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AN ENERGY SAVING STRATEGY IN DIGITAL COGNITIVE RADIO NETWORKS AND ITS PERFORMANCE ASSESSMENT

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Abstract. *With the explosive growth of wireless application, how to improve the spectrum efficiency as well as reduce the communication consumption is a hot topic of research. In this paper, we propose a novel energy saving strategy in digital cognitive radio networks (CRNs). The key idea of this strategy is to set the base station (BS) of CRNs into sleep state when there are not any packets to be transmitted. Accordingly, we develop a Markov chain model to assess the average latency of secondary user (SU) packets and the energy saving ratio of system. Finally, we provide numerical results to show that there is a tradeoff when setting the sleep timer length for the proposed energy saving strategy.*

Keywords: Cognitive radio networks, Energy saving, Priority queue, Multiple vacations, Sleep timer

1. **Introduction.** The rapid growth of wireless application results in an increase in demand for spectrum resource and communication energy. Green energy powered cognitive radio networks (CRNs) are capable of liberating wireless communications from spectral and energy constraints [1].

In wireless networks, sleep mode is one of key techniques to reduce energy consumption. One important way to address the energy saving problem is to introduce sleep mode to the base station (BS). In [2], Dini et al. studied the BS sleep mode as an approach to decrease the energy consumption of LTE HetNets. Rengarajan et al. [3] characterized the maximum energy saving that can be achieved in a cellular wireless access network with sleep mode under a given performance constraint. The analysis results show that the power consumption is reduced by up to 29% by using sleep mode in passive optical networks [4].

Recently, the opportunistic spectrum access mechanism in CRNs has been paid more attention to make the spectrum scarcity less severe that wireless communications face now. The concept of CRNs is regarded as a prosperous technology duo to high spectrum efficiency [5, 6]. In addition to efficient spectrum usage, how to reduce energy consumption is the current problem to be solved. An energy harvesting CRN design will not only ease the spectrum shortage problem, but also result in a green design [7].

From the literature mentioned above, we find that the main method to release the energy constraint is sleep mode, by which communication power can be reduced when the BS is at the sleep state. We also find that the cognitive radio (CR) technology has been studied as an effective solution to alleviate the limitation of the spectrum resource.

In this context, we propose an energy saving strategy with sleep mode in digital CRNs. The proposed strategy highlights how the BS will be switched between the sleep state and awake state to achieve the tradeoff of the energy saving effect and response performance.

In addition, we assess the system performance by constructing a Markov chain model and validate the analytical results with simulations.

The remainder of this paper is organized as follows. In Section 2, we propose an energy saving strategy with sleep mode and build a Markov chain model. In Section 3, we analyze the model and derive the formulas for the performance measures. In Section 4, we demonstrate the influence of system parameters on the system performance with numerical results. Finally, we summarize the conclusions in Section 5.

2. Energy Saving Strategy with Sleep Mode and Markov Chain Model.

2.1. **Energy saving strategy with sleep mode.** In CRNs, the primary user (PU) has high priority to occupy the spectrum. If the spectrum sensing results are perfect, the transmission of a PU packet will not be influenced by secondary user (SU) packets, while the transmission of an SU packet is possible to be interrupted. The interrupted SU packet will queue at the head of the buffer for future transmission.

The BS in conventional digital CRNs is always awake even though there are not any packets, either primary user packet or secondary user packet, to be transmitted or received. In this paper, we propose an energy saving strategy. In order to reduce the energy consumption, the BS will be switched into the sleep state from the awake state when the spectrum is idle and the buffer of SU packets is empty.

Figure 1 shows the state transition of BS in digital CRNs with the energy saving strategy.

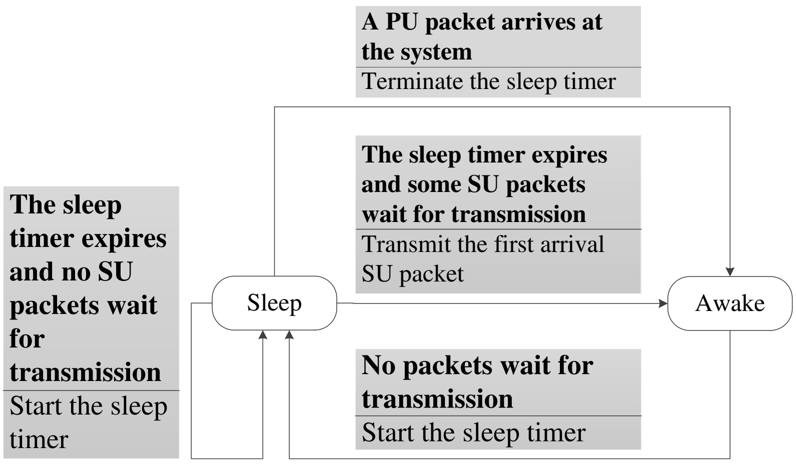

FIGURE 1. The state transition in the energy saving strategy

In Figure 1 we use the rounded corner rectangle to show the state, the bold text above a horizontal line to show the event, and the regular text to show the action. We use the horizontal line to separate the event from the action and the arrow to show the state transition of BS. In the proposed energy saving strategy, the BS will be switched between two states, namely sleep state and awake state, respectively.

a. ***Sleep state.*** When the BS is in the sleep state, two events may occur. If there is no packet arrival before the sleep timer expires, the BS will start another sleep period once the sleep timer is over. If a PU packet arrives at the system during the sleep state, the sleep timer will be stopped immediately, and the BS will be switched to the awake state. Otherwise, if there is at least one SU packet arrival, the BS will be switched to the awake state once the sleep timer expires.
b. ***Awake state.*** If the BS is in the awake state, all the packets will be transmitted continuously. PU packets will be transmitted with high priority, while SU packets

will be transmitted opportunistically. When all the packets are transmitted completely, a sleep timer will be started and the BS will be switched to the sleep state.

We note that the energy consumption is lower when the BS is in the sleep state than that in the awake state. By this way, communication energy will be saved in digital CRNs with the sleep mode.

2.2. **Markov chain model.** We consider a digital CRN with a single licensed channel. The energy saving strategy proposed above is adopted by this system.

We consider the queueing model in discrete-time field. We assume that the arriving intervals of PU and SU packets follow geometric distributions with parameters λ_{pu} ($0 < \lambda_{pu} < 1$, $\overline{\lambda}_{pu} = 1-\lambda_{pu}$) and λ_{su} ($0 < \lambda_{su} < 1$, $\overline{\lambda}_{su} = 1-\lambda_{su}$), respectively. We assume that the transmission time of a PU packet and an SU packet follow geometric distributions with parameters μ_{pu} ($0 < \mu_{pu} < 1$, $\overline{\mu}_{pu} = 1 - \mu_{pu}$) and μ_{su} ($0 < \mu_{su} < 1$, $\overline{\mu}_{su} = 1 - \mu_{su}$), respectively. In addition, we also suppose that the sleep timer length follows a geometric distribution with sleeping parameter θ.

We divide the time axis into equal intervals, and the interval is called a slot. The slots are marked as n ($n = 1, 2, \ldots$). Let $X_n = i$ ($i = 0, 1, 2, \ldots$) be the total number of SU packets at the instant n^+; $Y_n = j$ ($j = 0, 1, 2$) be the state of the BS at the instant n^+ ($j = 0$ means the BS is in the sleep state, $j = 1$ means the BS is awake and a PU packet is being transmitted, $j = 2$ means the BS is awake and an SU packet is being transmitted). According to the above descriptions, a Markov chain model incorporating the total number of SU packets and the state of the BS is established. The state space of the Markov chain $\{(X_n,\ Y_n),\ n \geq 1\}$ is given as follows:

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

Let $\pi_{i,j}$ be the steady state probability that the number of SU packets is i and the state of the BS is j. $\pi_{i,j}$ is given as follows:

$$\pi_{i,j} = \lim_{n\to\infty} P\{X_n = i,\ Y_n = j\}, \quad i = 0, 1, 2, \ldots,\ j = 0, 1, 2. \tag{1}$$

Let $\boldsymbol{\pi_k}$ be the matrix vector representing the number of SU packets is k. $\boldsymbol{\pi_k}$ is then given by

$$\boldsymbol{\pi_k} = (\pi_{k,0}, \pi_{k,1}, \pi_{k,2}),\ k \geq 0. \tag{2}$$

Let $\mathbf{\Pi}$ be the distribution of the steady state of the system which is given as follows:

$$\mathbf{\Pi} = (\boldsymbol{\pi_0}, \boldsymbol{\pi_1}, \boldsymbol{\pi_2}, \ldots). \tag{3}$$

3. Model Analysis and Performance Measures.

3.1. **Model analysis.** We define $\boldsymbol{P}$ as the one step state transition probability matrix of the Markov chain $\{(X_n,\ Y_n),\ n \geq 1\}$. According to the number of SU packets, we give the one step state transition probability matrix $\boldsymbol{P}$ as a block structure as follows:

$$\boldsymbol{P} = \begin{pmatrix} \boldsymbol{B}_{00} & \boldsymbol{B}_{01} & & & \\ \boldsymbol{B}_{10} & \boldsymbol{A}_1 & \boldsymbol{A}_0 & & \\ & \boldsymbol{A}_2 & \boldsymbol{A}_1 & \boldsymbol{A}_0 & \\ & & \ddots & \ddots & \ddots \end{pmatrix}.$$

(1) $\boldsymbol{B}_{00}$ means that there is no SU packet in the system at the instant $t = n^+$, and that no SU packet arrives at the system within the $(n + 1)$th slot. The state transition of the system depends on the behaviors of PU packets. $\boldsymbol{B}_{00}$ is then given by

$$\boldsymbol{B}_{00} = \overline{\lambda}_{su} \begin{pmatrix} \overline{\lambda}_{pu} & \lambda_{pu} & 0 \\ \mu_{pu}\overline{\lambda}_{pu} & \overline{\mu}_{pu} + \mu_{pu}\lambda_{pu} & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

(2) $\boldsymbol{B}_{01}$ means that there is no SU packet in the system at the instant $t = n^+$, and that an SU packet arrives at the system within the $(n+1)$th slot. The state transition of the system is relevant to the behaviors of PU packets and that whether the sleep period is over or not at the instant $t = (n+1)^+$. $\boldsymbol{B}_{01}$ is then given by

$$\boldsymbol{B}_{01} = \lambda_{su} \begin{pmatrix} \overline{\lambda}_{pu}\overline{\theta} & \lambda_{pu} & \overline{\lambda}_{pu}\theta \\ 0 & \overline{\mu}_{pu} + \mu_{pu}\lambda_{pu} & \mu_{pu}\overline{\lambda}_{pu} \\ 0 & 0 & 0 \end{pmatrix}.$$

(3) $\boldsymbol{B}_{10}$ means that there is an SU packet in the system at the instant $t = n^+$, the transmission of an SU packet is completed successfully within the nth slot, and there is no SU packet arrival at the system within the $(n+1)$th slot. The change of the system state depends on the behavior of PU packets. $\boldsymbol{B}_{10}$ is then given by

$$\boldsymbol{B}_{10} = \mu_{su}\overline{\lambda}_{su} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \overline{\lambda}_{pu} & \lambda_{pu} & 0 \end{pmatrix}.$$

(4) $\boldsymbol{A}_0$ means that there is at least one SU packet in the system at the instant $t = n^+$, no SU packet leaves the system within the nth slot, and that there is an SU packet arrival at the system within the $(n+1)$th slot. If the BS is in the sleep state ($j = 0$) at the instant $t = n^+$, the state transition of the system is relevant to the behavior of PU packets and that whether the sleep period is over or not at the instant $t = (n+1)^+$. If the BS is in the awake state ($j = 1$ or $j = 2$) at the instant $t = n^+$, the state transition of the system only is relevant to the behavior of PU packets. $\boldsymbol{A}_0$ is then given by

$$\boldsymbol{A}_0 = \lambda_{su} \begin{pmatrix} \overline{\lambda}_{pu}\overline{\theta} & \lambda_{pu} & \overline{\lambda}_{pu}\theta \\ 0 & \overline{\mu}_{pu} + \mu_{pu}\lambda_{pu} & \mu_{pu}\overline{\lambda}_{pu} \\ 0 & \overline{\mu}_{su}\lambda_{pu} & \overline{\mu}_{su}\overline{\lambda}_{pu} \end{pmatrix}.$$

(5) $\boldsymbol{A}_1$ means the number of SU packets is fixed at a value larger than 0 during one step transition. When $j = 0$ at the instant $t = n^+$, the change of the BS state is relevant to the behavior of PU packets and that whether the sleep period is over or not at the instant $t = (n+1)^+$. If $j = 1$ or $j = 2$ at the instant $t = n^+$, the state transition of the system is relevant to the behavior of PU packets and SU packets. $\boldsymbol{A}_1$ is then given by

$$\boldsymbol{A}_1 = \begin{pmatrix} \overline{\lambda}_{su} & 0 & 0 \\ 0 & \overline{\lambda}_{su} & 0 \\ 0 & 0 & \overline{\mu}_{su}\overline{\lambda}_{su} + \mu_{su}\lambda_{su} \end{pmatrix} \times \begin{pmatrix} \overline{\lambda}_{pu}\overline{\theta} & \lambda_{pu} & \overline{\lambda}_{pu}\theta \\ 0 & \overline{\mu}_{pu} + \mu_{pu}\lambda_{pu} & \mu_{pu}\overline{\lambda}_{pu} \\ 0 & \lambda_{pu} & \overline{\lambda}_{pu} \end{pmatrix}.$$

(6) $\boldsymbol{A}_2$ means that there is at least two SU packets in the system at the instant $t = n^+$, there is an SU packet departure from the system within the nth slot, and that there is no SU packet arrival at the system within the $(n+1)$th slot. The state transition of the system is relevant to the behavior of PU packets. $\boldsymbol{A}_2$ is then given by

$$\boldsymbol{A}_2 = \mu_{su}\overline{\lambda}_{su} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \lambda_{pu} & \overline{\lambda}_{pu} \end{pmatrix}.$$

Up to now, all the sub matrice in $\boldsymbol{P}$ are addressed. The structure of $\boldsymbol{P}$ shows that the system transition occurs only in adjacent levels. So the two dimensional Markov chain $\{(X_n,\ Y_n),\ n \geq 1\}$ can be seen as a kind of quasi birth and death (QBD) process. Moreover, it is clear that the rows of the transition probability matrix $\boldsymbol{P}$ are repeating after the third row.

For the QBD chain of the transition probability matrix $\boldsymbol{P}$, the necessary and sufficient condition of Markov chain $\{(X_n,\ Y_n),\ n \geq 1\}$ positive recurrence is that the matrix quadratic equation

$$\boldsymbol{R}^2\boldsymbol{A}_2 + \boldsymbol{R}\boldsymbol{A}_1 + \boldsymbol{A}_0 = \boldsymbol{R} \tag{4}$$

has a minimal non-negative solution $\boldsymbol{R}$ and the spectral radius $SP(\boldsymbol{R}) < 1$, and the 6 dimensional stochastic matrix

$$B[\boldsymbol{R}] = \begin{pmatrix} \boldsymbol{B}_{00} & \boldsymbol{B}_{01} \\ \boldsymbol{B}_{10} & \boldsymbol{A}_1 + \boldsymbol{R}\boldsymbol{A}_2 \end{pmatrix}$$

has left invariant vector. When Markov chain is positively recurrent, its stationary distribution satisfies

$$\begin{cases} \boldsymbol{\pi}_k = \boldsymbol{\pi}_1\boldsymbol{R}^{k-1},\ k \geq 1 \\ (\boldsymbol{\pi}_0, \boldsymbol{\pi}_1) = (\boldsymbol{\pi}_0, \boldsymbol{\pi}_1)B[\boldsymbol{R}] \\ \boldsymbol{\pi}_0\boldsymbol{e} + \boldsymbol{\pi}_1(\boldsymbol{I} - \boldsymbol{R})^{-1}\boldsymbol{e} = 1 \end{cases} \tag{5}$$

where $\boldsymbol{e}$ is a 3 dimensional column vector with all elements being equal to one.

With the help of the matrix geometric solution, we can get the steady state probability $\pi_{i,j}$ defined in Equation (1) with numerical results.

3.2. **Performance measures.** We define the latency of an SU packet as the time duration from the instant at which an SU packet joins the system to the instant that the SU packet is successfully transmitted. With Little's formula, the average latency $\overline{W}_{su}$ of SU packets is given by

$$\overline{W}_{su} = \frac{1}{\lambda_{su}} \sum_{i=0}^{\infty} \sum_{j=0}^{2} i\pi_{i,j}. \tag{6}$$

The energy saving ratio is defined as the reduction of the energy consumption per slot due to the introduction of the sleep mode. Energy is consumed normally in the awake state and is saved in the sleep state. In addition, each listening procedure also needs to consume energy. Therefore, the energy saving ratio δ is given as follows:

$$\delta = (C_A - C_S) \sum_{i=0}^{\infty} \pi_{i,0} - C_L\overline{\lambda}_{pu}\theta \sum_{i=0}^{\infty} \pi_{i,0} \tag{7}$$

where C_A and C_S are the energy consumptions per slot when the BS in the awake state and the sleep state, respectively; C_L is the energy consumption for each listening procedure.

4. **Numerical Results.** In this section, we first describe our experiment environment and then discuss the numerical results. To investigate the performance of digital CRNs with sleep mode for different sleeping parameters as well as the arriving parameters of PU and SU packets, we carry out a comparison between the proposed digital CRNs with an energy saving strategy and the conventional IEEE 802.11 network.

Referencing to [8], we assume that every IEEE 802.11 user independently generates its data packet, and that the packet size is geometrically distributed with a mean of 8000 bits. Accordingly, we set the parameters in Table 1.

Figure 2 shows how the average latency $\overline{W}_{su}$ of SU packets changes versus the sleeping parameter θ for given arriving parameters λ_{su} of SU packets and λ_{pu} of PU packets.

By observing Figure 2, we find that for the same arriving parameters λ_{pu} of PU packets and λ_{su} of SU packets, the average latency $\overline{W}_{su}$ of SU packets will decrease as the sleeping

Table 1. Numerical parameters

Parameter	Value
Carrier frequency	2.4 GHz
Data transmission rate	2 Mbps
Unit time slot	1 ms
Energy consumption of sleep period for per slot (C_S)	1 mJ
Energy consumption of awake period for per slot (C_A)	6 mJ
Energy consumption for each listening procedure (C_L)	2 mJ
Serving parameter μ_{pu} of PU packets	0.7
Serving parameter μ_{su} of SU packets	0.8

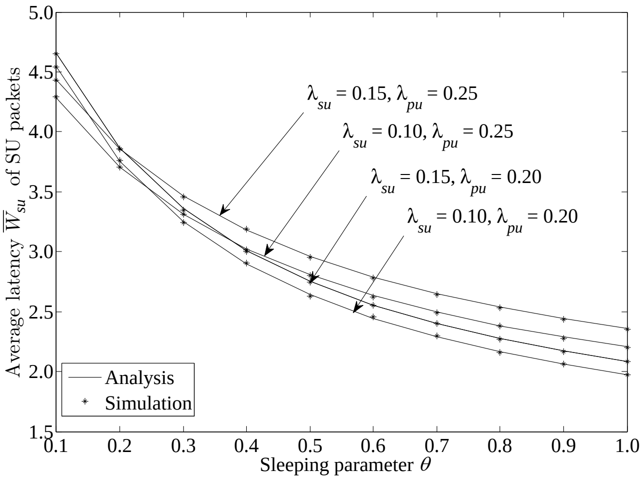

Figure 2. Average latency $\overline{W}_{su}$ of SU packets

parameter θ increases. The reason is that the larger the sleeping parameter is, the shorter the average sleep timer length is, and the earlier the instant that a newly arriving SU packet will start to occupy the spectrum is. So the average latency $\overline{W}_{su}$ of SU packets will be smaller.

In addition, when fixing the arriving parameter λ_{su} of SU packets, we find that the arriving parameter λ_{pu} of PU packets has impact on the average latency $\overline{W}_{su}$ of SU packets. For a smaller sleeping parameter θ, the average latency $\overline{W}_{su}$ of SU packets will decrease as the arriving parameter λ_{pu} of PU packets increases. However, for a larger sleeping parameter θ, the average latency $\overline{W}_{su}$ of SU packets will increase as the arriving parameter λ_{pu} of PU packets increases. From another point of view, we find that for the same arriving parameter λ_{pu} of PU packets and the same sleeping parameter θ, the larger the arriving parameter λ_{su} of SU packets is, the greater the average latency $\overline{W}_{su}$ of SU packets will be.

Figure 3 illustrates how the energy saving ratio δ changes versus the sleeping parameter θ for different arriving parameters λ_{su} of SU packets and λ_{pu} of PU packets.

From Figure 3, we find that for the same arriving parameters λ_{pu} of PU packets and λ_{su} of SU packets, the energy saving ratio δ will decrease as the sleeping parameter θ increases. It is because that the larger the average sleeping parameter is, the shorter the sleep timer length is, and the less the energy is saved. On the other hand, we also find that for the same sleeping parameter θ, the energy saving ratio δ will increase as the arriving parameters λ_{su} of SU packets and λ_{pu} of PU packet decrease.

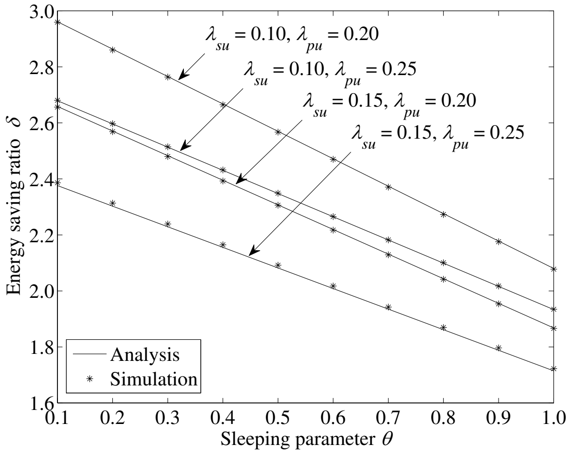

Figure 3. Energy saving ratio δ

Comparing the results shown in Figures 2 and 3, we get the conclusion that a greater sleeping parameter will result in not only a smaller average latency of SU packets but also a smaller energy saving ratio; a smaller sleeping parameter will result in not only a greater average latency of SU packets but also a larger energy saving ratio. That is to say, there is a tradeoff to be considered when designing the sleeping timer length in the proposed energy saving strategy.

5. **Conclusions.** In this paper, we propose and survey a novel energy saving strategy in digital CRNs. By building a two dimensional Markov chain, the system model is analyzed in steady state, and the average latency of SU packets and the energy saving ratio are derived. With the numerical results of analysis and simulation, the influence of the sleep timer length on the system performance is illustrated. Moreover, the tradeoff between the system performance is investigated. As future research, we will study the optimization problem of the sleep timer length.

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