with the increase in the arrival rate λ_{pu} of PU packets. The reason is when the average time length of the sleep timer is shorter, the more frequently the PU packets arrive at the system, the more likely is that the licensed spectrum is occupied by PU packets, the longer the SU packets wait in the buffer, so the higher the average latency of SU packets will be. When the average time length of the sleep timer becomes larger, the lesser the PU packets arrive at the system, the more likely the sleep timer is to be terminated as schedule, the transmission of SU packets are delayed longer time in sleep state, that results in an increase in the average latency of SU packets.

Additionally, when the threshold $N=1$, for the same arrival rate λ_{su} of SU packets, the average latency ω of SU packets will increase with the increase in the arrival rate λ_{pu} of PU packets. The reason is similar to the latency discussion for the case of a shorter average time length $E[\xi]$ of the sleep timer when the threshold $N>1$.

In Figure 3(b), we show the variation of the average latency of SU packets without N-policy sleep mode. We find that the response performance in our proposed strategy is better than that without N-policy. This is what we expect, also the aim of the energy saving strategy with N-policy sleep mode in CRNs.

From the numerical experiments shown in Fig. 2 and Fig. 3, we see that the analysis results match well with the simulation results. In addition, we also notice that with the increase in the average time length of sleep timer, both of the energy saving rate and the average latency of SU packets will increase. That is to say, there is a trade-off between the experience quality of SU packets and the energy conservation of the system. For this, we will optimize the sleep parameter in the next section.

5 Optimization of Sleep Parameter

In order to balance different performance measures given in Section 4, we establish a cost function $F(\theta)$ of the system as follows:

$$F(\theta)=a_1\omega(\theta)-a_2\zeta(\theta) \quad \textbf{(26)}$$

where a_1 and a_2 are the impact factors of the average latency of SU packets and the energy saving rate, respectively, to the cost function. ω is the average latency of SU packets given in Eq. (25), ζ is the energy saving rate given in Eq. (24).

We note that, for a delay sensitive application, the impact factor a_1 should be set greater, on the other hand, when the requirement for energy conservation is higher, the impact factor a_2 should be set larger. However, the values of a_1 and a_2 could not affect essentially the trade-off between the average latency of SU packets and the energy saving rate. Setting $a_1=0.8$ and $a_2=0.3$ as an example in numerical results of cost function of system, we illustrate how the cost function $F(\theta)$ of the system changes along with the average time length $E[\xi]$ of the sleep timer for different thresholds and different arrival rates of PU packets and SU packets in Figure 4.

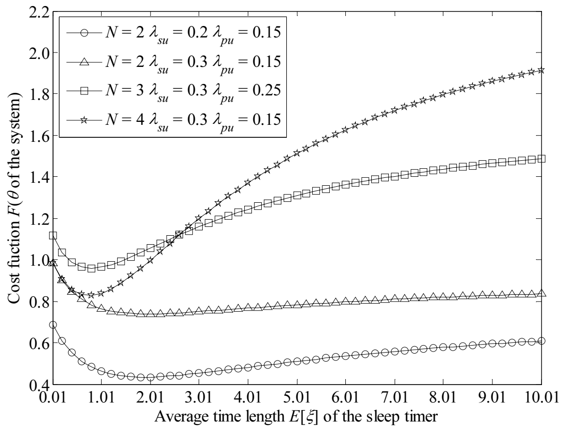


Figure 4. Variation for the cost function $F(\theta)$ of the system

As shown in Figure 4, we find that the cost function $F(\theta)$ of the system firstly shows a downward trend and then shows a rising trend along with the average time length $E[\xi]$ of the sleep timer. Recall that both of the average latency of SU packets and the energy saving rate will increase with the increase in the average time length of the sleep timer. When the average time length of the sleep timer is shorter, the energy saving rate is a dominate impact factor relative to the average latency of SU packets. Hence, it shows a downward trend in Figure 4. On contrary, when the average time length of the sleep timer becomes larger, the average latency of SU packets will become a dominate impact factor relative to the energy saving rate. Hence, it shows a rising trend in Figure 4. Obviously, there exists a minimum cost function $F(\theta^*)$ when the sleep parameter is set to the optimal value θ^*.

We note that both of the average latency ω of SU packets in Eq. (25) and the energy saving rate ζ in Eq. (24) are difficult to be given in a close-form. In order to obtain the exact value of the optimal sleep parameter θ^*, we present an artificial bee colony (ABC) algorithm method. ABC is a new optimization algorithm based on the intelligent behavior of honey bee swarm. Compared with the conventional particle swarm optimization (PSO) algorithms, ABC is very simple and very flexible. Due to its simplicity and ease of application, the ABC has been widely used to solve both continuous and discrete optimization problems [27-28]. The main steps of the algorithm to obtain the optimal sleep parameter are given as follows:

Step 1: Initialize the total number S of bees. Set the upper bound $\theta_{\max} = 20$ and lower bound $\theta_{\min} = 0.01$ of sleep parameter θ. Initialize the times array $trial(i) = 0,\ (i = 1,2,\cdots,S/2)$ for a food source not to be updated. Set the maximum number of trials as $Max\_trial = 100$. Initialize the cycle times $cycle = 1$ for searching the optimal sleep parameter. Set the maximum number of cycles as $Max\_cycle = 5$.

Step 2: **for** $i = 1:1:S/2$
  Calculate an initial location θ_i of the i th food source
  $\theta_i = \theta_{\min} + rand(0,1)(\theta_{\max} - \theta_{\min})$;
  Calculate the cost $F(\theta_i)$ for searching the i th food source
  $F(\theta_i) = a_1\omega(\theta_i) - a_2\zeta(\theta_i)$;
  Calculate the fitness value $fit(\theta_i)$ of the i th food source

$$fit(\theta_i) = \begin{cases} \dfrac{1}{1+F(\theta_i)}, & F(\theta_i) \geq 0 \\ 1+\left|F(\theta_i)\right|, & F(\theta_i) < 0 \end{cases};$$

  endfor

Step 3: **for** $i = 1:1:S/2$
  The i th employed bee seeks a new location $\theta_i^{'}$ of the i th food source near θ_i
  $\theta_i^{'} = \theta_i + \varphi_i(\theta_i - \theta_k),\ k \neq i$; % φ_i is a
  % random number selected from [-1, 1];
  Calculate the cost $F(\theta_i^{'})$ and fitness value $fit(\theta_i^{'})$ with $\theta_i^{'}$;
  if $fit(\theta_i^{'}) > fit(\theta_i)$
    $\theta_i = \theta_i^{'}$;
  else
    $trial(i) = trial(i) + 1$;
  endif
  endfor

Step 4: Approximate the probability that the i th employed bee to be followed by an onlooker bee

$$P_i = \varepsilon_1 \frac{fit(\theta_i)}{\max\limits_{1\leq j\leq S/2} fit(\theta_j)} + \varepsilon_2,\ i \in (1,2,\cdots,S/2).$$

  % Set $\varepsilon_1 = 0.9$ and $\varepsilon_2 = 0.1$ as an example.

Step 5: $i = 1,\ t = 1$
  while $t \leq S/2$
    if $P_i > rand(0,1)$
      The i th onlooker bee follows the i th employed bee to seek a new location $\theta_i^{'}$ of the i th food source near θ_i;
      Calculate the cost $F(\theta_i^{'})$ and fitness value $fit(\theta_i^{'})$ with $\theta_i^{'}$;
      if $fit(\theta_i^{'}) > fit(\theta_i)$
        $\theta_i = \theta_i^{'}$;
      else
        $trial(i) = trial(i) + 1$;
      endif
      $t = t + 1$;
    endif
    if $i = S/2 + 1$
      $i = 1$;
    else
      $i = i + 1$;
    endif
  endwhile

Step 6: Find the maximum $trial(i^*) = \max\limits_{1\leq j\leq S/2} trial(j)$;
  if $trial(i^*) > Max\_trial$
    Abandon θ_{i^*} and set $trial(i^*) = 0$;
    The i^* th bee seeks a new location θ_i of the i th food source;
    Calculate the cost $F(\theta_i)$ and fitness value $fit(\theta_i)$ with θ_i;
  endif

Step 7: **if** $cycle < Max\_cycle$
    $cycle = cycle + 1$;
    go to **Step 3**;
  else
    Find the minimum cost
    $F(\theta^*) = \min\limits_{1\leq j\leq S/2} F(\theta_j)$;
  endif

Step 8: Output the optimal sleep parameter θ^* and the corresponding minimum cost $F(\theta^*)$.

The complexity of this algorithm ABC (T) depends on the number of bees (S) and the maximum number of cycles (*Max_cycle*). T is then given as follows:

$$T = O(S \times Max\_cycle) \tag{27}$$

Several groups of threshold, arrival rate λ_{su} of SU packets and arrival rate λ_{pu} of PU packets are passed as input of the algorithm, we obtain the optimal sleep parameter θ^* and the corresponding minimum cost function $F(\theta^*)$ of the system in Table 1.

Table 1. Optimal Sleep Parameter θ^* and the Corresponding Minimum Cost Function $F(\theta^*)$

N	λ_{su}	λ_{pu}	θ^*	$F(\theta^*)$
2	0.2	0.15	0.5181	1.2757
2	0.3	0.15	0.5493	1.5814
3	0.3	0.25	1.2642	1.7208
4	0.3	0.15	1.3138	1.6689

6 Conclusions

In this paper, for the purpose of saving energy consumption as well as improving the response performance of SU packets, we proposed a novel energy saving strategy with N-policy sleep mode in overlay CRNs. Considering the number of SU packets and BS state, we built a two-dimensional continuous-time Markov chain model. Then we derived the steady-state probability distribution of the system, and estimated the system performance mathematically. Numerical experiments show that the proposed energy saving strategy is effective and the performance analysis is reasonable. Based on the trade-off between different performance measures, we constructed a cost function of the system. Finally, we presented an artificial bee colony algorithm method to obtain the optimal sleep parameter.

The research of this paper has potential application in other wireless networks with heterogeneous users and energy saving requirements.

Acknowledgments

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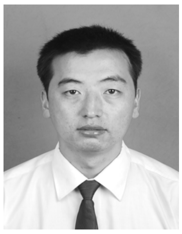

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