# Energy–Spectral Efficiency Tradeoff in Cognitive Radio Networks

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***Abstract*—In this paper, we propose a general framework to evaluate the tradeoff between energy efficiency (EE) and spectral efficiency (SE) in cognitive radio networks (CRNs). The proposed framework is discussed in three typical CRN paradigms: underlay CRNs (UCRNs), overlay CRNs (OCRNs), and interweave CRNs (ICRNs). The EE–SE relation for three CRNs is expressed in the closed-form formulation, in which the optimal (suboptimal) EE solution as the function of SE is deduced with the corresponding limits. The theoretical analysis and numerical results indicate that the EE–SE relation in CRNs is not contrary, i.e., an optimal EE–SE tradeoff can be achieved. The proposed framework provides a useful guidance in the design of practical green CRNs.**

***Index Terms*—Cognitive radio networks (CRNs), energy efficiency (EE), energy–spectral efficiency tradeoff, spectral efficiency (SE).**

## I. Introduction

Cognitive radio networks (CRNs), aiming to deal with the current scarcity of useful spectrum by dramatically improving the spectral efficiency (SE), were originally proposed in Mitola's Ph.D. dissertation [1] and have now become one of the most promising communication technologies in both academia [2], [3] and industry [4].

According to the coexistence mechanism with the primary user (PU) systems, there are three CRN paradigms: underlay CRNs (UCRNs), overlay CRNs (OCRNs), and interweave CRNs (ICRNs) [5]. A UCRN can simultaneously access the PU's spectrum if its interference to the PU systems is below a given threshold [6]. The instantaneous (short-term) or statistical (long-term) transmit power constraints should be imposed to the UCRNs, to limit harmful interference [7]. However, the transmit power should be sufficiently large to satisfy the quality of service (QoS) requirements of UCRNs. An OCRN earns the additional spectrum for their communications from the PU systems by relaying the PU's data packets. The OCRNs have to spend part of their transmit power to assist (or relay) the PU's transmissions [5]. The OCRNs should also satisfy the QoS requirements for the transmit power. An ICRN opportunistically accesses the white spectrum holes, which belong to the PU systems but are not occupied. Spectrum sensing (SS) and dynamic spectrum access (DSA) techniques are used to locate the white spectrum and return those frequency bands to the PU systems in time [8]. The UCRNs and ICRNs have to meet two requirements: QoS requirements and interference limits. These two kinds of CRNs working in an underlay way should find more available spectrum to satisfy their QoS requirements and limit the harmful interference to the PU systems. On the other hand, the OCRNs working in an overlay way only need to satisfy their QoS requirements. As the fundamental functions of the ICRNs, the SS and DSA have been heavily discussed from the physical (PHY) layer to the medium access control (MAC) layer [9]–[13].

A critical goal of CRNs is to improve SE by reusing frequency bands. The spectrum reuse is implemented by the coordination mechanism, which is fulfilled by the CRN functions such as SS, DSA, and spectrum hopping. These functions are usually considered as energy-consuming operations, which certainly increase the energy consumption in CRNs and reduce the corresponding energy efficiency (EE). However, in the view of CRNs, the extra energy consumed by the cognition functions can be compensated by the system gains, including reliability, capacity, or throughput improvements. Furthermore, a better transmission channel can be selected by cognition operations, which can reduce the system congestion and packet collision. Therefore, the totally consumed energy of the CRNs can be saved in turn [14]–[16].

In wireless communications, there are some fundamental tradeoffs, such as EE versus SE, EE versus capacity efficiency, EE versus economic efficiency (EcE) [17], [18], in which the tradeoff between the EE and SE dominates the design issues in CRNs. Even in the fifth-generation (5G) wireless communication systems [19], the EE–SE tradeoff in CRNs should also be considered [20]. As a critical issue in the design of wireless communication systems, the tradeoff between EE and SE was

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discussed for MIMO systems [21], [22], relay-aided wireless cellular networks [23], and heterogeneous wireless systems [24]–[26]. The tradeoff between the EE and SE for interfere-tolerant CRNs at low and high signal-to-noise ratios (SNRs) was initially discussed in [27]. Another tradeoff between energy and infeasibility in CRNs was discussed in [28]. The aforementioned works discussed the tradeoff issues in wireless communications under varying constraints. However, all of them did not deal with the EE–SE tradeoff in the specific CRNs, in which the cognition functions should be fulfilled and the QoS requirements should be satisfied. To design green CRNs, the optimal EE should be achieved under the constraint that the SE should satisfy the QoS requirements. Different from the previous works, this paper aims to deal with the EE–SE tradeoff issues in three kinds of CRNs: UCRNs, OCRNs, and ICRNs.

The main contributions of this paper can be summarized as follows:

- A general framework is proposed to evaluate the tradeoff between EE and SE for three types of CRNs with their corresponding limits. Based on the proposed framework, an optimal (suboptimal) EE is deduced in the closed-form expression as the function of SE for varying CRNs. The EE and SE are indicated by CRNs' specific characteristics, which are calibrated by the newly proposed parameters, such as the relay factor for the OCRNs and the sensing factor for the ICRNs.
- It is pointed out that the EE–SE relation in CRNs is not contrary, although "extra" energy is consumed to implement the cognition functions. The total consumed power includes not only the transmit power but also the circuit power, including the relay power for the OCRNs and the sensing power for the ICRNs. Different from conventional wireless communication systems, the "extra" consumed energy in CRNs can be compensated by performance gains.

The remainder of this paper is organized as follows: In Section II, we describe a general coexistence model between PU systems and three kinds of CRNs. The general problems with specific limits for three CRNs are formulated in Section III. In Section IV, the general framework for the EE–SE relation is proposed, which is followed by the optimal EE solutions for three kinds of CRNs. Numerical results are given in Section V to verify the proposed framework. Finally, concluding remarks are given in Section VI.

## II. General Coexistence Model Between Primary User Systems and Cognitive Radio Networks

A general coexistence model between PU systems and CRNs is shown in Fig. 1, in which there are two kinds of PU systems, i.e., a TV system with large-scale signal and a wireless microphone (WM) system with small-scale signal, and three kinds of CRNs, i.e., UCRNs, OCRNs, and ICRNs. In this figure, the TV and WM systems are denoted by PUS_L with large-scale signal and PUS_S with small-scale signal, respectively. In the PUS_L, PUB and PUE denote base station and equipment, respectively. There are two kinds of PUEs in the PUS_L: PUE without relay

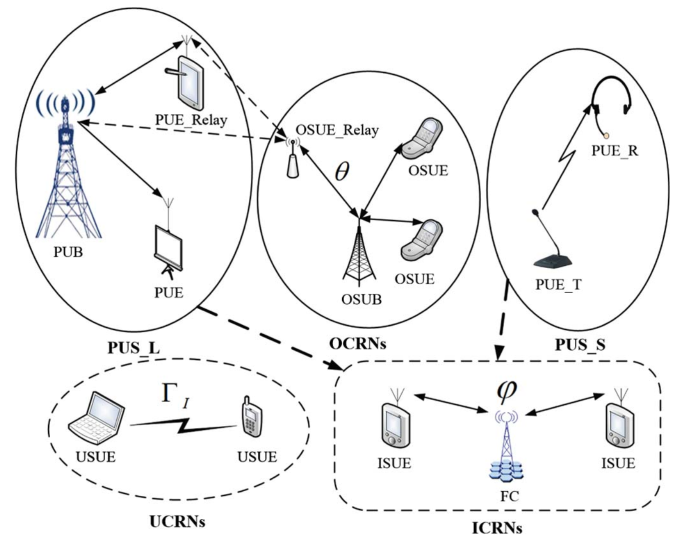


Fig. 1. General coexistence model between PU systems (large- and small-scale PU systems) and three CRNs (UCRNs, OCRNs, and ICRNs).

and PUE_Relay with relay. There are two links between the PUB and the PUE_Relay: one is direct and the other is relayed by the OCRNs. In the PUS_S, there are only the transmitter PUE_T and the receiver PUE_R. For the CRNs, it is not tough to detect or monitor the large-scale TV signal due to its high transmit power (e.g., 50 dBm). However, it is a challenge to sense the small-scale WM signal due to its short transmission range and small transmit power (e.g., 10 dBm) [29].

It is reasonable to assume that three kinds of CRNs are included in the same transmission circumstance due to their different operation mechanisms. For UCRNs, the USUE denotes the secondary user (SU) equipment working in an underlay mechanism. There is no base station and only a link between two USUEs, under the constraint that the transmit power should be below a given threshold $\Gamma_I$, which is determined by PU systems. For OCRNs, there are a base station (OSUB) and two kinds of SU equipments: OSUE and OSUE_Relay. The OSUE_Relay is used to relay the PU's data packets to earn the required spectrum from PU systems. In Fig. 1, we can see that there is a link between the PUB of PUS_L and the OSUE_Relay of the OCRNs. The data packets from the PUB to the PUE_Relay can be relayed by the OSUE_Relay. There is a bargain between two systems to determine the "price" of the spectrum, in terms of relayed data packets. We define a relay factor $\theta$ to evaluate the trade between the PU systems and the OCRNs. For ICRNs, there are a fusion center (FC) and some SU equipments (ISUEs) working as the distributed spectrum sensors. The SS function is fulfilled with a cooperative SS scheme, in which the ISUEs periodically sense the PU signal and send the samples to the FC and the final decision of the presence of PU signal is generated by the FC. A sensing factor $\varphi$ is defined to indicate the tradeoff between sensing time and transmit time for the ICRNs. In this mechanism, the ICRNs exploit a retreat operation to hop to other spectrum holes when the PU signals return.

To generalize our discussions, we put two kinds of PU systems and three CRNs in a coexistence model under the assumption that two PU systems should be considered in the design of practical CRNs and that there is no interinterference among the three CRNs. In addition, it is a simple and efficient way to illustrate a practical scenario for PU systems and CRNs.

## III. Problem Formulation

### A. General Problems

Here, the preliminaries of the EE and SE with some key definitions are introduced. The total system bandwidth $W$ is equally divided into $K$ subchannels, each with the bandwidth of $B = W/K$. Let $Q$ and $U$ denote the total number of PUs and the total number of SUs, respectively. Let $p_{u,k}$ denote the transmit power of the SU $u$ in a specific subchannel $k$. The active user set is $\mathbf{U} = \{1, 2, \ldots, U\}$, and the available subchannel set is $\mathbf{K} = \{1, 2, \ldots, K\}$, which denotes the unoccupied subchannels for the CRNs. The PU systems follow a Poisson model, and the duration of presence or absence follows the exponential distribution [30]. The data rate $r_{u,k}$ for the SU $u$ in the subchannel $k$ can be calculated as

$$r_{u,k} = B\log_2\left(1 + \frac{p_{u,k}g_{u,k}}{N_0 B + \varsigma\left(\sum\limits_{i\in\mathbf{U}, i\neq u} p_{i,k}g_{i,k} + \sum\limits_{j} p_{j,k}g_{j,k}\right)}\right) \tag{1}$$

where $N_0$ is the noise spectral density; $p_{u,k}$, $p_{i,k}$, and $p_{j,k}$ are the transmit power of the SU $u$, the SU $i$, and the PU $j$, respectively; $g_{u,k}$, $g_{i,k}$, and $g_{j,k}$ are the corresponding channel gains. $\varsigma$ denotes the interference factor, and $\varsigma = 1$ or $\varsigma = 0$ indicate whether the interferences from other SUs or PUs are considered. To calculate the data rate of the SU $u$, the transmit powers of the PUs and other SUs can be regarded as the interferences. Considering all SUs in all available subchannels, the throughput of CRNs can be calculated as

$$R = \sum_{u\in\mathbf{U}}\sum_{k\in\mathbf{K}} r_{u,k}. \tag{2}$$

The total transmit power of CRNs can be calculated as

$$P_t = \sum_{u\in\mathbf{U}}\sum_{k\in\mathbf{K}} p_{u,k}. \tag{3}$$

The total bandwidth available to CRNs can be written as

$$W = \sum_{u\in\mathbf{U}}\sum_{k\in\mathbf{K}} B_{u,k} \tag{4}$$

where $B_{u,k}$ denotes that the $k$th subchannel is occupied by SU $u$.

In addition to the transmit power in the CRNs, the circuit power $P_c$ to maintain the system operation is required. For different CRNs, the specific power is required to fulfill their specific operations. For example, the OCRNs need the relay power $P_r$ to relay the PU's data packets to earn more spectrum, and the ICRNs have to spend the SS power $P_s$ to find unoccupied spectrum holes. Moreover, there are some specific limits on the transmit power for different CRNs. For example, the transmit power $P_t$ in the UCRNs should be less than a threshold given by PU systems, but $P_t$ should also be larger than the QoS requirements imposed by UCRNs. Therefore, considering the constraints, the total system power can be formulated as

$$P = P_c + P_t + \mu P_r + \nu P_s \tag{5}$$
$$\Gamma_Q \leq P_t \leq \Gamma_I \tag{6}$$

where the factors $\mu = 0, 1$ and $\nu = 0, 1$ are used to indicate whether the corresponding power is required for a specific CRN, $\Gamma_Q$is the lower limit of the transmit power determined by the system QoS requirements, and $\Gamma_I$ denotes the upper limit of the transmit power imposed by the interference limit from PU systems. For the CRNs, the EE is defined as the ratio of total system throughput to total system power, i.e.,

$$\eta_e \triangleq \frac{R}{P}. \tag{7}$$

The SE can be defined as the ratio of total system throughput to total bandwidth, i.e.,

$$\eta_s \triangleq \frac{R}{W}. \tag{8}$$

### B. Specific Limits

Here, the limits on total throughput $R$, system power $P$, and total bandwidth $W$ for three kinds of CRNs are specified. To distinguish the three kinds of CRNs, we put the capital superscripts $U, O, I$ to the variables, to indicate the UCRNs, OCRNs, and ICRNs, respectively. For example, $P_t^X, X = U, O, I$ denotes the transmit power for the UCRNs, OCRNs, and ICRNs, respectively.

*1) Limits for the UCRNs:* According to the mechanism of UCRNs, the transmit power $p_{u,k}^U$ of the SU $u$ in the subchannel $k$ should be below a given threshold imposed by the PU systems. On the other hand, the transmit power should also be larger than a value to satisfy its QoS requirements. Therefore, the transmit power limits can be expressed as

$$\gamma_Q^U \leq p_{u,k}^U \leq \gamma_I^U \tag{9}$$

where $\gamma_Q^U$ is based on the QoS requirements, and $\gamma_I^U$ is calculated by the interference limits. The limits of the total transmit power $P_t^U$ can then be expressed as

$$\Gamma_Q^U \leq P_t^U \leq \Gamma_I^U \tag{10}$$

which is based on (6) and specified for the UCRNs. In the UCRNs, the power factors $\mu$ and $\nu$ in (5) can both be set to 0, meaning that the functions of relaying and SS are not required in the underlay operation paradigm. Therefore, the total power can be expressed as

$$P^U = P_c^U + P_t^U \tag{11}$$

where only the transmit power $P_t^U$ and the circuit power $P_c^U$ are required in the UCRNs.

*2) Limits for the OCRNs:* The OCRNs have to relay the PU's data packets to earn the spectrum for their transmissions. The total throughput $R^O$ is combined by two parts: One part is $R_t^O$, denoting its own transmission; the other $R_r^O$ is for the relay

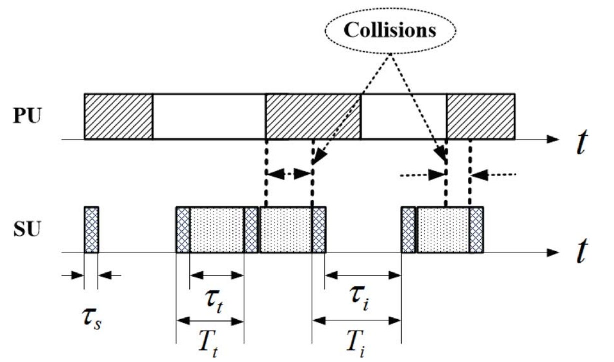


Fig. 2. Operation mechanism of ICRNs.

transmission of the PU systems. Therefore, the total throughput can be expressed as

$$R^O = R_t^O + R_r^O. \quad (12)$$

The power consumed in the OCRNs includes three parts: the circuit power $P_c^O$, the transmit power $P_t^O$, and the relay power $P_r^O$. The power factors $\mu$ and $\nu$ are set to 1 and 0 in (5), i.e.,

$$P^O = P_c^O + P_t^O + P_r^O. \quad (13)$$

For the OCRNs, there are no power limits from PU systems, and the transmit power $P_t^O$ should only satisfy the QoS requirement $\Gamma_Q^O$ and the relay power $P_r^O$ should satisfy the PU's requirement $\Gamma_P^O$. Therefore, the limits of the transmit power and the relay power can be expressed as

$$P_t^O \geq \Gamma_Q^O \quad (14)$$
$$P_r^O \geq \Gamma_P^O. \quad (15)$$

*3) Limits for the ICRNs:* The mechanism of the ICRNs is shown in Fig. 2, in which there are two kinds of periods: the transmit period $T_t$ and the idle period $T_i$. Those two kinds of periods can be expressed as

$$T_t = \tau_s + \tau_t \quad (16)$$
$$T_i = \tau_s + \tau_i \quad (17)$$

where $\tau_s$, $\tau_t$, and $\tau_i$ denote the SS time, the transmit time, and the idle time, respectively. In this paper, we assume that $\tau_t$ and $\tau_i$ are identical, for simplicity.

The SS time $\tau_s$ is mainly determined by the sensing ability of the ICRNs and the interference tolerance of the PU systems. If $\tau_s$ is set to a large value, the detection performance (the probability of detection $\zeta_D$) can be satisfied, and the harmful interference to the PU systems can be limited. However, more SS power is consumed, and the data rate decreases due to less transmit time. The tradeoff between the SS time and the system throughput has been discussed in [31], in which the total throughput can be improved by taking an optimal sensing time. In this paper, we focus on the tradeoff issue between the EE and SE in the ICRNs, under the assumption that the optimal SS time $\tau_s$ is selected. If the target frequency band is sensed to be occupied, the ICRNs sense again after the idle time $\tau_i$. Otherwise, if the target frequency band is unoccupied, the ICRNs start their transmissions in the coming transmit time $\tau_t$. The transmit time $\tau_t$ and the idle time $\tau_i$ are mainly decided by the QoS requirements of the ICRNs and the interference limits from the PU systems. There should also be optimal durations $\tau_i$ and $\tau_t$ for the maximum throughput and the minimum limits. However, such topics are out of our discussions; we set $\tau_t = \tau_i$, for simplicity. Therefore, we generally use $T$ to denote both the transmit period $T_t$ and the idle period $T_i$ in the ICRNs. In Fig. 2, we can see that there are collisions between the ICRNs and the PU systems during the SU's transmissions. Such collisions cannot be avoided due to the PU's random transmissions and the ICRNs' limited capacity of SS. Therefore, the transmit power $P_t^I$ of the ICRNs should be less than a threshold imposed by the PU systems. The power factors $\mu$ and $\nu$ are set to 0 and 1 in (5), and the power consumed in the ICRNs can therefore be expressed as

$$P^I = P_c^I + P_t^I + P_s^I \quad (18)$$
$$\Gamma_Q^I \leq P_t^I \leq \Gamma_I^I \quad (19)$$

where $P_c^I$, $P_s^I$, and $P_t^I$ are the circuit power, the sensing power, and the transmit power, respectively, and $\Gamma_Q^I$ and $\Gamma_I^I$ are the power limits imposed by the QoS requirements of the ICRNs and the interference limit by the PU systems, respectively.

## IV. Energy Efficiency–Spectral Efficiency Tradeoff in Cognitive Radio Networks

Here, a general framework of the tradeoff between EE and SE in the CRNs is introduced. The specific EE–SE relation for three kinds of CRNs (UCRNs, OCRNs, and ICRNs) is then deduced based on the proposed framework.

### A. General EE–SE Relation

In an ideal wireless transmission scenario, if only the transmit power is considered, the general EE–SE relation can be formulated as [18]

$$\eta_e = \frac{\eta_s}{(2^{\eta_s} - 1)N_0/G_t} \quad (20)$$

where the formulation is deduced from the following equations:

$$R = B\log_2\left(1 + \frac{P_t G_t}{BN_0}\right) \quad (21)$$
$$\eta_s = \frac{R}{B} \quad (22)$$
$$\eta_e = \frac{R}{P_t} \quad (23)$$

where $G_t$ denotes the total channel gain, and the interference factor $\varsigma$ in (1) is set to zero. The EE–SE relation in this case is shown in Fig. 3, in which the noise spectral density $N_0$ is $-111$ dBm/MHz, the maximum transmit power $P_t$ is 30 dBm, the subchannel bandwidth $B$ is 10 kHz, and the channel power gain $G_t$ is calculated based on the Okumara–Hata model [32]. The normalized channel power gain, including the distance effect, is set to 15 dB, 10 dB, and 5 dB in the following numerical results. In Fig. 3 and (20), we can see that the SE increases with the reduction of the EE and the EE–SE relation looks contradictory. Such relation indicates that the system should cost

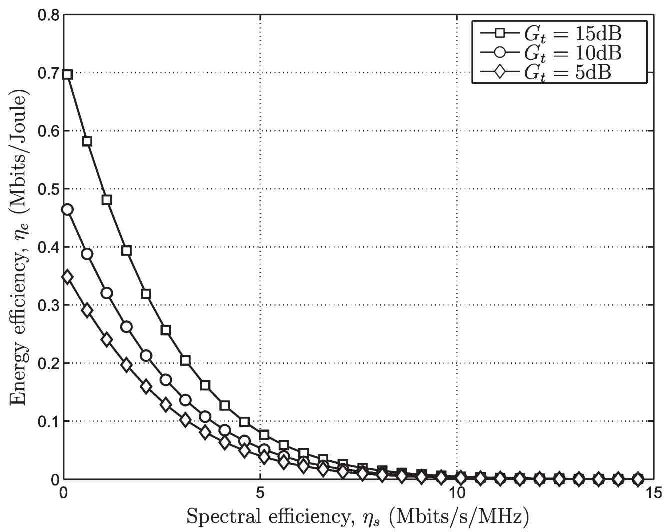


Fig. 3. EE–SE relation considering only the transmit power in the CRNs.

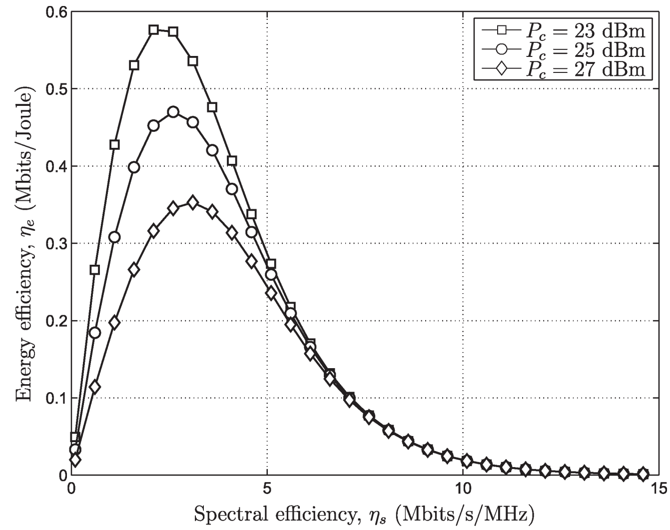


Fig. 4. EE–SE relation in a practical CRN with varying circuit powers $P_c$.

more energy to enhance the SE and *vice versa*. In such a simple scenario, we cannot find an optimal tradeoff between the EE and SE. However, it should be noted that, in (20), there is an assumption that only the transmit power is considered. For a practical communication system, in addition to the transmit power $P_t$, there are other kinds of power consumed to maintain the whole system; more details can be found in (5) and Section III-A. Here, we temporarily denote the other kinds of power as the circuit power $P_c$. If the circuit power $P_c$ is considered, the EE–SE relation shown in (20) can be rewritten as

$$\eta_e = \frac{\eta_s}{P_c/B + (2^{\eta_s} - 1)N_0/G_t} \tag{24}$$

where $P_c$ is averaged by the subchannel bandwidth $B$. The aforementioned formulation is deduced by the altered expression of the EE, which is

$$\eta_e = \frac{R}{P_t G_t + P_c}. \tag{25}$$

Seeing (24) and (20), we can notice that the circuit power $P_c$ should certainly reduce the system EE. The EE–SE relation shown in (24) is shown in Fig. 4, in which a practical communication system with the same parameters in Fig. 3 is shown. In this simulation, the channel gain $G_t$ is set to 10 dB, and the circuit power $P_c$ is set to 23, 25, and 27 dBm. Note that the EE–SE relation considering the circuit power was initially shown in [18, Fig. 2c] without practical parameters. In Fig. 4, we can see that an optimal EE can be achieved in each line. In other words, the EE–SE relation is not contradictory any more, and the optimal tradeoff can be achieved. Different from the aforementioned communication systems, the CRNs should cost more energy to earn the extra spectrum for their transmissions, and the tradeoff between the EE and SE is more attractive and challenging.

### B. Optimal or Suboptimal EE–SE Tradeoff

Based on the general EE–SE relation shown in (24), the optimization issues for EE and SE in the CRNs are discussed here. Optimal EE–SE tradeoff solutions for the UCRNs and OCRNs and a suboptimal EE–SE tradeoff solution for the ICRNs can be consequently deduced from the optimal EE and optimal SE. To simplify the discussions and emphasize the key points, we make the following assumptions.

- There are only one pair of SUs ($U = 2$, i.e., one transmitter and one receiver) in the given CRNs and only one pair of PUs ($Q = 2$, i.e., one transmitter and one receiver), and the number of the subchannel is set to one ($K = 1$).
- The circuit power $P_c$, the transmit power $P_t$, the relay power $P_r$, and the sensing power $P_s$ are proportional to the time $\tau$.
- The CRN period $T_{t,i} = \tau_s + \tau_{t,i}$ is fixed. We assume that the transmit time and the idle time for the CRNs are identical. In a CRN period, the PU systems are independent of the CRNs.

*1) General Optimization for the EE:* In the CRNs, considering all constraints, the optimal EE can be generally formulated as

$$\begin{aligned} \max_{\tau_t, p} \quad & \eta_e(\tau_t, p, \zeta_F, \zeta_D) = \frac{R(\tau_t, p, \zeta_F, \zeta_D)}{P(\tau_t, p, \zeta_F, \zeta_D)} \\ \text{s.t.} \quad & \tau_t \le T \\ & \Gamma_Q \le P_t \le \Gamma_I \\ & \alpha \ge \zeta_F \\ & \beta \le \zeta_D \end{aligned} \tag{26}$$

where $\tau_t$ denotes the transmit time, the total transmit power $P_t$ should satisfy the QoS requirement $\Gamma_Q$ and the interference constraint $\Gamma_I$, the probability of false alarm $\zeta_F$ should be less than $\alpha$, and the probability of detection $\zeta_D$ should be larger than $\beta$. Both the criterions $\alpha$ and $\beta$ are inherently imposed and determined by the PU systems. It should be noted that the aforementioned constraints are all not required for a specific CRN.

*2) General Optimization for the SE:* The optimal SE can be expressed as

$$\begin{aligned} \max_{\tau_t, p} \quad & \eta_s(\tau_t, p, \zeta_F, \zeta_D) = \frac{R(\tau_t, p, \zeta_F, \zeta_D)}{W(\tau_t, p, \zeta_F, \zeta_D)} \\ \text{s.t.} \quad & \tau_t \le T \\ & \Gamma_Q \le P_t \le \Gamma_I \\ & \alpha \ge \zeta_F \\ & \beta \le \zeta_D \end{aligned} \tag{27}$$

where $W(\tau_t, p, \zeta_F, \zeta_D)$ denotes the unoccupied frequency bands, which are obtained from the PU systems.

### C. EE–SE Tradeoff in the CRNs

The EE–SE tradeoff for three types of CRNs is discussed here based on the general EE–SE relation and EE–SE tradeoff framework.

*1) For the UCRNs:*

*Theorem 1:* An optimal EE for the UCRNs with the interval SE: the EE $\eta_e$ for the UCRNs with the interval SE $\eta_s$ can be formulated as

$$\eta_e = \frac{\eta_s}{P_c/B + (2^{\eta_s} - 1)N_0/G_t}, \quad \eta_s \in [\eta_{sQ}, \eta_{sI}] \tag{28}$$

where the minimum SE $\eta_{sQ}$ and the maximum SE $\eta_{sI}$ are determined by the constraints of the transmit power. The optimal EE can be achieved in the aforementioned expression.

*Proof:* Based on the optimal EE and SE shown in (26) and (27) with their constraints, considering the mechanism of the UCRNs, the optimal EE can be rewritten as

$$\begin{aligned} \max_{T, p} \quad & \eta_e(T, p) = \frac{R(T, p)}{P(T, p)} \\ & \Gamma_Q \le P_t \le \Gamma_I \end{aligned} \tag{29}$$

where the transmit time is $T$, and only one limit is required, i.e., the total transmit power should satisfy the requirements of QoS $\Gamma_Q$ and should not be larger than $\Gamma_I$ to limit the harmful interference to the PU systems. The UCRNs do not need to sense the PU signal; therefore, the limits for the probability of false alarm $\alpha$ and the probability of detection $\beta$ are not required.

The optimal SE can be rewritten as

$$\begin{aligned} \max_{T, p} \quad & \eta_s(T, p) = \frac{R(T, p)}{W(T)} = \frac{R(T, p)}{B} \\ & \Gamma_Q \le P_t \le \Gamma_I \end{aligned} \tag{30}$$

where only one subchannel with bandwidth $B$ is considered. Considering the system capacity $R = B\log_2(1 + (P_t G_t / B N_0))$ in (21) and the system power $P = P_t + P_c$, the EE can be formulated as the function of SE in (28). Based on the interval of $P_t \in [\Gamma_Q, \Gamma_I]$ and the relation between $\eta_s$ and $P_t$, the SE interval $[\eta_{sQ}, \eta_{sI}]$ can be determined. For the UCRNs, the SE is increasing with the transmit power $P_t$, with the fixed circuit power $P_c$ and the bandwidth $B$. Considering the EE–SE relation and the SE interval, the optimal EE $\eta_e$ can be achieved. □

*2) For the OCRNs:*

*Theorem 2:* An optimal EE for the OCRNs with a relay factor $\theta$: for the OCRNs, let $\theta$ denote the relay factor defined as the ratio of the relay time $\tau_r$ to the transmit time $\tau_t$, i.e., $\theta = \tau_r/\tau_t$. The transmit power and the relay power are assumed to follow this relation, i.e., $P_r = P_t\theta$. In the interval of the SE, there is an optimal EE $\eta_e$, i.e.,

$$\eta_e = \frac{\eta_s}{P_c/B + (2^{\eta_s} - 1)(1+\theta)N_0/G_t}, \quad \eta_s \in [\eta_{sQ}, \eta_{sR}] \tag{31}$$

where the lower limit $\eta_{sQ}$ and the upper limit $\eta_{sR}$ are decided by the QoS requirement of the OCRNs and the relay requirement of the PU systems.

*Proof:* For the OCRNs, the optimal EE can be rewritten as

$$\max_{T, p} \quad \eta_e(T, p) = \frac{R(T, p)}{P(T, p)} = \frac{R_t(\tau_t, p)}{P_c + P_t + P_r} \tag{32}$$

$$\text{s.t.} \quad \tau_t \le \frac{T}{1+\theta} \tag{33}$$

$$\Gamma_Q \le P_t \le P_r/\theta \tag{34}$$

where the total power is $P(\tau_t, p) = P_c + P_t + P_r$, the transmit time $\tau_t$ should be less than $T/(1+\theta)$, and the transmit power $P_t$ should be less than the relay power divided by $\theta$. The system throughput $R(T, p)$ includes two parts: the transmit throughput $R_t(\tau_t, p)$ and the relay throughput $R_r(\tau_r, p)$, i.e.,

$$R(T, p) = R_t(\tau_t, p) + R_r(\tau_r, p) \tag{35}$$

where $T$ denotes the OCRN period $T = \tau_t + \tau_r$.

The coefficient $\theta$ is imposed by the PU systems, and it can be considered as the exchange rate between the relayed data packet for the PU systems and the spectrum earned from the PU systems. It should be noted that such rate is always dominated by the PU systems. For the OCRNs, it does not need to sense the PU signal; therefore, $\alpha$ and $\beta$ do not appear in the expression. The optimal SE can be rewritten as

$$\max_{T, p} \quad \eta_s(T, p) = \frac{R(T, p)}{W(T, p)} = \frac{R_t(\tau_t, p)}{B} \tag{36}$$

$$\text{s.t.} \quad \tau_t \le \frac{T}{1+\theta} \tag{37}$$

$$\Gamma_Q \le P_t \le P_r/\theta \tag{38}$$

where the bandwidth is equal to $B$. It is assumed that the OCRNs earn one whole spectrum slot $B$ from the PU systems by relaying the PU's data packets, and the coexistence model is based on a time-division mode. Considering the system throughput $R = B\log_2(1 + (P_t G_t / B N_0))$, the system power $P = P_t + P_c + P_r$, and the relation between $P_t$ and $P_r$, the EE can be formulated as the function of the SE in (31). For the OCRNs, the SE is increasing with the transmit power $P_t$; for the fixed circuit power $P_c$ and the relay power $P_r$, there is an interval for the SE $[\eta_{sQ}, \eta_{sR}]$. The upper limit $\eta_{sR}$ is decided by the coefficient $\theta$, i.e., the OCRNs should spend the required power to relay the PU's data packets to earn the bandwidth. In the SE interval, considering the EE–SE relation, an optimal EE can be achieved. □

*3) For the ICRNs:*

*Lemma 1:* An optimal SS time $\tau_s$ in the ICRNs for the maximum system throughput $R$: for the ICRNs, there is an optimal SS time $\tau_s$ to generate the maximum system throughput $R$. The optimization can be formulated as [31]

$$\max_{\tau_s} \quad R(T) = R_0(T-\tau_s) + R_1(T-\tau_s) \tag{39}$$

$$\text{s.t.} \quad \zeta_F \le \alpha \tag{40}$$

$$\zeta_D \ge \beta \tag{41}$$

where $R_1$ and $R_0$ denote the throughput of ICRNs under two assumptions: The PU signal is present, and the PU signal is absent; the total period $T = \tau_s + \tau_t$ is combined by the sensing time $\tau_s$ and the transmission time $\tau_t$; $\zeta_F$ and $\zeta_D$ should satisfy their respective limits $\alpha$ and $\beta$. Under the given constraints $\alpha$ and $\beta$, an optimal sensing time $\tau_s$ can be determined for the maximum system throughput.

*Proof:* Based on the mechanism of ICRNs and the system throughput $R$, an optimal sensing time $\tau_s$ can be achieved. More details can be found in [31], in which the tradeoff between the SS and the system throughput has also been discussed. □

Based on the mechanism of the ICRNs shown in Fig. 2 and the optimal sensing time $\tau_s$ given in Lemma 1, we can get the following theorem.

*Theorem 3:* A suboptimal EE for the ICRNs with the probability of access $\zeta_A$: for the ICRNs, let $\zeta_A$ denote the probability of access that calibrates the probability that the ICRNs can access the target frequency band $B$. For an optimal SS time $\tau_s$, the EE can be formulated as

$$\eta_e = \frac{\eta_s}{\frac{P_c+P_s}{B} + (2^{\frac{\eta_s}{\zeta_A}} - 1)N_0/G_t} \tag{42}$$

where $\zeta_A$ can be statistically calculated as

$$\zeta_A = \zeta_{H_0}\zeta_D + \zeta_{H_1}(1-\zeta_D). \tag{43}$$

In the aforementioned equation, $\zeta_{H_0}$, $\zeta_{H_1}$, and $\zeta_D$ denote the probability of PU signal absence, the probability of PU signal presence, and the probability of detection by the ICRNs, respectively.

*Proof:* The optimizations for the EE in (26) and the SE in (27) can still work for the ICRNs. Considering Lemma 1 and the optimal SS time $\tau_s$, the optimal EE can be rewritten as

$$\begin{aligned} \max_{\tau_t,p} \quad & \eta_e(\tau_t,p,\zeta_F,\zeta_D) = \frac{R(\tau_t,p,\zeta_F,\zeta_D)}{P(T,p,\zeta_F,\zeta_D)} \\ \text{s.t.} \quad & \tau_t \le T - \tau_s \\ & \Gamma_Q \le P_t \\ & \alpha \ge \zeta_F \\ & \beta \le \zeta_D \end{aligned} \tag{44}$$

where the transmit time $\tau_t$ can be calculated as

$$\begin{aligned} \tau_t &= (T-\tau_s)[\zeta_{H_0}\zeta_D + \zeta_{H_1}(1-\zeta_D)] \\ &= (T-\tau_s)\zeta_A. \end{aligned} \tag{45}$$

The total system power is $P(T,p,\zeta_F,\zeta_D) = P_c + P_t + P_s$. Following the same way, the optimal SE can be rewritten as

$$\begin{aligned} \max_{\tau_t,p} \quad & \eta_s(\tau_t,p,\zeta_F,\zeta_D) = \frac{R(\tau_t,p,\zeta_F,\zeta_D)}{B} \\ \text{s.t.} \quad & \tau_t \le T - \tau_s \\ & \alpha \ge \zeta_F \\ & \beta \le \zeta_D \end{aligned} \tag{46}$$

where the system throughput can be calculated as

$$R(\tau_t,p,\zeta_F,\zeta_D) = B\zeta_A \log_2\left(1 + \frac{P_t G_t}{N_0 B}\right) \tag{47}$$

where the system throughput is jointly determined by $P_t$ and $\zeta_A$, and hence, we cannot obtain an interval for $\eta_s$ similar to (28) and (31). Based on (44), (46), and (47), the suboptimal EE can be deduced in (42), which is finally formulated as the function of the SE and the probability of access $\zeta_A$. The suboptimal $\eta_e$ can only be evaluated from the numerical way for varying $\eta_s$ and $\zeta_A$. □

Based on (47) and (44), the EE of the ICRNs can be further formulated as

$$\eta_e = \frac{B\zeta_A \log_2\left(1 + \frac{P_t G_t}{N_0 B}\right)}{P_c + P_t(1+\varphi)} \tag{48}$$

where $\varphi$ denotes the sensing factor defined as the ratio of the SS power $P_s$ to the transmit power $P_t$, i.e., $\varphi = P_s/P_t$. The formulation (48) is based on the assumptions that the optimal SS time $\tau_s$ is used and the PU signal is constant. From (48), we can see that the EE in the ICRNs decreases with the increase of the transmit power $P_t$. In the ICRNs, under an assumption that the total consumed power $P$ and the circuit power $P_c$ are constant, the relation between the SE and the probability of access $\zeta_A$ can be formulated as

$$\eta_s = \zeta_A \log_2\left(1 + \frac{(P-P_c)G_t}{(1+\varphi)\zeta_A N_0 B}\right). \tag{49}$$

From this formulation, we can see that, if the sensing ability of the ICRNs is better, i.e., a smaller sensing factor $\varphi$, the corresponding SE is better. It should be noted that, in the aforementioned formula, the occupied spectrum by the ICRNs is assumed to be $\zeta_A B$ when the system SE is considered.

## V. Numerical Results and Analysis

Here, the numerical results are presented to evaluate the EE–SE tradeoff for three kinds of CRNs, with the proposed general framework. In the numerical results, the related system parameters are summarized in Table I.

Fig. 5 shows the EE–SE relation in the UCRNs, for varying SE intervals, based on (28) in Theorem 1. The whole SE region is divided into three feasible ranges by two given SE thresholds $\eta_{s1}$ and $\eta_{s2}$, which are determined by the SE thresholds $\eta_{sQ}$ and $\eta_{sI}$, respectively. In the feasible range 2, $\eta_{s1}$ and $\eta_{s2}$ denote the minimum and maximum limits, respectively. The minimum limit $\eta_{s1}$ is determined by $\eta_{sQ}$, which is inherently imposed by the QoS requirements of the UCRNs. The maximum limit

TABLE I
SYSTEM PARAMETERS

| Parameters | Value |
|---|---|
| Carrier frequency, f | 1.5 GHz |
| Thermal noise power, $N_o$ | $-111$ dBm/MHz |
| Circuit power, $P_c$ | 23 dBm |
| Maximum transmit power, | 30 dBm |
| Sub-channel bandwidth, $B$ | 10 KHz |
| CRNs system period, $T$ | 0.01 s |
| Number of sub-channels, $K$ | 1 |
| Number of SUs, $U$ | 2 |
| Number of PUs, $Q$ | 2 |
| Probability of false alarm, $\alpha$ | 0.01 |
| Probability of detection, $\beta$ | 95% |
| Channel model | Okumura-Hata model |

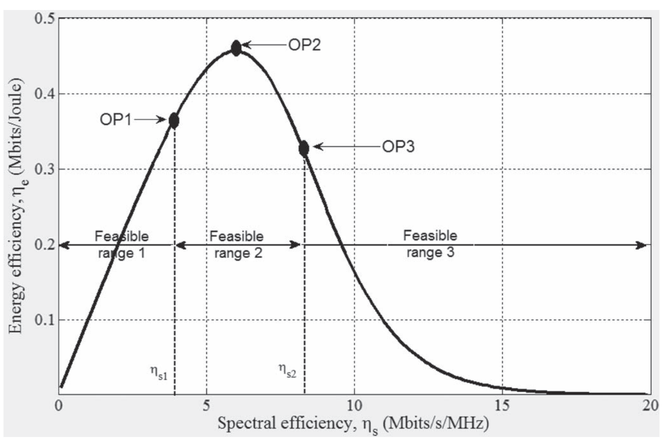


Fig. 5. EE–SE relation in the UCRNs with varying SE intervals.

$\eta_{s2}$ is determined by $\eta_{sI}$, which is inherently given by the PU systems. The threshold $\eta_{sI}$ is used to limit the interference to the PU systems. The EE distribution in the feasible range 2 is concave, and an optimal point (OP2) can be achieved. However, for the feasible range 1 and the feasible range 3, the EE distributions are monotonic, and the possible optimal points (see OP1 and OP3) can only be achieved at $\eta_{s1}$ and $\eta_{s3}$. This figure indicates that an optimal EE with a specific SE can always be achieved in different SE feasible ranges for the UCRNs.

Fig. 6 shows the EE–SE relation in the OCRNs with varying relay factors. It is shown that the EE decreases with the increase of the relay factor $\theta$. Comparing the maximum EE of $\theta = 0.1$ with those of $\theta = 1$ and $\theta = 2.5$, there are about 20% and 35% attenuations for different SEs, respectively. The reason is straightforward, and this is because the OCRNs spend more power to relay the PU's data packets. The EE of the OCRNs with the relay factor $\theta = 0.1$ can achieve about 3.7 Mb/J, when the SE is 5 Mb/s/Hz. The EE–SE tradeoff for the OCRNs can be achieved by designing the relay factor, which is inherently determined by the PU systems.

The effect of the relay factor $\theta$ with varying $\eta_s$ in the OCRNs is shown in Fig. 7. With the increase of $\theta$, the OCRNs spend more energy to relay the PU's data packets. In this figure, if the energy consumed to relay the PU's data is five times of that to transmit under $\eta_s = 3$ Mb/s/MHz, the EE decreases about 0.2 Mb/J. It should be noted that that the numerical results in Figs. 6 and 7 are based on the assumption that both the EE

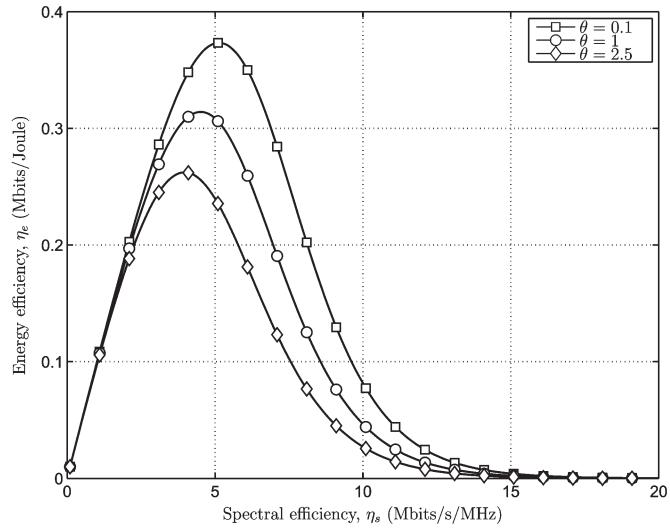


Fig. 6. EE–SE relation in an OCRN with varying relay factors $\theta$.

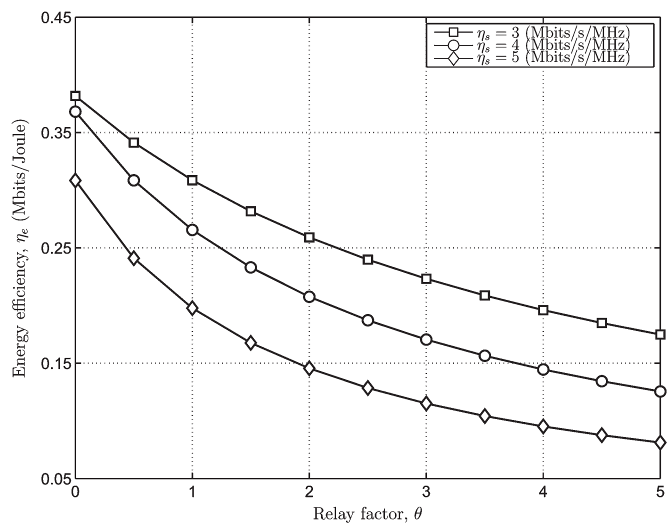


Fig. 7. EE of the OCRNs against the relay factor $\theta$ with varying SEs.

and SE consider only the throughput $R_t$ of the OCRNs; the throughput of the PU systems $R_r$ relayed by the OCRNs is not considered. Equations (32) and (36) indicate this assumption.

The EE–SE relation for the ICRNs is shown in Fig. 8, in which the EE increases with the larger probability of access $\zeta_A$. We use $\zeta_A$ to denote the accessibility of the target frequency bands. In this figure, we can see that there is almost a 0.25-Mb/J gain for the EE in the ICRNs, if $\zeta_A$ increases 10%. The SE corresponding to the optimal EE increases about 1 Mb/s/MHz with the enhance of $\zeta_A$. When the SE is less than 5 Mb/s/MHz, the EEs for different $\zeta_A$ are almost identical. This numerical result indicates that an optimal tradeoff between EE and SE can be achieved for varying $\zeta_A$.

The quantitative analysis of the EE–SE relation for three CRNs, under the given conditions and parameters, is shown in Fig. 9, in which the relay factor of the OCRNs is $\theta = 0.1$, and the probability of access and the sensing factor of the ICRNs are set to $\zeta_A = 0.95$ and $\varphi = 0.6$, respectively. In this figure, we can see that, under identical simulation conditions, the EE of the UCRNs is the largest and the SE of the ICRNs is the

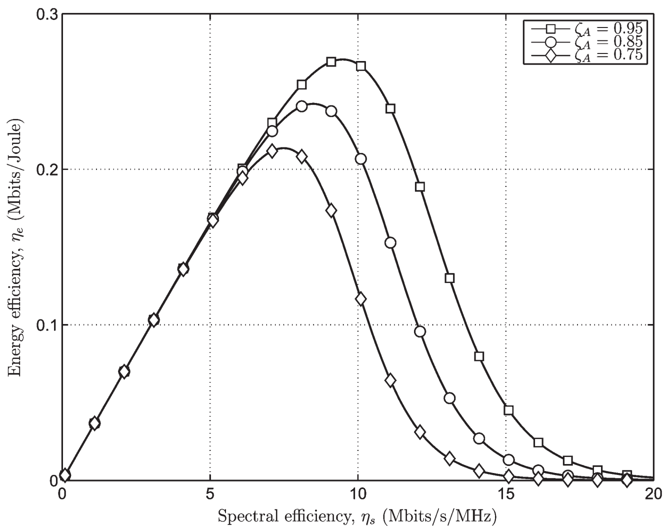


Fig. 8. EE–SE relation in the ICRNs with varying probabilities of access $\zeta_A$.

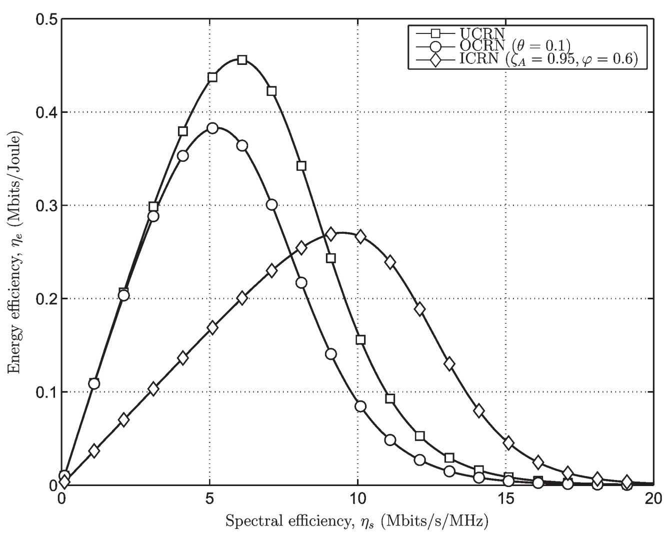


Fig. 9. EE–SE relation for three CRNs: the UCRNs, the OCRNs, and the ICRNs.

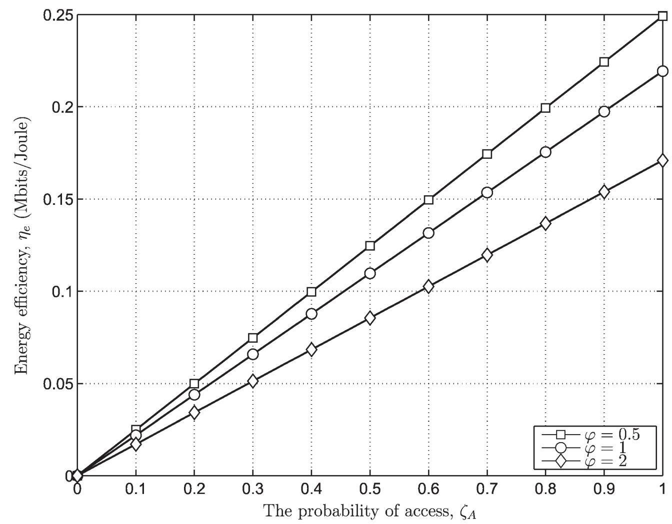


Fig. 10. EE in the ICRNs against the probability of access with varying sensing factors $\varphi$.

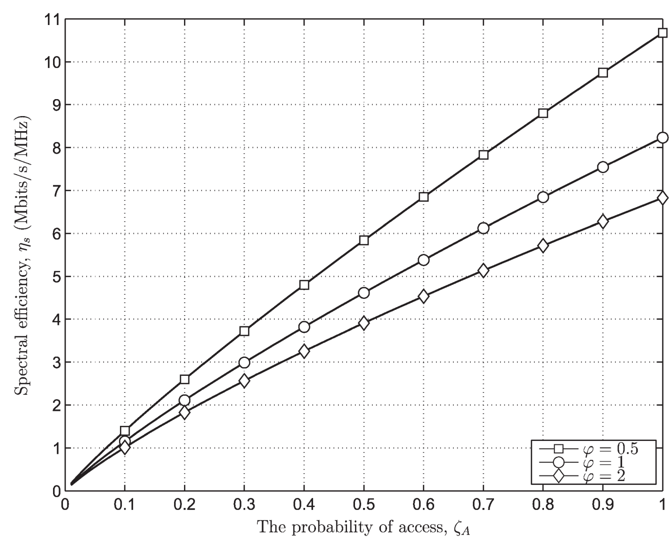


Fig. 11. SE in the ICRNs against the probability of access with varying sensing factors $\varphi$.

best. The reason for the obvious performances of three CRNs is straightforward and inherently dependent on their respective operation mechanisms. Compared with the OCRNs and ICRNs, the UCRNs do not need to spend extra energy to earn the spectrum, and their largest EE can, hence, achieve about 0.45 Mb/J, when the corresponding SE is 6 Mb/s/Hz, under the given conditions. It is about 0.07 Mb/J and 0.18 Mb/J larger than the largest EEs of the OCRNs and ICRNs, respectively. The numerical results in Fig. 9 provide a general overview of the EE–SE relation of three CRNs.

Fig. 10 shows the EE in the ICRNs for varying sensing factors with the probability of access $\zeta_A$ from 0 to 1, under the condition that the sensing time is taken as an optimal value. In this figure, we can see that the EE in the ICRNs increases with the enhance of $\zeta_A$. This means that the ICRNs can achieve better EE, if the systems obtain more spectrum. On the other hand, if the sensing factor $\varphi$ is larger, i.e., the ICRNs cost more energy to SS, the EE goes to worse. This figure also indicates that the energy can be saved by improving the sensing ability of the ICRNs. Based on (49), the relation between the SE and the probability of access $\zeta_A$ for varying sensing factors in the ICRNs is shown in Fig. 11, in which the totally consumed power $P$ is set to 31.8 dBm. In this figure, we can see that the ICRNs with better SS ability can achieve better SE. For example, the SE gain is about 2 Mb/s/MHz ($\zeta_A = 0.9$) when the sensing factor $\varphi$ transfers from 1 to 0.5. The aforementioned numerical results are generated under the given conditions summarized in Table I, in which both the number of PUs and SUs is set to 2. If the number of PUs is larger, i.e., $Q > 2$, and the PU systems follow a Poisson model, the proposed EE–SE framework can still work by adjusting the corresponding parameters. For the UCRNs and the OCRNs, the SE upper limits of the UCRNs $\eta_{sI}$ and the OCRNs $\eta_{sR}$ should be redefined for a varying number of PUs. However, for the ICRNs, the system should cost more sensing power $P_s$ to achieve the probability of access $\zeta_A$, under the assumption that the optimal sensing time $\tau_s$ can still be obtained. The new EE–SE relation in the ICRNs with varying number of PUs is shown in Fig. 12, in which

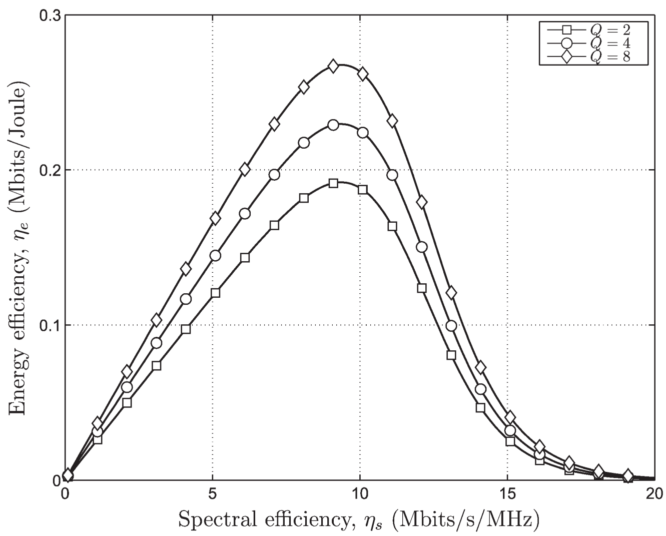


Fig. 12. EE–SE relation in the ICRNs with varying number of PUs.

the number of PUs, the number of SUs, and the probability of access are set to $Q = 2, 4, 8$, $U = 2$, and $\zeta_A = 0.9$, respectively. Compared with the EE of the ICNRs, there is about 0.07-Mb/J attenuation, when the number of PUs changes from $Q = 2$ to $Q = 8$. The reason is straightforward, and the ICRNs cost more energy to achieve the required SE.

## VI. Conclusion

The EE–SE tradeoff for three kinds of CRNs (UCRNs, OCRNs, and ICRNs) has been discussed in this paper. A general framework has been proposed to evaluate the EE–SE tradeoff, and the corresponding closed-form EE functions in terms of SE have been deduced. Based on the proposed framework and the deduced functions, the optimal (suboptimal) EE can be achieved. We have evaluated the proposed framework for three CRNs with practical system parameters. Numerical results have indicated that the ICRN can achieve the best SE and the UCRN can achieve the best EE, under the same transmission circumstance.

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