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SLEEP MODE OF BASE STATION IN COGNITIVE RADIO NETWORKS AND ITS PERFORMANCE ANALYSIS

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Abstract. *With the purpose of reducing energy consumption in line with green communication, we propose a sleep mode in cognitive radio networks, in which the base station in secondary networks will enter a sleep state when there are not any packets to be transmitted. Taking into account both the dynamic spectrum allocation strategy and also the proposed sleep mode, we build a continuous-time priority queueing model with multiple vacations. We derive the stability condition, beyond which the network cannot be operative any longer. In addition, we present formulas for performance measures in terms of average latency of secondary users and energy saving rate of system. Moreover, we provide statistical experiments with analysis and simulation to validate the feasibility of the proposed strategy and to reveal the trade-off between different performance measures. Finally, by taking into account different performance measures, we establish a cost function, and develop an iteration algorithm to optimize the energy saving strategy with a reasonable sleep parameter.*

Keywords: Cognitive radio networks, Sleep mode, Continuous-time priority queueing model, Multiple vacations, Iteration algorithm

1. Introduction.

With the development of economy and the change of environment data, the energy shortage is a burning question in the field of communications and networks. A concept of green communication [1] is proposed in cognitive radio networks (CRNs) to reduce the energy consumption [2].

CRNs enable the radio spectrum to be utilized effectively due to opportunistic packet transmission [3, 4, 5, 6] and dynamic spectrum access [7, 8], but a great deal of powerful resources are needed to support these functions. Therefore, energy efficiency becomes a valuable research topic. In [9], Bayhan and Alagoz proposed a scheduling strategy, in which the base station makes frequency allocations to the cognitive radios at the beginning of each frame and the energy efficiency maximization problem is formulated. In [10], to improve the energy-efficiency of channel sensing in CRNs, Su and Zhang investigated the energy-aware channel sensing scheduling scheme with which the sensing energy consumption is minimized. Most of these studies are focused on spectrum scheduling strategy concerning energy conservation.

Sleep mode is considered to be a better solution to improve the energy efficiency [11], since the energy consumption is greatly reduced when the base stations of CRNs are sleep. Chen *et al.* proposed a distributed base station sleep scheduling scheme in relay-assisted cellular networks [12]; the energy efficiency was maximized under the constraint of spectral efficiency. In [13], Qiao *et al.* briefly described the heterogeneous hierarchical cognitive radio sensor networks and introduced a centralized sleep and established a mathematical model. Experimental results indicate that energy efficiency can be significantly increased by this sleep scheduling algorithm. In [14], Xiao *et al.* proposed sleeping actions in finding the optimal schedule in order to improve the energy efficiency in CRNs. From the available literature, we see that there is no yet research work on analysis framework of sleep mechanism in CRNs.

With the increasing of spectrum utilization, base station (BS) will consume more energy. From the available literature, we see that most researches are generally concentrated on improving the spectrum utilization rate rather than the energy efficiency. In this paper, we propose an energy saving strategy with sleep mode in CRNs. Then, we establish a continuous-time priority queueing model with multiple vacations to capture the stochastic behavior in CRNs. Moreover, we evaluate the system performance in terms of the energy saving rate of system and the average latency of SU packets. In order to trade off different performance measures, we establish a cost function to optimize the proposed energy saving strategy.

The rest of this paper is organized as follows. In Section 2, we propose a sleep mode in CRNs and build a queueing model accordingly. In Section 3, we analyze the queueing model by matrix geometric solution. With statistical experiments, we estimate the system performance in Section 4. In Section 5, we optimize the sleep parameter with a cost function. Finally, Section 6 concludes this paper.

2. **Strategy Description and System Model.**

In this section, we firstly propose an energy saving strategy with sleep mode in CRNs. Then, we establish a continuous-time priority queueing model with multiple vacations.

2.1. **Strategy description.**

In conventional CRNs, BS is always in awake state. We know that lots of energy will be wasted in the awake state even though there are not any packets in the system. With the purpose of reducing energy consumption in BS, we propose an energy saving strategy with sleep mode.

During the awake state of BS, all the packets are transmitted continuously. The primary user (PU) packets are transmitted with preemptive priority, while the secondary user (SU) packets are transmitted opportunistically. Once there are not any packets to be transmitted, the BS will be switched to sleep state. There may exist multiple sleep periods in a sleep state. At the beginning of a sleep period, a sleep timer is started. The sleep timer limits the maximum time length of the sleep period. Once a PU packet arrives at the system within a sleep period, the sleep timer will be terminated immediately, that is to say, the BS will be switched to awake state precociously, and the PU packet will be timely transmitted. If there is no PU packet but at least an SU packet arrival at the system within a sleep period, when the sleep timer expires, namely the sleep period is over, the BS will be switched to awake state as scheduled, and the arrived SU packets will be transmitted. If there are not any packet arrivals at the system when the current sleep timer expires, the system will enter another sleep period.

Based on the energy saving strategy with the sleep mode mentioned above, we discuss the activity of PU packet and SU packet, respectively.

1) The PU packet activity: When a PU packet arrives at the system during the transmission procedure of another PU packet, the newly arriving PU packet will be blocked. When a PU packet arrives at the system during the transmission procedure of an SU packet, the newly arriving PU packet will occupy the spectrum preemptively, the SU packet being transmitted in the system will be interrupted, and the interrupted SU packet will be discarded by the system. When a PU packet arrives at the system in the sleep

period, the sleep period will be terminated immediately no matter the sleep timer expires or not, and the newly arriving PU packet will be immediately transmitted.

2) The SU packet activity: When an SU packet arrives at the system during the transmission procedure of a PU packet, the newly arriving SU packet will enter the system buffer prepared for SU packets. The SU packet queueing at the head of the buffer will occupy the spectrum opportunistically when the transmission of PU packets in the system is completed. When an SU packet arrives at the system during the transmission procedure of another SU packet, the newly arriving SU packet will enter the system buffer and the SU packet queueing at the head of the buffer will be transmitted once the spectrum is vacant. If there is an SU packet arrival at the system when the BS is in the sleep period, the newly arriving SU packet will enter the system buffer, and the SU packet queueing at the head of the buffer will be transmitted when the sleep timer expires normally.

2.2. **Model building.**

Based on the proposed energy saving strategy with sleep mode, we establish a continuous-time priority queueing model with multiple vacations. In this system model, the SU packets are abstracted as customers with low priority, the PU packets are abstracted as customers with preemptive priority, the data transmission in the spectrum is abstracted as a service, the licensed channel is abstracted as a server, and the sleep period is abstracted as a vacation.

The queueing buffer of the SU packets is supposed to be infinite. Let random variable $n(t) = i$, $i \in \{0, 1, 2, \ldots\}$ be the total number of SU packets in the system at the time instant t. $n(t)$ is called as system level. Let random variable $s_c(t) = j$, $j \in \{0, 1, 2\}$ be the system stage at the time instant t. $s_c(t)$ is called as system stage. $s_c(t) = 0$ means the BS is in the sleep state; $s_c(t) = 1$ means the BS is being occupied by a PU packet; $s_c(t) = 2$ means the BS is being occupied by an SU packet. $\{n(t), s_c(t), t \geq 0\}$ constitutes a two-dimensional continuous-time stochastic process with state space $\mathbf{\Omega}$ as follows:

$$\mathbf{\Omega} = \{(i, j) \mid i \in \{0, 1, 2, \ldots\},\ j \in \{0, 1, 2\}\} \tag{1}$$

Considering one spectrum, we assume that the arriving intervals of SU packets and PU packets follow exponential distribution with parameters λ_{su} ($\lambda_{su} > 0$) and λ_{pu} ($\lambda_{pu} > 0$), respectively. The transmission times of an SU packet and a PU packet follow exponential distribution with parameters μ_{su} ($\mu_{su} > 0$) and μ_{pu} ($\mu_{pu} > 0$), respectively. Moreover, we assume that the time length of the sleep timer follows an exponential distribution with parameter θ ($\theta > 0$).

From the assumptions above, we conclude that $\{n(t), s_c(t), t \geq 0\}$ is a two-dimensional continuous-time Markov chain.

2.3. **Steady-state condition.**

The necessary and sufficient condition for a queueing system to be stable is that the offered load ρ of system is less than 1.

We will firstly discuss the offered load ρ_{pu} of PU packets. We note that the offered load ρ_{pu} of PU packets is the probability that the channel is occupied by a PU packet. So we have:

$$\rho_{pu} = \int_0^\infty \int_0^x \lambda_{pu} e^{-\lambda_{pu} t} dt \mu_{pu} e^{-\mu_{pu} x} dx = \frac{\lambda_{pu}}{\lambda_{pu} + \mu_{pu}} \tag{2}$$

Similar to ρ_{pu}, the offered load ρ_{su} of SU packets is the probability that the channel is occupied by an SU packet. Let P_i be the probability that the transmission of an SU packet is interrupted by the arrival of a PU packet. P_i can be given as follows:

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

From the perspective of interruption procedure, P_i can also be given as follows:

$$P_i = \int_0^\infty \int_0^x \lambda_{pu} e^{-\lambda_{pu} t} dt \mu_{su} e^{-\mu_{su} x} dx = \frac{\lambda_{pu}}{\lambda_{pu} + \mu_{su}} \tag{4}$$

Combining Equations (3) and (4), we give the offered load ρ_{su} of SU packets as follows:

$$\rho_{su} = \frac{\lambda_{su}}{\lambda_{pu} + \mu_{su}} \tag{5}$$

The offered load ρ_{pu} of PU packets and the offered load ρ_{su} of SU packets combine to construct the offered load ρ of system, i.e., $\rho = \rho_{pu} + \rho_{su}$. When the offered load ρ of system is less than 1, that is to say, system will reach a steady state. The stable-state condition is $\dfrac{\lambda_{pu}}{\lambda_{pu} + \mu_{pu}} + \dfrac{\lambda_{su}}{\lambda_{pu} + \mu_{su}} < 1$.

3. Model Analysis.

In this section, we derive the steady-state probability distribution for the continuous-time priority queueing model with multiple vacations established in Section 2.

3.1. Transition rate matrix of the two-dimensional Markov chain.

Let $\boldsymbol{Q}$ be the one step transition rate matrix of the two-dimensional continuous-time Markov process $\{n(t), s_c(t), t \geq 0\}$. Let $\boldsymbol{Q}(i,k)$ be the one step transition rate sub-matrix from system level i to system level k. We deal with the analysis process of $\boldsymbol{Q}(i,k)$ as follows.

(1) $\boldsymbol{Q}(0,0)$ means the system level is always 0. If the system stage is always 0 through one step transition, there is no SU packet nor PU packet arrival at the system, and the transition rate is $-\lambda_{su} - \lambda_{pu}$. If the system stage changes from 0 to 1 via one step transition, namely, there is a PU packet arrival at the system, and the transition rate is λ_{pu}. If the system stage changes from 1 to 0 via one step transition, the transmission of PU packet is completed, and the transition rate is μ_{pu}. If the system stage is always 1 through one step transition, namely, the transmission of the PU packet occupying the spectrum is not completed, there is no SU packet arrivals at the system, and the transition rate is $-\lambda_{su} - \mu_{pu}$. Due to the fact that the system stage 2 does not exist for the case of system level 0, all the transition rates associated with the system stage 2 are 0.

(2) $\boldsymbol{Q}(i,i+1)$ means the system level changes from i to $i+1$ via one step transition. For the case of $i = 0$, the system stage will be fixed at 0 or 1. For the case of $i \geq 1$, the system stage will be fixed at 0, 1 or 2. For both cases, there is an SU packet arrival at the system, and the transition rate is λ_{su}.

(3) $\boldsymbol{Q}(i,i-1)$ means the system level changes from i to $i-1$ via one step transition. For the case of $i = 1$, if the system stage changes from 2 to 0 via one step transition, the transmission of the SU packet occupying the spectrum is completed, and the transition rate is μ_{su}. If the system stage changes from 2 to 1 via one step transition, a PU packet arrives at the system, the arriving PU packet is transmitted immediately, namely, the SU packet being transmitted in the system is interrupted, and the transition rate is λ_{pu}. For the case of $i \geq 2$, if the system stage changes from 2 to 1 via one step transition, the analysis process is the same as that for the case of $i = 1$. If the system stage is fixed at 2 via one step transition, the transmission of the SU packet occupying the spectrum is completed, and the transition rate is μ_{su}.

(4) $\boldsymbol{Q}(i,i)$ $(i \geq 1)$ means the number of SU packets remains i via one step transition. If the system stage is always 0 through one step transition, neither SU packet nor PU packet arrives at the system, the sleep timer does not expire, and the transition rate is $-\lambda_{su} - \lambda_{pu} - \theta$. If the system stage changes from 0 to 1 via one step transition, a PU packet arrives at the system, and the transition rate is λ_{pu}. If the system stage changes

from 0 to 2 via one step transition, the sleep timer expires, and the transition rate is θ. If the system stage is always 1 through one step transition, namely, the transmission of the PU packet occupying the spectrum is not completed, no SU packet arrives at the system, and the transition rate is $-\lambda_{su} - \mu_{pu}$. If the system stage changes from 1 to 2 via one step transition, the transmission of the PU packet occupying the spectrum is completed, and the transition rate is μ_{pu}. If the system stage remains 2 through one step transition, the transmission of the SU packet occupying the spectrum is not completed, neither SU packet nor PU packet arrives at the system, and the transition rate is $-\lambda_{su} - \lambda_{pu} - \mu_{su}$.

The state transition may occur only in adjacent level, and the one step transition rate sub-matrix of system can be expressed as a block matrix. From the system structure, we note that the two-dimensional continuous-time Markov process $\{n(t), s_c(t), t \geq 0\}$ is a Quasi Birth-and-Death process.

3.2. Steady-state distribution.

For the two-dimensional continuous-time Markov chain $\{n(t) = i,\ s_c(t) = j\}$, $i \in \{0, 1, 2, \ldots\}$, $j \in \{0, 1, 2\}$, we define the steady-state distribution $\pi_{i,j}$ as follows:

$$\pi_{i,j} = \lim_{t\to\infty} P\{n(t) = i,\ s_c(t) = j\} \tag{6}$$

We define the stationary vector $\boldsymbol{\pi_i}$ as the probability distribution in steady state that the number of SU packets in the system is i. $\boldsymbol{\pi_i}$ can be given as follows:

$$\boldsymbol{\pi_i} = (\pi_{i0}, \pi_{i1}, \pi_{i2}) \tag{7}$$

The steady-state probability distribution $\boldsymbol{\Pi}$ of the two-dimensional continuous-time Markov chain is composed of $\boldsymbol{\pi_i}$ $(i \geq 0)$, and $\boldsymbol{\Pi}$ is given as follows:

$$\boldsymbol{\Pi} = (\boldsymbol{\pi_0}, \boldsymbol{\pi_1}, \boldsymbol{\pi_2}, \ldots) \tag{8}$$

Combining the balance equation and the normalized condition, we have:

$$\begin{cases} \boldsymbol{\Pi Q} = \boldsymbol{0} \\ \boldsymbol{\Pi e} = 1 \end{cases} \tag{9}$$

where $\boldsymbol{e}$ is a column vector with ones.

By using the geometric-matrix method [15], we can give the equation system as follows:

$$\begin{cases} (\boldsymbol{\pi_0}, \boldsymbol{\pi_1}) B[\boldsymbol{R}] = 0 \\ \boldsymbol{\pi_0 e} + \boldsymbol{\pi_1}(\boldsymbol{I} - \boldsymbol{R})^{-1}\boldsymbol{e} = 1 \\ \boldsymbol{\pi_i} = \boldsymbol{\pi_1 R}^{i-1},\ i \geq 2 \end{cases} \tag{10}$$

Matrix $\boldsymbol{R}$ is the minimum non-negative solution of the equation $\boldsymbol{R^2 B} + \boldsymbol{RA} + \boldsymbol{C} = \boldsymbol{0}$ and the spectral radius of $\boldsymbol{R}$ is less than 1. $B[\boldsymbol{R}]$ is a block matrix given as follows:

$$B[\boldsymbol{R}] = \begin{bmatrix} \boldsymbol{A}_0 & \boldsymbol{C}_0 \\ \boldsymbol{B}_1 & \boldsymbol{RB} + \boldsymbol{A} \end{bmatrix} \tag{11}$$

We can obtain the approximate solution of the matrix $\boldsymbol{R}$ iteratively. Substituting the approximate solution of $\boldsymbol{R}$ into Equation (10), we can get the steady-state probability distribution $\boldsymbol{\Pi}$.

4. Performance Measures and Statistical Experiments.

In this section, we derive performance measures and provide statistical experiments to evaluate the sleep mode proposed in this paper.

4.1. **Performance measures.** We define the delay of an SU packet as the time duration from the arrival of an SU packet to the transmission termination (transmitted successfully or interrupted by PU packets) of this SU packet. By using Little's law [8], the average latency W of SU packets is given as follows:

$$W = \frac{1}{\lambda_{su}} \left(\sum_{i=0}^{\infty} i(\pi_{i0} + \pi_{i1} + \pi_{i2}) \right) \tag{12}$$

We define the energy saving rate as the reduced energy consumption in BS per unit time. Let C_1 be the energy conservation of BS per unit time during sleep period. Let C_2 be the energy consumption in BS for each switching procedure from a sleep period to either another sleep period or an awake period. The energy saving rate S is given as follows:

$$\begin{aligned} S &= C_1 \sum_{i=0}^{\infty} \pi_{i0} - C_2 \sum_{i=0}^{\infty} \pi_{i0}(\theta + \lambda_{pu}) \\ &= (C_1 - C_2(\theta + \lambda_{pu})) \left(1 - \frac{\lambda_{pu}}{\lambda_{pu} + \mu_{pu}} - \frac{\lambda_{su}}{\lambda_{pu} + \mu_{su}} \right) \end{aligned} \tag{13}$$

In order to make the energy saving strategy meaningful, the energy saving rate S should be equal to or greater than 0, i.e., $S \geq 0$. From Equation (13), the constrained condition is given as $C_1 \geq C_2(\theta + \lambda_{pu})$.

4.2. **Statistical experiments.** We provide some statistical experiments to study the influence of the parameters on the main performance characteristics. To validate our analytic model, we simulate energy saving strategy proposed in this paper. The simulation results are obtained by averaging over 10 independent runs using MATLAB. From the statistical experiments shown in Figures 1 and 2, we see that the analysis results match well with the simulation results. In order to make sense for our parameter values in this section, we investigate the parameters measures for the same service rates of $\mu_{pu} = 0.7$

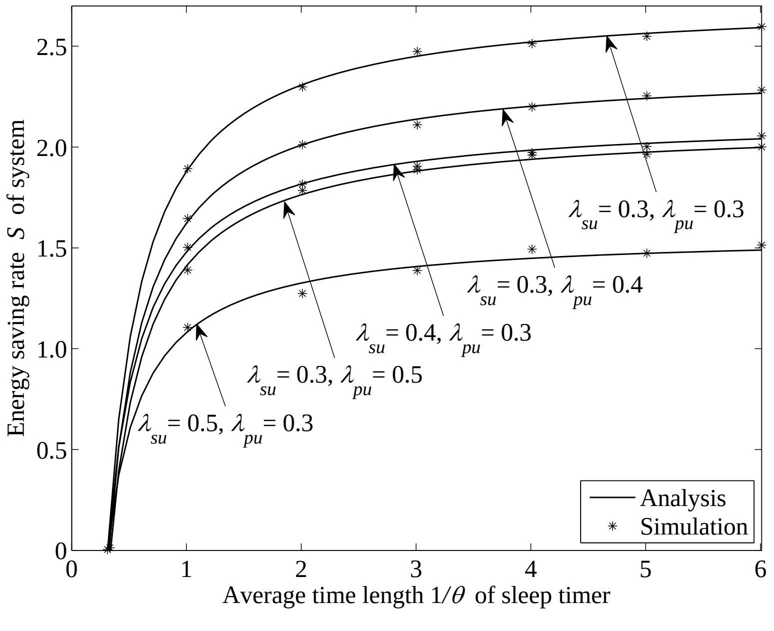

FIGURE 1. Energy saving rate S of system

and $\mu_{su} = 0.8$ as used in [16]. Referencing to [17], the energy conservation of BS per unit time during sleep period is supposed to be $C_1 = 7$ mJ, and the energy consumption in BS for each switching process is supposed to be $C_2 = 2$ mJ.

Figure 1 demonstrates the energy saving rate S of system versus the average time length $1/\theta$ of sleep timer for the different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

From Figure 1, we observe that for the same arrival rate λ_{su} of SU packets and λ_{pu} of PU packets, the energy saving rate S of system will increase as the average time length $1/\theta$ of sleep timer increases. Recall that the energy consumption of BS in sleep state is less than that in awake state. When the average time length of sleep timer is shorter, the probability of BS in awake state is greater. For this case, the energy saving rate of system will be smaller. As the average time length of sleep timer increases, the probability of BS being at awake state will decrease accordingly. So the energy consumption of BS will be reduced, i.e., the energy saving rate of system will increase.

We also notice that for the same average time length of sleep timer, when the arrival rate λ_{pu} of PU packets is given, such as $\lambda_{pu} = 0.3$, the energy saving rate S of system will decrease as the arrival rate λ_{su} of SU packets increases. The reason is that the bigger the arrival rate of SU packets is, the more SU packets will join the system and will be transmitted continuously. Namely, the probability of BS being at awake state becomes greater; accordingly, the probability of BS in sleep state becomes smaller. For this case, the energy saving rate of system will decrease.

Moreover, we see that for the same average time length of sleep timer, when the arrival rate λ_{su} of SU packets is given, such as $\lambda_{su} = 0.3$, as the arrival rate λ_{pu} of PU packets increases, the energy saving rate S of system will decrease inversely. The analysis process is similar to that in the case that for the same average time length of sleep timer and the same arrival rate of PU packets.

Figure 2 illustrates the average latency W of SU packets versus the average time length $1/\theta$ of sleep timer for the different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

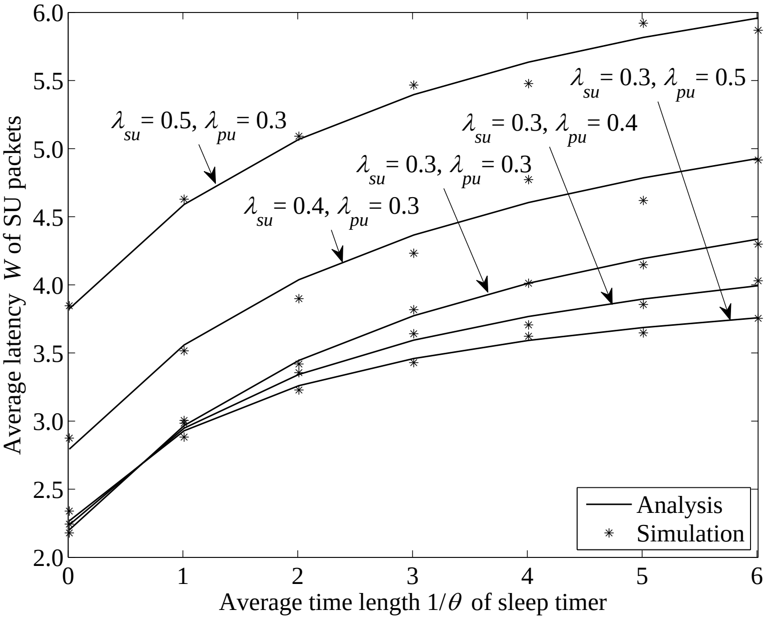

FIGURE 2. Average latency W of SU packets

From Figure 2, we observe that for the same arrival rate λ_{su} of SU packets and λ_{pu} of PU packets, the average latency W of SU packets will increase as the average time length $1/\theta$ of sleep timer increases. The SU packets arriving at the system during sleep period will be transmitted when the sleep timer expires. As the average time length of sleep timer increases, the waiting time of the SU packets in the buffer becomes longer, and the average latency of SU packets will increase accordingly.

We also notice that for the same average time length $1/\theta$ of sleep timer, when the arrival rate λ_{pu} of PU packets is given, such as $\lambda_{pu} = 0.3$, the average latency W of SU packets will increase as the arrival rate λ_{su} of SU packets increases. The increasing arrival rate of SU packets means that more SU packets will queue in the buffer, i.e., SU packets will wait at the buffer for a longer time; hence, the average latency of SU packets will increase.

Moreover, we see that for the same average time length $1/\theta$ of sleep timer, when the arrival rate λ_{su} of SU packets is given, such as $\lambda_{su} = 0.3$, as the arrival rate λ_{pu} of PU packets increases, the average latency W of SU packets will decrease. This is because that the larger the arrival rate of PU packets is, the more PU packets will arrive at the system, the more possible is that the transmission of an SU packet will be interrupted, the shorter the actual transmission time of the interrupted SU packet will be, so the average latency of SU packets will be shorter.

We find that the increase in the average time length $1/\theta$ of sleep timer with our proposed strategy leads to an increase in the energy saving rate. This is an advantage of our proposed energy saving strategy. Comparing the average latency of SU packets in the energy saving strategy with sleep mode for $1/\theta > 0$ with that in conventional CRNs without sleep mode for $1/\theta \to 0$, we see that the response performance will be declined a bit in our proposed strategy. It is an expense of energy conservation. For this reason, we need to reasonably set the sleep parameter θ by trading off the energy saving rate and the average latency of SU packets.

5. Optimization of Sleep Parameter.

By trading off different performance measures, we establish a cost function F_c of system as follows:

$$F_c = f_w W - f_s S \tag{14}$$

where f_w and f_s are treated as the impact factors of the average latency of SU packets and the energy saving rate of system to the cost function, respectively. W is the average latency of SU packets, and S is the energy saving rate of system. W and S have been obtained in Equations (12) and (13), respectively.

Use the parameters given in Section 4.2, and set $f_w = 0.3$ and $f_s = 0.8$ as an example. Figure 3 illustrates how the cost function F_c of system changes along with the average time length $1/\theta$ of sleep timer for different arrival rates λ_{su} of SU packets and λ_{pu} of PU packets.

As shown in Figure 3, for all the combinations of arrival rates λ_{su} of SU packets and λ_{pu} of PU packets, the cost function F_c of system firstly decreases and then increases as the average time length $1/\theta$ of sleep timer increases. Recall that both of the average latency of SU packets and the energy saving rate of system will increase as the average time length of sleep timer increases. When the average time length of sleep timer is smaller, the escalating trend of the energy saving rate of system is bigger than that of the average latency of SU packets, and the energy saving rate of system is a dominate impact factor. Hence, there is a decreasing stage in Figure 3. When the average time length of sleep timer is greater, the escalating trend of the average latency of SU packets is bigger than that of the energy saving rate of system, and the average latency of SU packets is a dominate impact factor. Hence, there is an increasing stage in Figure 3. Obviously, there

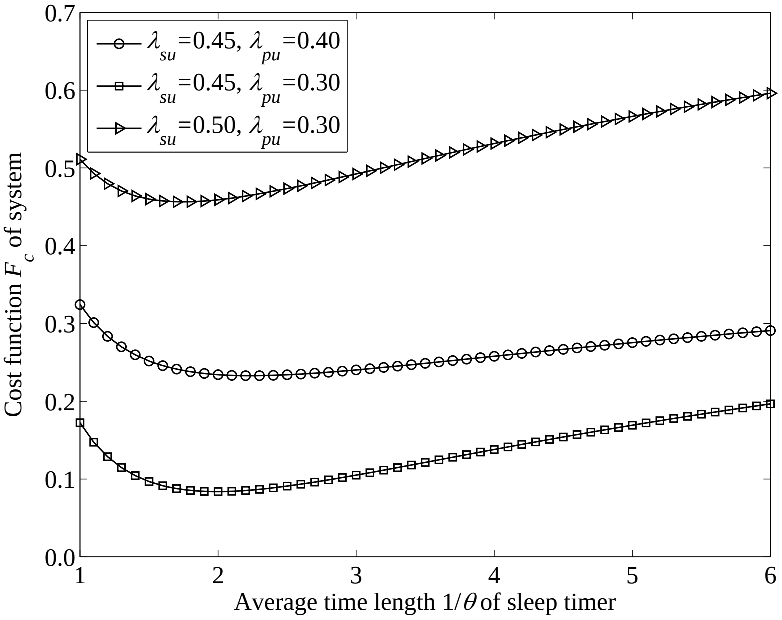

Figure 3. Change trend for the cost function F_c of system

is a minimum cost function F_c^* when the sleep parameter is set to the optimal value θ^* (the average time length of sleep timer is set to the optimal value $1/\theta^*$).

We note that the average latency W of SU packets in Equation (14) is difficult to be given in a close-form. In order to obtain the exact value for the optimal sleep parameter θ^*, we present an efficient iteration algorithm by using the steepest descent optimization method. The steepest descent optimization method is to resolve an unconstrained optimization problem. Referencing to Figure 3, we set the sleep parameter $\theta \in (0, 1]$ in Equation (14); hence the optimization problem in this paper has a constraint of $\theta \in (0, 1]$.

We build an internal point penalty function $F(\theta)$ as follows:

$$F(\theta) = -F_c + g\left(\frac{1}{1-\theta} + \frac{1}{\theta}\right) \tag{15}$$

where $g > 0$ is a penalty factor.

Combining the steepest descent optimization method and the internal point penalty function, we give an iteration algorithm to estimate the optimal sleep parameter θ^* in Table 1.

In Table 1, ϕ is the step factor which is set according to the iteration accuracy of θ, θ_0 is the initial value of θ, θ_k is the kth order approximation of θ, D is the decline coefficient of the penalty factor, and Δ is a number sufficiently close to 0. ϵ is an arbitrary small number. The smaller the value of ϵ is, the higher the accuracy of the optimal sleep parameter θ^*; however, the slower the iteration speed will be.

In iteration algorithm given in Table 1, we set $\phi = 0.02$, $D = 0.10$, $\Delta = 10^{-6}$ and $\epsilon = 10^{-6}$, then we obtain the optimal sleep parameter θ^* and the corresponding minimum cost function F_c^* of system in Table 2.

In Table 2, the estimates of θ^* and F_c^* are accurate to four decimal places.

6. **Conclusions.** In this paper, we addressed the problem of reducing the energy consumption in BS. This is achieved by proposing an energy saving strategy with sleep mode in CRNs. By constructing a two-dimensional continuous-time Markov chain model, we

Table 1. Iteration algorithm to obtain the optimal sleep parameter θ^*

```
Input: $\phi$, $\theta_0$, $D$, $\Delta$, $\epsilon$ and $g$
Output: $\theta^*$

Begin
    $Y_0 = F(\theta_0)$;
    $k = 1$;
    while 1
        $\theta_k = \theta_k - \phi\frac{F(\theta_{k-1}+\Delta) - F(\theta_{k-1})}{\Delta}$;
        $Y_k = F(\theta_k)$;
        if $g\tau(\theta_k) < \epsilon$ and $|Y_k - Y_{k-1}| < \epsilon$ and $|\theta_k - \theta_{k-1}| < \epsilon$
            break;
        end if
        $g = g * D$;
        $k = k + 1$;
    end while
    $\theta^* = \theta_k$;
End
```

Table 2. Optimal proportion θ^* of system

λ_{su}	λ_{pu}	θ^*	$F_c(\theta^*)$
0.50	0.30	0.5741	0.4564
0.45	0.30	0.5029	0.0839
0.45	0.40	0.4470	0.2329

derived the expressions of the performance measures in terms of the average latency of SU packets and the energy saving rate of system. Moreover, we gave statistical experiments with analysis and simulation, and investigated the influences of the system parameter on the performance measures. Numerical results show that there is a trade-off between different performance measures when setting the sleep parameter. Accordingly, a cost function of system was constructed to show the trade-off. Finally, we gave an iteration algorithm to obtain the optimal sleep parameter. The research work in this paper has potential applications in the improvement of energy saving strategy in CRNs.

As a future research, we will investigate the Nash equilibrium and social optimization of the SU packets with the energy saving strategy.

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