Auction-based Energy-Spectrum Trading in Green Cognitive Cellular Networks

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Auction-based Energy-Spectrum Trading in Green Cognitive Cellular Networks

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Abstract—Green communications has received much attention recently. For cellular networks, the base stations (BSs) account for more than 50 percent of the energy consumption of the networks. Therefore, reducing the power consumption of BSs is crucial to enhance the energy efficiency of cellular networks. Meanwhile, the mobile data traffic is expected to increase exponentially. To accommodate the increasing data traffic with the limited radio frequency, enhancing the spectrum efficiency is critical for next generation cellular networks. In this paper, we propose an auction-based energy-spectrum trading scheme which exploits the cooperation between primary base stations (PBSs) and the secondary base stations (SBSs) to enhance the energy as well as spectrum efficiency of cellular networks. In the cooperation, by leveraging cognitive radio, PBSs share the licensed spectrum with SBSs, and the SBSs provide data service to the primary users under its coverage utilizing the shared bandwidth. The cooperation between PSBs and SBSs can significantly improve the energy and spectral efficiency of cellular networks. However, optimizing the bandwidth sharing between PBSs and SBSs is an NP-hard problem. Solving such problem using centralized algorithms is not computationally efficient, especially when considering a large number of PBSs and SBSs. Thus, we design an auction-based decentralized mechanism to enable the cooperation between PBSs and SBSs. Simulation results that demonstrated the performance and viability of the proposed decentralized mechanism.

I. INTRODUCTION

Owing to the direct impact of greenhouse gases on the earth environment and the climate change, the energy consumption of Information and Communications Technology (ICT) is becoming an environmental and thus social and economic issue. Cellular networks are among the major energy huggers of communication networks, and their contributions to the global energy consumption increase rapidly. Therefore, greening cellular networks is crucial to reducing the carbon footprints of ICT, and attracts tremendous research efforts from both academia and industry [1]–[8].

In this paper, we propose an auction-based energy-spectrum trading (EST) scheme to improve the energy efficiency as well as the spectral efficiency of cellular networks. By taking advantages of cognitive radio techniques, the EST scheme enables spectrum sharing between primary base stations (PBSs) and secondary base station (SBSs) to reduce the power consumption of PBSs and increase the spectral efficiency of cellular networks. Here, a PBS is a macro/micro BS which owns the spectrum and provides data services to primary users (PUs) within a large area. The SBS is a radio access point aiming to provide data services to secondary users (SUs) within its coverage area via either the unlicensed spectrum or the licensed spectrum. The PBS has the exclusive access to the licensed band. However, owing to the wireless channel fading between the PBS and PUs, providing high data rates to the PUs, especially to those located at the cell edge, is both bandwidth and power consuming. As compared with the PBS, the SBSs which are closer to the PUs may experience less wireless channel fading and have higher spectral and energy efficiency in providing data services to the PUs. However, owing to its openness, the unlicensed spectrum becomes increasingly crowded, and the quality of service (QoS) of data services on unlicensed band cannot be guaranteed. The proposed auction-based EST scheme, by exploiting the merits of both the PBS and SBSs, enables the PBSs trading their spectrum for power savings. The EST scheme, PBSs share the licensed spectrum with SBSs, and the SBSs provide data service to the primary users under its coverage. In the EST scheme, at the beginning of each time slot, the SBSs bid for the spectrum usage. Then, the PBSs decide the winning bids according to the proposed winning bid selection algorithm. After each round of auctions, in order to enhance their probabilities of winning the auction, the SBSs adjust their bids by adapting the data requirements according to the auction result of the previous time slot. Meanwhile, the PBSs, to maximize their energy savings, also adjust the amount of bandwidth that are provided for auction by adapting the power consumption weight of individual PUs. In the auction-based EST scheme, the truth telling is proved to be a dominant strategy for SBSs that enables the auction game to converge to the Nash equilibrium.

II. SYSTEM MODEL

In this paper, we consider a graphic area consisting of one PBS and several SBSs. The PBS provides data service to the PUs within its coverage area via licensed spectrum. SBSs are randomly located in the area and aim to opportunistically utilize the licensed spectrum to transmit data to SUs. The PUs within SBSs’ coverage area can be associated with either

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the PBS or SBSs. In cellular networks, the total spectrum is usually split into multiple channels which are allocated to the users to fulfill their QoS requirements. In the following, we assume the licensed spectrum band can be split into channels with arbitrary amount of bandwidth. Each channel is allocated to an individual PU as needed. The amount of bandwidth allocated in each channel is optimized to minimize the PBS’s power consumption. For simplicity, we assume both PUs and SUs experience frequency flat fading. Therefore, we focus on the amount of bandwidth allocated to PUs and SBSs instead of specifying which part of the spectrum to be allocated. The time horizon is assumed to be divided into time frames of duration $T$. Users’ locations are assumed to be static during one time frame. We assume the channel fading changes slowly and can be considered as a constant within a time frame. Therefore, the wireless channel is modeled as a slow-fading channel which reflects the large-scale fading between BSs and users. Denote $r_{i}^{\text{min}}$ and $w_{i}$ as PU $i$’s data rate requirement and bandwidth requirement in associating with the PBS. Since there may exist a SBS $k$ which is much closer to PU $i$, PU $i$, in association with SBS $k$, requires less bandwidth than $w_{i}$ to satisfy the data rate requirement. Thus, given the amount of bandwidth $w_{i}$, if PU $i$ is associated with SBS $k$, a portion of bandwidth will be underutilized. SBS $k$ is able to exploit the underutilized spectrum for data transmission for SUs, thus enhancing the spectral efficiency of the networks. We assume one time frame is further divided into multiple time slots. At the beginning of each time slot, SBSs calculate the bandwidth requirements in serving individual PUs, and send the bids to the PBS. Upon receiving the bids, the PBS selects the bids with the least amount of bandwidth requirements on individual PUs, calculates the maximum amount of bandwidth that can be allocated to the PUs, and then determines user-BS associations and bandwidth allocations.

The PBS’s power consumption consists of two parts: the static power consumption and the dynamic power consumption [9]. The static power consumption is the power consumption of a BS without any traffic load. The dynamic power consumption refers to the additional power consumption caused by traffic load on the BS. Although the static power consumption contributes a significant amount of the total power consumption on a BS, we do not model the static power consumption in our problem because we focus on reducing the dynamic power consumption of a PBS by offloading its traffic to SBSs. Therefore, we model the PBS’s power consumption as the summation of the PBS’s transmission power toward the PUs that are associated with the PBS.

### III. An Auction-based EST Scheme

The profit of a PBS for cooperating with SBSs is reducing its energy consumption. Therefore, the PBS aims to maximize its energy savings by sharing its spectrum with SBSs. Meanwhile, the incentive of SBSs for cooperating is to gain spectrum for their own data transmission. To compensate for the cost in providing data service to the PUs, SBSs set a minimum data rate requirement. SBSs cooperate with PBSs only when the minimum data rate is satisfied. According to the Shannon-Hartley theorem, given the channel fading coefficient $h_{i}$, the PBS’s transmit power toward PU $i$, $p_{i}$, is a function of the bandwidth allocation $w_{i}$ and the data rate $r_{i}$, and it can be expressed as

$$p_{i} = \frac{N_{0}w_{i}(2^{\frac{r_{i}}{h_{i}}} - 1)}{h_{i}^{2}}. \quad (1)$$

Here, $N_{0}$ is the channel noise density. Let $U$ be the set of PUs, $U^{p}$ be the set of PUs who are associated with the PBS, $U^{k}$ be the set of PUs who are associated with SBS $k$, and $S$ be the set of SBSs. The energy consumption minimization (ECM) problem can be expressed as follows,

$$\min \sum_{i \in U^{p}} p_{i} \quad (2)$$

subject to:
- $\sum_{i \in U^{p}} w_{i} + \sum_{i \in U^{k}} \bar{w}_{i} \leq W$,
- $r_{i} \geq r_{i}^{\text{min}}, \forall i \in U$,
- $p_{i} \leq p_{i}^{\text{max}}, \forall i \in U^{p}$,
- $p_{i} \leq p_{k}^{\text{max}}, \forall k \in S, \forall i \in U^{k}$,
- $\bar{r}_{k,i} \geq \bar{r}_{k,i}^{\text{min}}, \forall k \in S, \forall i \in U^{k}$. \quad (3)

Here, $p_{i}$ is the PBS’s transmit power to PU $i$, $p_{i}^{\text{max}}$ is the PBS’s maximum transmit power, $\bar{p}_{i}$ is the SBS’s transmit power, $p_{k}^{\text{max}}$ is the maximum transmit power of SBS $k$, $W$ is the total amount of bandwidth, $\bar{w}_{i}$ is the amount of bandwidth allocated to SBS who provide data service to PU $i$, $r_{i}^{\text{min}}$ is the minimum data rate requirement of SBS $k$ in serving one PU, and $\bar{r}_{k,i}$ is the secondary data rate (SDR) achieved by SBS $k$ in serving PU $i$. $\bar{r}_{k,i}$ can be expressed as

$$\bar{r}_{k,i} = (\bar{w}_{i} - \hat{w}_{k,i}) \log \left(1 + \frac{\hat{p}_{i}^{\text{h}}}{N_{0}\bar{w}_{k,i}}\right) \quad (4)$$

Here, $\hat{p}_{i}$ is the fading coefficient between SBS $k$ and its secondary user, and $\hat{w}_{k,i}$ is the amount of bandwidth required by SBS $k$ to satisfy PU $i$’s data rate requirements, which can be derived by solving

$$r_{i} = \hat{w}_{k,i} \log \left(1 + \frac{\hat{p}_{i}^{\text{h}}}{N_{0}\hat{w}_{k,i}}\right). \quad (5)$$

Here, $\hat{h}_{k,i}$ is the fading coefficient between SBS $k$ and PU $i$.

**Lemma 1.** The ECM problem is an NP-hard problem.

**Proof:** In the ECM problem, PUs can associate with either the PBS or SBSs. Different user-BS association results in different solutions for the ECM problem. Therefore, achieving the optimal solution of the ECM problem involves a 0-1 integer programming problem which is an NP-hard problem [10]. Therefore, the ECM problem is an NP-hard problem. □

Since the ECM problem is NP-hard, it is not easy to solve the problem efficiently, especially when the network consists of a large number of PBSs and SBSs. We thus design an auction-based EST scheme to approximate the solution of the...
ECM problem. In the auction-based EST scheme, SBSs bid for the spectrum usage while the PBS selects its cooperators based on the given bids to minimize its power consumption. The interactions between the PBS and SBSs can be modeled as a repeated auction game, in which the players are the PBS and SBSs, and the actions are 1) SBSs choose the bandwidth requirement in serving individual PUs within their coverage; 2) the PBS calculates the maximum amount of bandwidth that can be allocated to individual PUs and decides the winning bids. We shall next present both SBSs’ and the PBS’s actions.

A. SBSs’ Actions

At the beginning of each time slot, SBSs calculate their bids in serving individual PUs. The incentive of SBSs in cooperating with the PBS is to utilizing the licensed bandwidth to transmit data for SUs. Define the data rate achieved by individual SBSs in cooperating with the PBS as the secondary data rate (SDR). Each SBS has its own valuation in term of SDR. Therefore, SBSs have to learn the amount of bandwidth required in serving the PU. Since the SBS is bidding for while the second element presents decrease its expected SDR. However, SBS $i$ decreases its expected SDR in serving individual PUs, and SBSs have to learn the amount of bandwidth required in serving the PU. Since $\bar{w}_{k,i}$ decreases its expected SDR. However, SBS $i$ decreases its expected SDR. SBS $i$ expects to achieve a SDR of $\bar{w}_{k,i}$. Assuming SBSs always transmit with their maximal transmission power, $\bar{r}_{k,i}$ can be expressed as

$$\bar{r}_{k,i} = \bar{w}_{k,i} \log(1 + \frac{\bar{p}_k |\bar{h}_k|^2}{N_0 \bar{w}_{k,i}}) \quad (6)$$

Note that $\bar{w}_{k,i}$ can be derived by solving Eq 6. Then, the amount of bandwidth required by SBS $k$ in serving PU $i$ is $\bar{w}_{k,i} = \bar{w}_{k,i} + \tilde{r}_{k,i}$. Therefore, SBS $k$’s bid for serving PU $i$ is $(\bar{r}_{k,i}, \bar{w}_{k,i})$. The first element of the bid indicates which PU the SBS is bidding for while the second element presents the amount of bandwidth required in serving the PU. Since multiple SBSs may bid for the same PU, SBSs have to learn and adapt their expected SDR in serving individual PUs, and update the bandwidth requirements in their bids. When SBS $k$’s bid for PU $i$ is selected, at the next time slot, SBS $k$ increases its expected SDR in serving PU $i$. Otherwise, SBS $k$ decreases its expected SDR. However, SBS $k$ requires the minimum SDR $\bar{r}_{k,i}^{\min}$ in serving PU $i$. Therefore, $\tilde{r}_{k,i}$ should be larger than $\bar{r}_{k,i}^{\min}$ in order to incentivize SBS $k$ to cooperate with the PBS. Denote $\Delta \beta$ as the SBS’s data rate adaptation step. The individual SBS’s learning and adaptation algorithm is illustrated as Algorithm 1:

Algorithm 1 The SBS’s Rate Adaptation Algorithm

```text
for $i = 1$ to $|U|_k$ do
  if ($\bar{w}_i > \bar{w}_{k,i}^{\min}$) then
    $\tilde{r}_{k,i} = \bar{r}_{k,i} + \Delta \beta$;
  else
    $\tilde{r}_{k,i} = \max(\bar{r}_{k,i} - \Delta \beta, \bar{r}_{k,i}^{\min})$;
  end if
end for
Return $\tilde{r}_{k,i}, i \in U_k$.
```

B. The PBS’s Actions

Since the total amount of bandwidth is limited, the PBS sets the maximum amount of bandwidth that can be allocated to individual PUs. Denote $w_i^{\max}$ as the maximum bandwidth that the PBS is willing to allocate to PU $i$ at a given time slot. The PBS’s bidding selection includes two steps. Define the highest-bid as the bid that requires the least amount of bandwidth in serving individual PUs. The first step is to find the highest-bid for individual PUs. The second step is to decide the user-SUs associations and bandwidth allocations. Let $(i, \bar{w}_{m,i}^{\min})$ and $(i, \bar{w}_{m,i}^{\max})$ be the highest-bid and second highest-bid for PU $i$, respectively. If there is only one bid for a PU, we set $\bar{w}_{m,i}^{\min} = \min(\bar{w}_{k,i}^{\min}, w_i^{\max})$. If $\bar{w}_{k,i}^{\min} > w_i^{\max}$, PU $i$ is associated with the PBS at the current time slot. Otherwise, PU $i$ is associated with SBS $k$. If $\bar{w}_{m,i}^{\min} < w_i^{\max}$, the amount of bandwidth allocated to SBS $k$ equals to $\bar{w}_{m,i}^{\max}$, otherwise, it equals to $w_i^{\max}$. Let $B_i$ denote the set of SBSs who bid for serving PU $i$. The pseudo code of the winning bid selection algorithm is illustrated as Algorithm 2.

Algorithm 2 The Winning Bid Selection Algorithm

```text
for $i = 1$ to $|U|$ do
  $k = \arg \min_{j \in B_i} \bar{w}_{j,i}^{\min}$;
  if ($\bar{w}_{m,i}^{\min} \leq w_i^{\max}$) then
    $m = \arg \min_{j \in B, j \neq k} \bar{w}_{j,i}^{\min}$;
    if ($\bar{w}_{m,i}^{\min} \leq w_i^{\max}$) then
      The granted bandwidth $\bar{w}_{k,i} = \bar{w}_{m,i}^{\min}$;
    else
      The granted bandwidth $\bar{w}_{k,i} = w_i^{\max}$;
    end if
  end if
  Associates PU $i$ with SBS $k$;
end if
Return the user-BS associations and $\bar{w}_{k,i}, i \in U$.
```

Theorem 1. The winning bid selection algorithm enforces truth telling to be individual SBSs’ dominant strategy, which maximizes individual SBSs’ profits.

Proof: Let $\bar{w}_{k,i}^{\max}$ be the actual amount of bandwidth required by SBS $k$ in serving PU $i$, $\bar{w}_{k,i}^{\min}$ be the amount of bandwidth presented in the bid, and $\bar{w}_{m,i}^{\max}$ and $\bar{w}_{m,i}^{\min}$ be the amount of bandwidth presented in the second highest-bid. On the one hand, assume $\bar{w}_{k,i}^{\min} > \bar{w}_{k,i}^{\max}$, which indicates that SBS $k$ requires more bandwidth in its bid. If $\bar{w}_{k,i}^{\min} < \min(w_i^{\max}, \bar{w}_{m,i}^{\min})$, SBS $k$ wins the bid, and the amount of bandwidth allocated to SBS $k$ equals to $\min(w_i^{\max}, \bar{w}_{m,i}^{\min})$. However, if $\bar{w}_{k,i}^{\min} < \min(w_i^{\max}, \bar{w}_{m,i}^{\max})$, $\bar{w}_{k,i}^{\min} < \bar{w}_{m,i}^{\min}$, SBS $k$ loses the bid because of its presenting a larger bandwidth demand in its bid. In this case, if SBS $k$ bids its valuation, $\bar{w}_{k,i}$, then it wins the bid and is allocated the amount of bandwidth equaling to $\min(w_i^{\max}, \bar{w}_{m,i}^{\max})$. Therefore, asking for more than the actual required amount of bandwidth in the bid does not gain
more bandwidth but has the probability to lose the bid. On the other hand, assume \( \bar{w}_{k,i}^{\min} < \bar{w}_{k,i} \), which indicates that SBS \( k \) asks for less than its actual required amount of bandwidth in its bid. If \( \bar{w}_{k,i}^{\min} < \min(w_i^{\max}, \bar{w}_{m,i}) \), SBS \( k \) wins the bid, and the amount of bandwidth allocated to SBS \( k \) equals to \( \min(w_i^{\max}, \bar{w}_{m,i}) \). If \( \bar{w}_{k,i}^{\min} < \min(w_i^{\max}, \bar{w}_{m,i}) < \bar{w}_{k,i} \), although SBS \( k \) wins the bid, the amount of bandwidth allocated to SBS \( k \) is less than the amount of bandwidth required to achieve its expected SDR. Thus, SBS \( k \) achieves negative profits in the cooperation. Instead, if SBS \( k \) bids for its actual bandwidth requirements, \( \bar{w}_{k,i} \), it will lose the bid and has a zero profit. Therefore, there is no incentive for SBSs not to reveal their actual bandwidth requirements in their bids. Hence, truth telling is the dominant strategy for SBSs.

To minimize its power consumption, the PBS is to maximize the number of PUs associating with SBSs while minimizing the amount of bandwidth allocated to SBSs. Therefore, if PU \( i \) is successfully associated with SBSs at one time slot, the PBS is to reduce \( w_i^{\max} \) at the next time slot; otherwise, the PBS is to increase \( w_i^{\max} \). To adjust \( w_i^{\max} \), the PBS assigns PU \( i \) a power consumption weight \( \eta_i \) which is a positive number that indicates the importance of the PU on minimizing the PBS’s power consumption. Given \( \eta_i, \bar{w}_{k,i} \), \( w_i^{\max} \) can be calculated by the weighted power consumption minimization (WPCM) problem:

\[
\min \sum_{i \in U} \eta_i p_i \quad \text{(7)}
\]

subject to:

\[
\sum_{i \in U} w_i^{\max} \leq W, \quad r_i \geq r_i^{\min}, \forall i \in U, \quad w_i^{\max} \geq w_i^{\min}. \quad \text{(8)}
\]

When \( w_i > 0, \frac{\partial p_i}{\partial w_i} > 0 \). Thus, \( p_i \) is a convex function of \( w_i \). Therefore, the objective function is convex. The constraints of the WPCM problem satisfy the Slater’s conditions, and therefore the Karush-Kuhn-Tucher (KKT) conditions provide necessary and sufficient conditions for the optimality of the WPCM problem. The optimal solution of the WPCM problem can be obtained by solving its KKT conditions. If the PBS increases \( \eta_i, w_i^{\max} \) will be increased, and vice versa. Therefore, at the beginning of each time slot, the PBS updates \( \eta_i, i \in U \) to adapt \( w_i^{\max} \), \( i \in U \) according to the user-BS associations of the previous time slot. The power consumption weight adaptation algorithm works as follows, as shown in Algorithm 3.

Algorithm 3: The Power Consumption Weight Adaptation

```
for i = 1 to |U|
do
  if \( \eta_i^{\max} > \min\eta_{k,i}^{\min}, k \in B_i \) then
    \( \eta_i = \min(\eta_i - \Delta \eta, \eta_i^{\min}) \);
  else
    \( \eta_i = \max(\eta_i + \Delta \eta, \eta_i^{\max}) \);
  end if
end for

Return \( \eta_i, i \in U \)
```

Three simulations are set up to evaluate the performance of the auction-based EST scheme. In the simulations, the PBS’s maximum transmit power toward individual PU is 2 \( W \). We adopt COST 231 Walfisch-Ikegami [11] as the propagation model with 9 \( dB \) Rayleigh fading and 5 \( dB \) shadowing fading. The carrier frequency is 2110 \( MHz \), the antenna feeder loss is 3 \( dB \), the transmitter gain is 1 \( dB \), the noise density is \( 10^{-10} \) \( W/Hz \), and the receiver sensitivity is -97 \( dB \). We deploy one PBS and two SBSs in the network. The SBSs are located at the cell edge and close to each other. Thirty PUs are randomly distributed at the cell edge.

Fig. 1 compares the PBS’s power consumption of traditional cellular networks versus the cellular networks enabled with the EST scheme, and shows the total SDR achieved by the secondary networks. In the figure, the plot reflects the PBS’s power consumption and the SDR in five time frames. In each time frame, there are thirty time slots. As compared with traditional cellular networks, the EST scheme significantly reduces the PBS’s power consumption. Meanwhile, the data rate achieved by SBSs is up to 53 Mbps, which indicates that the EST scheme enhances the spectral efficiency of cellular networks. Because both SBSs and the PBS are considered to be greedy, and they always try to increase their profits, the PBS’s power consumption and the SBSs’ data rate fluctuate owing to the interactions between the PBS and SBSs. For example, if a PU is close to only one of the SBSs, the PU is associated that SBS. According to the EST scheme, at the next time slot, the SBS will increase its minimum SDR in serving this PU. Meanwhile, the PBS will reduce the power consumption weight on the PU. When meeting the SBS’s minimum...
SDR requires more bandwidth than the maximum bandwidth that the PBS is willing to spend, the PU is associated with the PBS, and thus the PBS’s power consumption will increase, and the SBSs’ data rate will decrease. At the next time slot, the SBS will reduce its minimum SDR while the PBS will increase the power consumption weight on the PU. As a result, the PU’s user-BS association may switch between the PBS and the SBS from one time slot to another, and thus the PBS’s power consumption and the SBSs’ data rate fluctuate. The amplitude of fluctuation is determined by adaptation step sizes of the PBS and the SBSs. These PUs are out of the coverage area of the other SBSs.

The first category of PUs can be associated with either of the SBSs. The SDR adaptations on SBS 1 and SBS 2, respectively. Since the PU can only be associated with SBS 1, the SBS 2’s minimum SDR on the PU keeps decreasing to the minimal value. The interactions between SBS 1 and the PBS lead to the fluctuations of SBS 1’s minimum SDR and the PBS’s power consumption weight on the PU. The PBS’s power consumption weight on the PU is plot in blue in the power consumption weight sub-figure. The second category of PUs can be associated with either of the SBSs. The SDR adaptations on SBS 1 and SBS 2 are plot in red with circle markers and square markers indicate the minimum SDR adaptations on SBS 1 and SBS 2, respectively. Since the PU can only be associated with SBS 1, the SBS 2’s minimum SDR on the PU keeps decreasing to the minimal value. The interactions between SBS 1 and the PBS lead to the fluctuations of SBS 1’s minimum SDR and the PBS’s power consumption weight on the PU. The PBS’s power consumption weight on the PU is plot in blue in the power consumption weight sub-figure. The second category of PUs can be associated with either of the SBSs. The SDR adaptations on SBS 1 and SBS 2 are plot in red with circle markers and square markers, respectively. The SBSs’ minimum SDR adaptations reflect the interactions between them. Taking advantages of the competition between the SBSs, the PBS is able to keep reducing the power consumption weight on the PU. This is shown in the power consumption weight plotted in red. The third category of PUs cannot be associated with either SBSs. These PUs are out of the coverage area of the SBSs. Therefore, there are no interaction between the PBS and the SBSs. As a result, for these PUs, the PBS keeps increasing their power consumption weight and the SBSs keep reducing their minimum SDRs. From the above observations, we can see that when the PUs are under the coverage of the SBSs, the proposed auction-based EST scheme enables the cooperation between the PBS and SBSs. Based on the proposed scheme, when the PUs are under the SBSs’ coverage, the SDRs of the SBSs fluctuate around a mean value. The amplitude of the variation is determined by the step sizes of the SBSs’ rate adaptations. In addition, the power consumption weights of the PBS also converge to a mean value. Hence, despite of the greediness of the PBS and SBSs, the proposed EST scheme enables the PBS and SBSs to reach an agreement on cooperating in serving PU mobile users. Therefore, the proposed auction-based scheme enables the energy spectrum trading between the PBS and SBSs.

V. Conclusion

In this paper, we have proposed an auction-based EST scheme, in which the PBS and SBSs share the licensed bandwidth to improve the power efficiency as well as spectral efficiency of the cellular networks. Achieving optimal bandwidth sharing among the PUs and the SBSs in term of maximizing the energy savings of the PUs is an NP-hard problem. The auction-based EST scheme approximates the solution of the ECM problem in a distributed manner, and significantly improves the power efficiency and spectral efficiency of cellular networks.

References