Enhanced 5G Cognitive Radio Networks Based on Spectrum Sharing and Spectrum Aggregation

Wensheng Zhang, *Member, IEEE,* Cheng-Xiang Wang, *Fellow, IEEE,* Xiaohu Ge, *Senior Member, IEEE,* Yunfei Chen, *Senior Member, IEEE*

***Abstract*—In this paper, the new enhanced cognitive radio networks (E-CRNs) based on spectrum sharing (SS) and spectrum aggregation (SA) are proposed for the fifth generation (5G) wireless networks. The E-CRNs jointly exploit the licensed spectrum shared with the primary user (PU) networks and the unlicensed spectrum aggregated from the industrial, scientific, and medical (ISM) bands. The PU networks include TV systems in TV white space (TVWS) and different incumbent systems in the long term evolution (LTE) time division duplexing (TDD) bands. The harmful interference from the E-CRNs to the PU networks are delicately controlled. Furthermore, the coexistence between the E-CRNs and other unlicensed systems, such as WiFi, is studied. The E-CRNs framework including dynamic spectrum management (DSM) is designed for the key parameters of licensed SS and unlicensed SA. The essential tradeoff between sharing efficiency (ShE) and aggregation efficiency (AgE) for the E-CRNs is discussed. Based on this tradeoff, a spectrum lean-management (SLM) scheme is proposed to fulfill the DSM. Moreover, a water-filling (WF) algorithm is designed to dynamically access the available spectrum. Numerical results demonstrate that the proposed E-CRNs can significantly improve the system performance in terms of data rate, outage probability, and spectrum efficiency (SE). In particular, the E-CRNs framework provides a spectrum usage prototype for 5G wireless communication networks.**

***Index Terms*—Cognitive radio networks, spectrum sharing, spectrum aggregation, spectrum lean-management, spectrum efficiency.**

I. Introduction

Cognitive radio networks (CRNs) have been proposed as one of the most promising communication technologies to deal with the "spectrum scarcity" issues with the rapid development of wireless applications, especially for the coming the fifth generation (5G) communication systems and beyond [1]–[7]. In this network, the primary user (PU) shares the spectrum with the CRNs under the condition that the PU's spectrum priority is guaranteed and the CRNs' harmful interference is avoided.

The TV white space (TVWS) is considered as the candidate spectrum for the CRNs and two key schemes including spectrum sensing and geolocation database have been proposed to exploit the unused spectrum [8]–[10]. Many sophisticated spectrum sensing schemes have been developed to locate the TVWS by monitoring PU's transmissions [11], [12]. However, the sensing schemes cannot completely avoid the CRNs' harmful interference to the PU networks due to the hidden terminal problem, especially for the passive PU receivers. The geolocation database scheme has provided commercially feasible solution to the CRNs [13], [14]. The geolocation database contains the up-to-date TVWS information and the accuracy of the TVWS information depends on the signal propagation model [10]. The TVWS is shared to the CRNs through three main spectrum sharing (SS) mechanisms: overlay, underlay, and interleaved [15]. The SS schemes can be fulfilled by combing the key functions of spectrum sensing and geolocation database. The SS issues in the CRNs have been heavily discussed in [16]–[22]. For example, the sensing-based SS scheme has been proposed in [16] and an opportunistic SS scheme with energy harvesting has been discussed in [17]. The channel gain estimation scheme for the SS-based CRNs has been evaluated in [18] and the power location issues in the SS-based CRNs have been discussed in [19]–[21]. An efficient frequency-domain cyclic prefix autocorrelation-based wideband spectrum sensing and sharing scheme has been proposed in [22]. The interference cancellation schemes with system capacity for the SS-based CRNs have been discussed in [23]–[25].

Different from the SS techniques for the TVWS, the new SS schemes including licensed shared access (LSA) in Europe and spectrum access system (SAS) in the U.S. have drawn much attention from industries [26], [27]. The 2.3-2.4 GHz Long Term Evolution (LTE) time division duplex (TDD) band 40 in Europe [28] and the 3.55-3.7 GHz LTE TDD bands 42 and 43 in the U.S. [29] can be shared under the condition that the incumbent systems are well protected. Based on the LSA and SAS schemes, the CRNs can also utilize the above LTE TDD bands to improve their quality-of-service (QoS). Therefore, the CRNs can jointly access the unoccupied TVWS and the shared LTE TDD bands. Both the TV systems and the incumbent

Manuscript received December 14, 2017; revised May 22, 2018 and July 21, 2018; accepted July 28, 2018. The authors acknowledge the support from the Key R&D Program of Shandong Province (No. 2016GGX101014), the Fundamental Research Funds of Shandong University (No. 2017JC029), the National Natural Science Foundation of China (No. 61371110, 61771293, 61603215), the Taishan Scholar Program of Shandong Province, Hubei Provincial Science and Technology Department (No. 2016AHB006), EU FP7-PEOPLEIRSES (No. 610524), EU H2020 Program (No. 723227), and the EC H2020 778305-DAWN4IoE. The associate editor coordinating the review of this paper and approving it for publication was M. Abdallah.

W. Zhang is with Shandong Provincial Key Lab of Wireless Communication Technologies, School of Information Science and Engineering, Shandong University, Qingdao, Shandong, 266237, China (e-mail: zhangwsh@sdu.edu.cn).

C.-X. Wang (corresponding author) is with State Key Laboratory of Mobile Communications, Southeast University, Nanjing, 210096, China (e-mail: chxwang@seu.edu.cn).

X. Ge is with the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China (e-mail: xhge@hust.edu.cn).

Y. Chen is with the School of Engineering, University of Warwick, Coventry, CV4 7AL, U.K. (e-mail: yunfei.chen@warwick.ac.uk). Yunfei Chen acknowledges the support of EC H2020 778305 DAWN4IoE.

systems are considered as the PU networks.

Spectrum aggregation (SA) is another critical technique for improving system performance by aggregating the distributed or discontinuous frequency slots [30]–[32]. The SA issues of the LTE-Unlicensed (LTE-U) systems have been discussed in [30], [33], [34]. The equivalent capacity for the LTE-Advanced (LTE-A) systems with carrier aggregation has been analysed in [35], in which two bandwidth location strategies were proposed. An energy-efficient uplink carrier aggregation in the LTE-A systems has been discussed in [36], in which a dynamic carrier aggregation scheduling scheme was proposed. The SA issues in the CRNs have been discussed in [37]–[39]. The secondary user (SU) networks can aggregate the PU's spectrum by imperfect spectrum sensing [37] and the performance of channel assembling and fragmentation in the CRNs has been analysed in [38]. The SA protocols for the CRNs have been designed for both media access control (MAC) layer and physical (PHY) layer [39]. Moreover, the spectrum management issues in the CRNs have been discussed in [40]–[42]. A price-based spectrum management scheme has been presented in [41], in which a good Nash equilibrium was achieved by a price-based water-filling (WF) algorithm. The spectrum efficiency (SE) can be used to evaluate the spectrum usage performance of the CRNs [43]–[45]. The tradeoff between SE and energy efficiency (EE) has been given in a closed-form expression for three kinds of CRNs [45].

It is believed that the conventional CRNs cannot satisfy the required system performance (especially for real-time service) by only using the TVWS. To guarantee the priority of the PU networks, the CRNs have to empty the target frequency bands by interrupting their transmissions, leading to unsatisfied system QoS. In order to improve the QoS, even the quality of experience (QoE) of the CRNs, the licensed LTE TDD bands and the unlicensed spectrum can also be exploited. The LSA and SAS schemes can be used to share the LTE TDD bands and the SA schemes can be used to aggregate the unlicensed spectrum. Following the core philosophy of the LTE-U systems, the CRNs can also aggregate the unlicensed spectrum if the CRNs can harmoniously coexist with the co-existing systems, such as WiFi networks, by delicately controlling their interference. Based on two spectrum operation mechanisms, SS and SA, the enhanced-CRNs (E-CRNs) are proposed in this paper. The E-CRNs jointly exploit the TVWS, the licensed LTE TDD bands and the unlicensed spectrum. The SS schemes including LSA and SAS are used to share the LTE TDD bands to the E-CRNs. Moreover, the E-CRNs exploit the SA schemes to dynamically access the unlicensed spectrum. The proposed E-CRNs provide a new spectrum usage paradigm, in which different types of frequency bands are efficiently used.

To the best of our knowledge, this is the first work that jointly exploits the TVWS, the licensed LTE TDD bands and the unlicensed spectrum by combining two spectrum operation techniques, SS and SA. Thus, the main contributions of this paper can be summarized as follows:

- The new E-CRNs are proposed by integrating the functions of SS and SA to jointly utilize the TVWS, the LTE TDD bands and unlicensed spectrum. For the SS schemes, the PU networks are the TV systems in the TVWS and the incumbent systems in the LTE TDD bands. For the SA schemes, the incumbent systems are WiFi systems in the unlicensed spectrum. A new coexistence mechanism between the E-CRNs and the incumbent systems (including the PU networks) is designed.
- We propose a new SS scheme, which integrates the SS schemes in the CRNs and the LSA and SAS schemes. The E-CRNs receive the information of the shared spectrum from a spectrum database. To use the shared spectrum, the E-CRNs should delicately control their operations according to the requirements imposed by the PU networks. To deal with the limits of the spectrum database, the sensing ability of the E-CRNs is still used to dynamically monitor the transmissions of the PU networks. A dynamic spectrum aggregation (DSA) scheme is proposed to aggregate the unlicensed spectrum dynamically by controlling the harmful interference. Two new performance metrics, i.e., sharing efficiency (ShE) and aggregation efficiency (AgE) are presented to evaluate the sharing performance and the aggregating performance.
- A spectrum management framework of the E-CRNs is designed to manage the shared licensed spectrum and the aggregated unlicensed spectrum. A new spectrum lean-management (SLM) scheme is proposed to utilize the available spectrum. The core philosophy of the SLM is to maximize the total system throughput under the internal and external constraints. In particular, an optimal band selection scheme is proposed to choose the optimal band among the shared and aggregated spectrum. Moreover, the challenges in the use of varying spectrum (e.g., flexible front-end issues) are studied.
- The essential tradeoff between ShE and AgE is evaluated in terms of system data-rate, system outage probability, and system SE. A new WF algorithm is designed to assign system data to the shared spectrum and aggregated spectrum according to spectrum conditions. A balance between the system traffic offloading and the system QoS can be achieved.

The remainder of this paper is organized as follows. Section II presents the system model. The E-CRNs framework with several key functions is presented in Section III. The system performance of the E-CRNs is discussed in Section IV. Numerical results and theoretical analysis are provided in Section V. This paper is concluded in Section VI.

II. System Models

A. Coexistence model

The coexistence model consisting of the E-CRNs, PU networks and WiFi networks[1] is shown in Fig. 1, in which the E-CRNs can access the shared spectrum including TVWS and the LSA spectrum and the aggregated unlicensed spectrum. As shown in Fig. 1, three ellipses with different line styles denote three systems: the TV-PU networks, the LSA-PU networks and the WiFi networks. Three kinds of networks working as the

[1]In this paper, we use WiFi networks to denote the incumbent systems in the ISM bands.

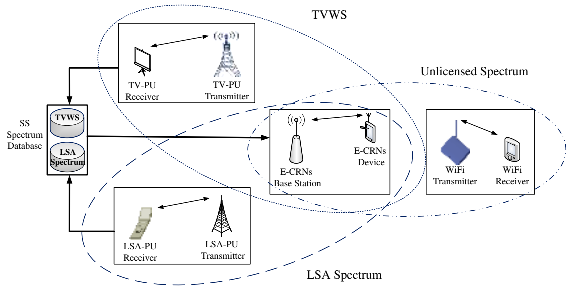

Fig. 1: Coexistence model of E-CRNs, PU networks and WiFi networks.

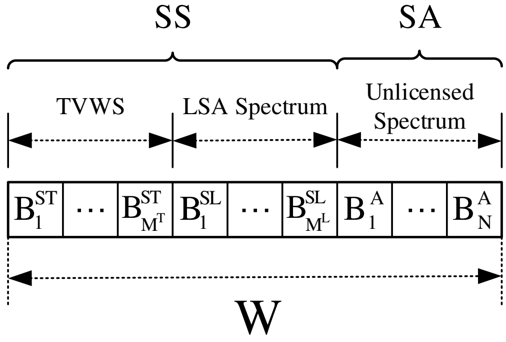

Fig. 2: Available spectrum for the E-CRNs.

incumbent systems provide the spectrum to the proposed E-CRNs with SS or SA. The TV-PU networks and the LSA-PU networks are considered as the PU networks and the shared spectrum includes the TVWS and the LSA spectrum. The information on the availability of the TVWS and the LSA spectrum is provided by the TV-PU networks and the LSA-PU networks. The two kinds of spectrum information are separately stored in the TVWS database and the LSA spectrum database, which can be integrated into one spectrum database, namely, SS spectrum database. The SS spectrum database provides the information of the available shared spectrum to the E-CRNs. The information indicates the available shared spectrum over specific time, geographic location and frequency. Furthermore, the E-CRNs aggregate the unlicensed spectrum in the ISM bands from the WiFi networks. Totally, the E-CRNs can access the shared licensed spectrum by SS and the aggregated unlicensed spectrum by SA.

For the proposed E-CRNs, the harmful interference to the PU networks should be delicately controlled. According to different operations of the TV-PU networks and the LSA-PU networks, the E-CRNs should avoid the harmful interference, especially for the near PU receivers. Compared with the LSA-PU networks, the TV-PU networks have relatively large transmission distance. For unlicensed SA, the E-CRNs should coexist with the WiFi networks harmoniously by delicately controlling their operations. The mutual interference between the PU networks and the WiFi networks is not considered as the two systems operate in different frequency bands. There are four kinds of point-point transmission pairs: the TV-PU transmitter (TPT) and TV-PU receiver (TPR), the LSA-PU transmitter (LPT) and LSA-PU receiver (LPR), the WiFi transmitter (WT) and WiFi receiver (WR), and the E-CRNs transmitter (ET) and E-CRNs receiver (ER). It is assumed that the proposed E-CRNs are working in an interleaved mode and spectrum sensing is employed to avoid the harmful interference to the PU networks. The use of the interleaved mode means that the E-CRNs operate with PU systems in the same frequency bands. In this case, spectrum sensing is necessary to monitor the PU transmission so that collision can be avoided. In the coexistence model, the channel state information is assumed to be known by the E-CRNs. The numbers of transmission pairs in the E-CRNs, TV-PU networks, LSA-PU networks, and WiFi networks are denoted by E, T, L, and I, respectively.

In Fig. 2, W denotes the total available spectrum consisting of three kinds of spectrum: TVWS, LSA spectrum and unlicensed spectrum. The TVWS and LSA are accessed via SS, while the unlicensed spectrum is accessed by SA. Let M and N denote the numbers of spectrum slots for shared spectrum and aggregated spectrum, respectively. There are a total of M^{T} TVWS bands $B^{\mathrm{ST}}_{m^{\mathrm{T}}}, (m^{\mathrm{T}} = 1, \cdots, M^{\mathrm{T}})$, which belong to the TV-PU networks and are shared by the E-CRNs via SS. Moreover, the LSA-PU networks share M^{L} LSA spectrum bands $B^{\mathrm{SL}}_{m^{\mathrm{L}}}, (m^{\mathrm{L}} = 1, \cdots, M^{\mathrm{L}})$ to the E-CRNs. Therefore, the total number of shared spectrum slots is $M = M^{\mathrm{T}} + M^{\mathrm{L}}$. There are total N unlicensed bands $B^{\mathrm{A}}_{n}, (n = 1, \cdots, N)$ that can be potentially aggregated by the E-CRNs via SA. Assume $B^{\mathrm{ST}}_{m^{\mathrm{T}}} = B^{\mathrm{SL}}_{m^{\mathrm{L}}} = B^{\mathrm{A}}_{n} = B$ for any m^{T}, m^{L} and n. Therefore, the total bandwidth for the E-CRNs is $W = (M + N)B$. It should be noted that the three parts of W are not required to be adjacent and the bands $B^{\mathrm{ST}}_{m^{\mathrm{T}}}$, $B^{\mathrm{SL}}_{m^{\mathrm{L}}}$ and B^{A}_{n} can be independently distributed.

B. Transmission model

For the E-CRNs, the usage status of the target frequency bands $B_m, (m = 1, \cdots, M)$, can be determined by sensing the PU's transmissions. Note that we use m to denote m^{T} and m^{L} for simplicity. The sensing operation of the i-th SU[2] for the m-th band B_m can be formulated as a binary hypothesis test (HT)

$$\begin{cases} \mathcal{H}_0 : y_i = n_{i,m} & \text{(1a)} \\ \mathcal{H}_1 : y_i = \sum_{j=1}^{J} x_j h^{(m)}_{j,i} + n_{i,m} & \text{(1b)} \end{cases}$$

where the absence and presence of PU signal are denoted by $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively, y_i is the received signal of the i-th SU and x_j is the PU signal located in the m-th band with zero mean and variance σ_x^2, $j = 1, \cdots, J$ is the index of PUs, $h^{(m)}_{j,i}$ denotes the channel gain and the noise $n_{i,m}$ is an independent and identical distributed (i.i.d.) Gaussian process with zero mean and variance σ_n^2, and the signal-to-noise ratio (SNR) is calculated as $\rho = \frac{\sigma_x^2 |h^{(m)}_{j,i}|^2}{\sigma_n^2}$.

[2]The distributed SUs in the E-CRNs can work as the cooperative sensors.

The sensing results can be evaluated in terms of the probability of detection ($\mathcal{P}_D$) under the hypothesis of $\mathcal{H}_1$ and the probability of false alarm ($\mathcal{P}_F$) under the hypothesis of $\mathcal{H}_0$. The total shared licensed spectrum for the E-CRNs can be determined by

$$W_{\text{SS}} = \sum_{m=1}^{M} \mu_m B_m, \tag{2}$$

where the sensing factor μ_m is used to indicate the sensing result and can be expressed as

$$\mu_m = \begin{cases} 0, & \mathcal{P}_D \geq \gamma_D | \mathcal{H}_1 \ || \ \mathcal{P}_F \geq \gamma_F | \mathcal{H}_0 \\ 1, & otherwise, \end{cases} \tag{3}$$

where γ_D and γ_F denote the given thresholds of $\mathcal{P}_D$ and $\mathcal{P}_F$, respectively, the symbol || denotes the logic function of 'OR'. Note that the sensing result μ_m indicates whether the m-th band B_m is shared by the E-CRNs.

The data-rate $r_{i,m}$ of the i-th SU transmission in the m-th band can be theoretically calculated as

$$r_{i,m} = \mu_m B_m \log\left(1 + \beta_{i,m}\right), \tag{4}$$

where $\beta_{i,m}$ denotes the signal to interference-plus-noise ratio (SINR). The SINR $\beta_{i,m}$ can be defined as

$$\beta_{i,m} \triangleq \tag{5}$$
$$\frac{P_i |h_{i,i}^{(m)}|^2}{B_m N_0 + \sum\limits_{u \in \mathbb{I}, u \neq i} P_u |h_{u,i}^{(m)}|^2 + \left[(1 - \mathcal{P}_D) | \mathcal{H}_1 + \mathcal{P}_F | \mathcal{H}_0\right] \sum\limits_{j=1}^{J} P_j |h_{j,i}^{(m)}|^2}$$

where N_0 is the noise power spectral density, the set $\mathbb{I} = \{1, \cdots, I\}$ denotes I SU transmissions, P_i, P_u, and P_j denote the transmit power of the i-th SU, u-th SU, and j-th PU, respectively, $h_{u,i}^{(m)}$ and $h_{j,i}^{(m)}$ are the channel gains. The interference from the PU networks is also considered in the calculation of $r_{i,m}$ due to imperfect spectrum sensing. We use $(1 - \mathcal{P}_D) | \mathcal{H}_1$ and $\mathcal{P}_F | \mathcal{H}_0$ to denote the probability of miss detection and the probability of false alarm, respectively. The sum rate $R_{I,M}$ of the E-CRNs in the shared spectrum W_{SS} can be calculated as

$$R_{I,M} = \sum_{i=1}^{I} \sum_{m=1}^{M} r_{i,m}. \tag{6}$$

Similarly, the total aggregated unlicensed spectrum for the E-CRNs can be expressed as

$$W_{\text{SA}} = \sum_{n=1}^{N} \nu_n B_{M+n}, \tag{7}$$

where the interference factor ν_n is used to indicate the E-CRNs' interference in the $(M + n)$-th band B_{M+n}. The interference factor ν_n is defined as

$$\nu_n = \begin{cases} 1, & \mathcal{I}_n < \gamma_I \\ 0, & \mathcal{I}_n \geq \gamma_I, \end{cases} \tag{8}$$

where $\mathcal{I}_n$ denotes the interference from SU transmissions to WiFi networks and γ_I is a given interference threshold imposed by WiFi networks. The data-rate $r_{i,n}$ of the i-th SU transmission in the n-th band is then expressed as

$$r_{i,n} = \nu_n B_{M+n} \log\left(1 + \beta_{i,n}\right), \tag{9}$$

where $\beta_{i,n}$ denotes the SINR. Here, the SINR $\beta_{i,n}$ is defined as

$$\beta_{i,n} \triangleq \frac{P_i |h_{i,i}^{(M+n)}|^2}{B_{M+n} N_0 + \sum\limits_{u \in \mathbb{I}, u \neq i} P_u |h_{u,i}^{(M+n)}|^2 + \sum\limits_{k=1}^{K} P_k |h_{k,i}^{(M+n)}|^2}, \tag{10}$$

where P_k is the transmit power of the k-th WiFi transmission and $h_{k,i}^{(M+n)}$ denotes the channel gain. The sum rate of the E-CRNs in the aggregated spectrum W_{SA} can be calculated as

$$R_{I,N} = \sum_{i=1}^{I} \sum_{n=1}^{N} r_{i,n}. \tag{11}$$

With the shared spectrum W_{SS} and aggregated spectrum W_{SA}, the sum rate of the E-CRNs can be straightforwardly expressed as

$$R_I = R_{I,M} + R_{I,N}. \tag{12}$$

III. The E-CRNs Framework

In this section, the framework of the proposed E-CRNs is presented from three spectrum operation paradigms: SS, SA, and SLM. The E-CRNs can access the target frequency bands by SS with imperfect spectrum sensing and SA with limited interference. The SLM, working as the key function in the framework, is used to manage the available spectrum in an efficient way.

A. Spectrum sharing with imperfect spectrum sensing

For the conventional CRNs, the perfect spectrum sensing ($\mathcal{P}_D = 1$ && $\mathcal{P}_F = 0$) can completely avoid the harmful interference to the PU networks [16]. However, in practice such ideal perfect spectrum sensing cannot be achieved due to the practical limitations, i.e., sensing techniques, insufficient sensing time, and uncertainty of PU's transmissions. If $\mathcal{P}_D < 1$ or $\mathcal{P}_F > 0$, the imperfect spectrum sensing cannot completely guarantee the priority of the PU networks. In this case, the SU transmissions should be delicately controlled to avoid the harmful interference to the PU networks. The interference cancellation techniques require that both the average transmit power and the peak transmit power should be below the given power constraints [21], [23], [25]. The proposed E-CRNs exploit the imperfect spectrum sensing to determine the white spectrum and the interference cancellation techniques to avoid the harmful interference to the PU networks.

Under the conditions of imperfect spectrum sensing and constrained transmit power, the ergodic sum rate of the E-

CRNs in the shared spectrum W_{SS} can be formulated as

$$\bar{R}_{I,M} = \mathbb{E}\left\{\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\mu_m B_m \log\left(1+\beta_{i,m}\right)\right]\right\} \quad (13)$$

$$\text{s.t.} \quad \mathcal{P}_D \geq \gamma_D \quad (14)$$

$$\mathcal{P}_F \leq \gamma_F \quad (15)$$

$$\mathbb{E}\left\{P_i\right\} \leq \bar{P}_{\text{avg}}, \forall i \in \mathbb{I} \quad (16)$$

$$\max\left\{P_i\right\} \leq P_{\text{peak}}, \forall i \in \mathbb{I}, \quad (17)$$

where the constraint (14) requires that the PU signal should be sensed agilely with an acceptable $\mathcal{P}_F$ of (15), the average transmit power and maximum transmit power should be limited by the average power constraint $\bar{P}_{\text{avg}}$ and the peak power constraint P_{peak}, respectively. Note that the sensing threshold γ_D is imposed by the PU networks to protect PU's transmission and the false alarm threshold γ_F should be delicately designed to guarantee the required system performance. Under the condition of imperfect spectrum sensing, the power constraints can further protect PU's transmissions by limiting harmful interference. The computational complexity of imperfect spectrum sensing has been well studied in the literature, which mainly depends on the specific sensing techniques. Here, energy detection is used to sense PU signals with the computational complexity of $\mathcal{O}\left(\aleph_s^2\right)$, where $\aleph_s$ denotes the number of PU signal samples.

Under the condition of imperfect spectrum sensing and transmit power constraints, the outage probability of the E-CRNs in the shared spectrum can be determined as

$$Q_{\text{SS}} = 1 - \text{P}_{\text{r}}\left\{\beta_{i,m} \geq \gamma_{i,m}\right\}, \forall i \in \mathbb{I}, \forall m \in \mathbb{M}, \quad (18)$$

where $\gamma_{i,m}$ is a given SINR threshold, the set $\mathbb{M} = \{1, \cdots, M\}$ denotes an M-length band sequence.

For the target frequency bands to be shared, we use a new metric, namely ShE, to evaluate the sharing performance of the E-CRNs. The ShE can be defined from two perspectives, i.e., the frequency domain and the time domain. The ShE in the frequency domain is straightforwardly defined as

$$\eta_{\text{ShE}}^{(f)} = \frac{W_{\text{SS}}}{W_M} = \frac{\sum_{m=1}^{M}\mu_m}{M}, \quad (19)$$

where W_M denotes the total bands to be shared and μ_m is the sensing factor given in (3). Moreover, the ShE for the target frequency bands W_M can also be provided in the time domain

$$\eta_{\text{ShE}}^{(t)} = \frac{\tau_t}{T} \quad (20)$$
$$\left\{\mathbb{E}[\mathcal{P}_F \leq \gamma_F|\mathcal{H}_0] + \mathbb{E}\left[\left(\mathcal{P}_D \leq \gamma_D \,\&\&\, \mathbb{E}\left\{P_i\right\} \leq \bar{P}_{\text{avg}}\right)|\mathcal{H}_1\right]\right\},$$

where $\forall i \in \mathbb{I}$, T denotes the system period consisting of two parts, τ_s is the spectrum sensing time and τ_t is the SU transmission time, $T = \tau_s + \tau_t$, the symbol && denotes the logic function of 'AND'. In the ShE definition of (20), it is assumed that the E-CRNs can still work under the condition of $\mathcal{H}_1$ by controlling the transmit power P_i.

B. Spectrum aggregation with limited interference

The proposed E-CRNs can also aggregate the unlicensed frequency bands, which are utilized through the incumbent systems, e.g., WiFi networks. To coexist with WiFi networks, the E-CRNs should control their transmit power to avoid the harmful interference to WiFi's transmissions.

The co-channel interference of the E-CRNs to WiFi networks in the $(M+n)$-th band B_{M+n} can be quantified in terms of the interference temperature (IT), which is defined as

$$\psi_{i,k}^{(M+n)} = \frac{P_i|h_{i,k}^{(M+n)}|^2}{B_{M+n}N_0}, \quad (21)$$

where $h_{i,k}^{(M+n)}$ denotes the channel gain between the SU transmitter in the i-th pair and the WiFi receiver in the k-th pair. To avoid the harmful interference to WiFi networks, the average IT and maximum IT of the E-CRNs should be limited, i.e., the constraints can be expressed as

$$\mathbb{E}\{\psi_{i,k}^{(M+n)}\} \leq \bar{\psi}_{\text{avg}}, \forall i \in \mathbb{I}, \forall k \in \mathbb{K}, \forall n \in \mathbb{N} \quad (22)$$

$$\max\{\psi_{i,k}^{(M+n)}\} \leq \psi_{\text{peak}}, \forall i \in \mathbb{I}, \forall k \in \mathbb{K}, \forall n \in \mathbb{N}, \quad (23)$$

where $\bar{\psi}_{\text{avg}}$ and ψ_{peak} denote the average IT threshold and peak IT threshold imposed by WiFi networks, respectively, and the set $\mathbb{N} = \{1, \cdots, N\}$ denotes an N-length band sequence.

For the E-CRNs, the imposed average and peak IT constraints cannot guarantee the avoidance of the harmful interference to WiFi networks. For example, if the E-CRNs follow the conventional protocols of the MAC layer and PHY layer, the E-CRNs will cause continuous interference to WiFi networks due to the listen-before-talk (LBT) mechanism. This would lead to non-stop back-off of WiFi networks as the channel state will always be busy. To deal with such a paradox of coexistence, a new aggregation algorithm named DSA is designed for the proposed E-CRNs.

Algorithm 1: The key idea of the DSA algorithm is that the E-CRNs need to dynamically adjust their operation parameters according to the current state of the unlicensed spectrum. The spectrum occupancy state and the operations of the incumbent systems are monitored by the E-CRNs using a revised spectrum sensing (RSS) function, which actually is a light quick energy detection scheme to monitor the WiFi signal in the frequency domain. Based on the sensing results, the SU's transmission parameters, such as transmit power, transmission duration, sensing time and so on, should be dynamically adjusted. We assume that only WiFi networks are considered as incumbent systems. If there are no WiFi transmissions, the E-CRNs should take a period of idle time to vacate the target frequency bands periodically at a millisecond scale [34]. For the bands B_{M+n}, the sensing time, transmit time and idle time are denoted by τ_s^A, τ_t^A and τ_i^A, respectively, so that the period is $T^A = \tau_t^A + \tau_s^A + \tau_i^A$. The transmit times are denoted by τ_t^{A1} and τ_t^{A0} for the presence and absence of the WiFi signals, respectively. The detection threshold is denoted by Γ_D^A, which can be theoretically determined by energy detection for given $\mathcal{P}_D$ and $\mathcal{P}_F$. The RSS result is denoted by D_n^A and the transmit power is P_i^A. There are two kinds of transmit power constraints, i.e., $\bar{P}_{\text{avg}}^A$ for the presence of WiFi signals and P_{max}^{A} for the absence of the WiFi signals, $P_{\text{max}}^{A} \geq \bar{P}_{\text{avg}}^{A}$. The DSA algorithm is described as follows.

Algorithm 1: Dynamic spectrum aggregation algorithm

- **Do** RSS, **Get** D_n^A;
- **While** $\left(D_n^A \geq \Gamma_D^A\right)$ **Do**
  $P_i^A \leq \bar{P}_{\text{avg}}^A$, $\tau_i^A = 0$, $\tau_t^{A1} = T^A - \tau_s^A$
  Else
  $P_i^A \leq P_{\text{max}}^A$, $\tau_i^A \neq 0$, $\tau_t^{A0} = T^A - \tau_s^A - \tau_i^A$
- **End**

Algorithm End □

We use a new metric AgE to evaluate the spectrum aggregation performance. The AgE in the frequency domain can be defined as

$$\eta_{\text{AgE}}^{(f)} = \frac{W_{\text{SA}}}{W_N} = \frac{\sum_{n=1}^{N} \nu_n}{N}, \tag{24}$$

where W_N denotes the total unlicensed bands to be aggregated by the E-CRNs and ν_n is the interference factor in (8). According to the proposed DSA algorithm, the AgE of the target frequency bands W_N can also be presented in the time domain as

$$\eta_{\text{AgE}}^{(t)} = \frac{\tau_t^{A1}}{T^A}\mathbb{E}\left[\left(P_i^A \leq \bar{P}_{\text{avg}}^A\right)|\mathcal{H}_1\right] + \frac{\tau_t^{A0}}{T^A}\mathbb{E}\left[\left(P_i^A \leq P_{\text{max}}^A\right)|\mathcal{H}_0\right], \tag{25}$$

where the operation period T_A is fixed and the transmission time τ_t^{A0} under $\mathcal{H}_0$ is less than τ_t^{A1} under $\mathcal{H}_1$ due to the non-zero idle time τ_i^A. The AgE is also affected by the transmit power P_i^A in both $\mathcal{H}_1$ and $\mathcal{H}_0$, which denote the presence and absence of the WiFi signals.

Similar to (18), the outage probability of the E-CRNs in the aggregated spectrum can be expressed as

$$Q_{\text{SA}} = 1 - \text{P}_\text{r}\left\{\beta_{i,n} \geq \gamma_{i,n},\right\}, \forall i \in \mathbb{I}, \forall n \in \mathbb{N}, \tag{26}$$

where $\gamma_{i,n}$ is a given SINR threshold. The ergodic sum rate of the E-CRNs in the aggregated spectrum can be written as

$$\begin{aligned}\bar{R}_{I,N} = \mathbb{E}&\left\{\sum_{i=1}^{I}\sum_{n=1}^{N}\left[\nu_n B_{M+n}\log\left(1+\beta_{i,n}\right)\right]\right\} \quad (27)\\ \text{s.t.}\quad & \mathbb{E}\{\psi_{i,k}^{(M+n)}\} \leq \bar{\gamma}_{I_{\text{avg}}}, \forall i \in \mathbb{I}, \forall k \in \mathbb{K}, \forall n \in \mathbb{N}\\ & \max\{\psi_{i,k}^{(M+n)}\} \leq \gamma_{I_{\text{peak}}}, \forall i \in \mathbb{I}, \forall k \in \mathbb{K}, \forall n \in \mathbb{N},\end{aligned}$$

where the constraints (22) and (23) limit the E-CRNs' interference to WiFi networks.

C. Spectrum lean-management with SS and SA

For the target frequency bands including shared spectrum and aggregated spectrum, the ultimate objective of the proposed E-CRNs is to achieve best system performance under imposed constraints. Specially, a new scheme of SLM is proposed for the E-CRNs to effectively and efficiently deal with the target spectrum. The SLM is based on the concept of lean-management, which has been widely discussed in the business world. The key idea of the lean-management is to maximize system output by reducing cost and improving product quality under given constraints.

The proposed SLM for the E-CRNs can be mathematically formulated as

$$\begin{aligned} P_{\text{out}} &= \max\left\{\mathbb{E}\left[F\left(W_{\text{in}}\right)\right]\right\} && (28)\\ \text{s.t.}\quad & C_{\text{in}} \leq \bar{C}_{\text{in}} && (29)\\ & C_{\text{ex}} \leq \bar{C}_{\text{ex}}, && (30)\end{aligned}$$

where P_{out} denotes the maximum ergodic performance of the function of $F(\cdot)$ with the required spectrum W_{in} under two constraints: the internal and external constraints C_{in} and C_{ex} with the corresponding thresholds $\bar{C}_{\text{in}}$ and $\bar{C}_{\text{ex}}$, respectively.

The so-called internal constraints refer to the required system performance in terms of the system data-rate, QoS, and outage probability and so on. For the proposed E-CRNs, the internal constraints can jointly be determined by

$$\bar{C}_{\text{in}} \rightarrow \begin{cases} R_I \geq \bar{R}_{\text{th}} \\ Q_{\text{SS}} \leq \bar{Q}_{\text{th}} \\ Q_{\text{SA}} \leq \bar{Q}_{\text{th}}, \end{cases} \tag{31}$$

where the system data-rate R_I in (12) should be larger than the required data-rate threshold $\bar{R}_{\text{th}}$ and the system outage probability Q_{SS} and Q_{SA} should be less than the given outage threshold $\bar{Q}_{\text{th}}$. The so-called external constraints are imposed by the PU networks for SS with imperfect sensing and the incumbent systems for SA with limited harmful interference. The external constraints $\bar{C}_{\text{ex}}$ can be expressed as

$$\bar{C}_{\text{ex}} \rightarrow \begin{cases} \{\mathcal{P}_D \geq \gamma_D|\mathcal{H}_1\} \,\&\&\, \{\mathcal{P}_F \leq \gamma_F|\mathcal{H}_0\} \\ \mathbb{E}\{\psi_I^N\} \leq \bar{\psi}_{\text{avg}}, \end{cases} \tag{32}$$

where the sensing performance is guaranteed by $\mathcal{P}_D$ and $\mathcal{P}_F$ for the PU networks and the average IT ψ_I^N should be less than the given IT threshold $\bar{\psi}_{\text{avg}}$ imposed by WiFi networks.

To fulfill the concept of SLM in the E-CRNs, two main spectrum access schemes (SS and SA) should be integrated to achieve the required system performance. With the function of SLM, the system data-rate of the E-CRNs in (12) can be rewritten as

$$\begin{aligned} R_I = \max&\left\{c_m W_{\text{SS}}\log\left(1+\beta_{I,\text{SS}}\right) + c_n W_{\text{SA}}\log\left(1+\beta_{I,\text{SA}}\right)\right\}\\ \text{s.t.}\quad & c_m + c_n = 1, c_m \in [0,1], c_n \in [0,1] \quad (33)\\ & Q_I \leq \bar{Q}_{\text{th}},\end{aligned}$$

where the spectrum coefficients c_m and c_n are exploited to combine W_{SS} and W_{SA}, $\beta_{I,SS}$ and $\beta_{I,SA}$ denote SS SINR and SA SINR, respectively. The system performance can be improved by adjusting two spectrum coefficients.

Among the available spectrum W_{SS} in (2) and W_{SA} in (7), the optimal band can be selected with the SLM mechanism to achieve the best system performance. The band selection scheme can be described as

$$\begin{aligned}\kappa = \arg\max_{\kappa}&\left\{B_\kappa \log\left(1+\frac{P_i|h_{i,i}^{(\kappa)}|^2}{B_\kappa N_0 + \bar{I}_{\text{avg}}^{\kappa}}\right)\right\}, \forall \kappa \in [1, M+N],\\ \text{s.t.}\quad & \mathbb{E}\left\{P_i\right\} \leq \bar{P}_{\text{avg}}, \forall i \in \mathbb{I} \quad (34)\\ & \mathbb{E}\{\psi_i^{(\kappa)}\} \leq \bar{\psi}_{\text{avg}}, \forall i \in \mathbb{I},\end{aligned}$$

where the κ-th band B_κ can be selected based on its data-rate under the constraints that the average transmit power and the average IT are below a finite threshold. For the E-CRNs, the SLM scheme is achieved by selecting the optimal band from $M+N$ bands. With the band selection scheme, the optimal band can be selected to achieve higher system data-rate. Moreover, a more robust system can be achieved by the band selection scheme, in which the selected bands can provide better system performance in terms of outage probability. For all available frequency bands, the band selection scheme can be fulfilled by the WF scheme, which will be described in the next section. The computational complexity of optimal band selection scheme is about $\mathcal{O}\left([I(M+N)]^2\right)$, where the total number of target frequency bands is $(M+N)$ and I denotes the number of WiFi transmission pairs.

The core principle of the proposed SLM is that the E-CRNs can maximize the system performance by dynamically using the target frequency bands under given constraints. The spectrum access schemes of SS and SA can be jointly exploited with (33) and the optimal band can be selected with (34). For a frequency band B with fixed bandwidth, the SLM scheme can be fulfilled by the band selection scheme in (34). Furthermore, if the scale of the band is not fixed, i.e., a finer granularity of channel access, the E-CRNs would be able to combine the target bands according to the system requirements, leading to a higher spectrum efficiency. However, an arbitrary granularity of spectrum access currently cannot be achieved due to practical hardware limitations.

IV. E-CRNs SYSTEM PERFORMANCE

In this section, the system performance in terms of the outage probability, spectrum efficiency, and system data-rate is discussed for the proposed E-CRNs. To achieve the required system performance, the E-CRNs should delicately design a spectrum usage mechanism by jointly exploiting the frequency bands shared by the PU networks and aggregated from WiFi networks.

A. Water-filling scheme with SS and SA

The traffic offloading issues in the E-CRNs need to be considered for two main spectrum access ways of SS and SA. To protect the PU networks and avoid the harmful interference to WiFi networks, the E-CRNs should delicately control their traffic offloading to the shared spectrum and aggregated spectrum. In the E-CRNs operation scenarios, two key tradeoffs should be considered. First, the tradeoff between system traffic offloading and interference controlling ought to be taken into consideration. Second, the tradeoff between system QoS and offloading assignment should also be considered.

To address the tradeoff issues, a new WF scheme is proposed. As shown in Fig. 3, the system data-rate can be divided by a switch function $\Omega(R_I;\delta_M,\delta_N)$ and assigned to two kinds of spectrum W_{SS} and W_{SA}. For W_{SS} and W_{SA}, the operation statuses including transmissions, channel state information are indicated by δ_M and δ_N. In other words, we use two normalized coefficients δ_M and δ_N to indicate the

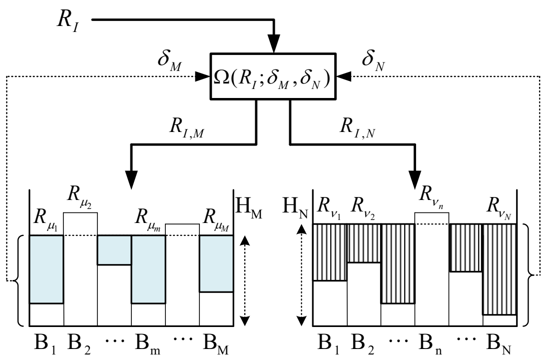

Fig. 3: System data-rate assignment with water-filling scheme.

transmission abilities of W_{SS} and W_{SA}. The switch function can be described as

$$(R_{I,M},R_{I,N})=\Omega(R_I;\delta_M,\delta_N), \tag{35}$$

where $R_{I,M}=\dfrac{R_I\delta_M}{\delta_M+\delta_N}$ and $R_{I,N}=\dfrac{R_I\delta_N}{\delta_M+\delta_N}$. In Fig. 3, R_{μ_m} denotes the data-rate transmitted by the m-th band B_m, the water levels (WLs) are denoted by H_M and H_N in terms of signal power.

Taking $R_{I,M}$ as an example, the WF algorithm can be formulated as

$$R_{I,M}=\sum_{m=1}^{M}R_{\mu_m}=\sum_{m=1}^{M}B_m\log\left[1+(H_M-\aleph_{\mu_m})^+\right], \tag{36}$$

where $(x)^+=\max(x,0)$ and $\aleph_{\mu_m}$ denotes the noise and interference of B_m. If the m-th band B_m is occupied by the PU networks or the noise is larger than H_M, such band cannot be used and $R_{\mu_m}=0$. As for the spectrum gathered by SA, the same WF scheme can be utilized. With the WF scheme, the system data-rate R_I can be assigned correspondingly. The transmission factors δ_M and δ_N can jointly be determined by the available bandwidth W_{SS} and W_{SA}, the WLs H_M and H_N, and the noise statuses $\aleph_{\mu_m}$ and $\aleph_{\mu_n}$. Taking δ_M as an example, it can be determined as

$$\delta_M\propto\left(W_{\text{SS}},H_M,\frac{1}{\bar{\aleph}_M}\right), \tag{37}$$

where $\bar{\aleph}_M$ denotes the average level of noise and interference. Actually, the transmission factor indicates the transmission ability of the target frequency bands. In particular, the E-CRNs can dynamically assign the system data to W_{SS} and W_{SA} according to their current transmission statuses. The data-rate $R_{I,M}$ and $R_{I,N}$ can be assigned to the bands through the WF scheme according to the corresponding usage statuses.

Note that the proposed WF scheme aims to dynamically assign data to two kinds of spectrum W_{SS} and W_{SA} based on the current state information of sub-bands. Thus, it is different from traditional WF algorithm used to achieve the maximum system capacity through signal power allocation method. The key parameters in the proposed WF scheme can be generated with a numerical way.

B. Spectrum efficiency analysis

The E-CRNs can achieve better system performance in terms of system data-rate, outage probability and so on by utilizing more spectrum combining SS and SA. Moreover, the system SE can also be improved for the shared and aggregated frequency bands. In particular, the SE can be evaluated by the ShE of the shared spectrum and the AgE of the aggregated spectrum.

Let ξ_{SE} denote the SE, which can be evaluated by the ratio of the system data-rate R_I and the available spectrum W as

$$\xi_{\text{SE}} = \frac{R_I}{W} = \frac{R_{I,M} + R_{I,N}}{W_{\text{SS}} + W_{\text{SA}}}. \tag{38}$$

For the proposed E-CRNs, the SE of the shared spectrum with imperfect spectrum sensing can be expressed as

$$\xi_{\text{SE}}^{\text{SS}} = \frac{\sum\limits_{i=1}^{I}\sum\limits_{m=1}^{M}\left[\mu_m B_m \log\left(1+\beta_{i,m}\right)\right]}{W_{\text{SS}}}, \tag{39}$$

where μ_m in (3) indicates the sensing result of the m-th band B_m. In particular, using the system data-rate assignments shown in Fig. 3, the SE of SS can be evaluated by the specific data-rate of the corresponding band. Therefore, the SE in the above formulation can be expressed as

$$\xi_{\text{SE}}^{\text{SS}} = \frac{\sum\limits_{m=1}^{M} R_{\mu_m}}{W_{\text{SS}}}. \tag{40}$$

The SE for the aggregated spectrum can be formulated as

$$\xi_{\text{SE}}^{\text{SA}} = \frac{\sum\limits_{i=1}^{I}\sum\limits_{n=1}^{N}\left[\nu_n B_{M+n} \log\left(1+\beta_{i,n}\right)\right]}{W_{\text{SA}}}, \tag{41}$$

where the interference factor ν_n in (8) indicates whether the $(M+n)$-th band B_{M+n} can be aggregated. Similarly, with the WF scheme, the above equation can also be formulated as

$$\xi_{\text{SE}}^{\text{SA}} = \frac{\sum\limits_{n=1}^{N} R_{\nu_n}}{W_{\text{SA}}}. \tag{42}$$

Considering jointly the shared spectrum and aggregated spectrum, the average SE for the E-CRNs can be finally formulated as

$$\xi_{\text{SE}}^{\text{E-CRNs}} = \tag{43}$$
$$\frac{\sum\limits_{i=1}^{I}\left[W_M \eta_{\text{ShE}}^{(f)} \log\left(1+\beta_{\text{SS}}^{(i)}\right) + W_N \eta_{\text{AgE}}^{(f)} \log\left(1+\beta_{\text{SA}}^{(i)}\right)\right]}{W_M \eta_{\text{ShE}}^{(f)} + W_N \eta_{\text{AgE}}^{(f)}},$$

where $\beta_{\text{SS}}^{(i)}$ and $\beta_{\text{SA}}^{(i)}$ denote the SINR of the i-th SU in the shared spectrum and the aggregated spectrum, respectively. Note that only the E-CRNs' data-rate in the target frequency bands W_M and W_N are considered to evaluate the SE. The data-rate of the PU networks in W_M and the data-rate of WiFi networks in W_N are not included, as they are not our focus in this work.

C. System performance evaluation

Based on different characteristics of shared spectrum and aggregated spectrum, the E-CRNs can flexibly assign different services to different spectrum using the proposed WF scheme to achieve a better system performance. The system performance can be evaluated in terms of system QoS including system outage probability and system data-rate. Moreover, the user QoE can also be included to evaluate the system performance. Considering the constraints imposed by the PU networks and WiFi networks, the E-CRNs should delicately control their operations to achieve the balance between the system QoS and the traffic offloading.

The outage probabilities of the E-CRNs for the shared spectrum and the aggregated spectrum are provided in (18) and (26), respectively. Therefore, the system outage probability of the E-CRNs can be written as

$$\begin{aligned} &Q_{\text{E-CRNs}} = Q_{\text{SS}} Q_{\text{SA}} && (44)\\ &= \left[1-\text{P}_\text{r}\left\{\beta_{i,m} \geq \gamma_{i,m},\right\}\right] \cdot \left[1-\text{P}_\text{r}\left\{\beta_{i,n} \geq \gamma_i, n,\right\}\right],\\ &= \left[1-\text{P}_\text{r}\left\{\left(\beta_{\text{SS}} \geq \gamma_{\text{SS}}\right)|\eta_{\text{ShE}}\right\}\right] \cdot \left[1-\text{P}_\text{r}\left\{\left(\beta_{\text{SA}} \geq \gamma_{\text{SA}}\right)|\eta_{\text{AgE}}\right\}\right], \end{aligned}$$

where β_{SS} (β_{SA}) denotes the average SINR in the shared (aggregated) spectrum, γ_{SS} (γ_{SA}) is the corresponding given SINR threshold, $\text{P}_\text{r}\left\{a|A\right\}$ calculates the probability of a under the condition of A. For the E-CRNs, the system outage probability is mainly determined by the system SINR, the sharing efficiency and aggregation efficiency. Compared to the conventional CRNs based only on the shared spectrum from the PU networks, the proposed E-CRNs are certainly more robust with a lower outage probability. It should be noted that the potential forced outage imposed by the PU networks or the incumbent systems is not considered in the system outage probability for simplicity.

The system ergodic data-rate $\bar{R}_{I,M}$ and $\bar{R}_{I,N}$ on the shared and aggregated spectrum can be determined by (13) and (27) with the system constraints imposed by the PU networks and WiFi networks. For the E-CRNs, the system ergodic data-rate can be formulated as

$$\bar{R}_{\text{E-CRNs}} = \bar{R}_{I,M} + \bar{R}_{I,N} = \tag{45}$$
$$\mathbb{E}\left\{\sum_{i=1}^{I}\left[W_M \eta_{\text{ShE}}^{(f)} \log\left(1+\beta_{\text{SS}}^{(i)}\right) + W_N \eta_{\text{AgE}}^{(f)} \log\left(1+\beta_{\text{SA}}^{(i)}\right)\right]\right\},$$
$$\text{s.t. } \mathcal{P}_D \geq \gamma_D|\mathcal{H}_1, \mathcal{P}_F \leq \gamma_F|\mathcal{H}_0, \mathbb{E}\left\{P_i\right\} \leq \bar{P}_{\text{avg}}, \forall i \in \mathbb{I} \tag{46}$$
$$\mathbb{E}\{\psi_i\} \leq \bar{\psi}_{\text{avg}}, \forall i \in \mathbb{I}, \tag{47}$$

where the constraints in (46) can guarantee the priority of the PU networks and the constraint in (47) limits the interference of the E-CRNs in the aggregated spectrum. The system ergodic data-rate can be evaluated with the average SINRs on the shared spectrum and aggregated spectrum with the corresponding constraints, e.g., limited transmit power, controlled IT, and so on. As shown in Fig. 3, the E-CRNs can fairly assign different kinds of service, e.g., real-time service and non real-time service, to the shared spectrum and aggregated spectrum according to their usage statuses δ_M and δ_N. Similar to LTE-U systems, the E-CRNs can also deal with the traffic offloading issues in a flexible mode, i.e., the basic traffic offloading is assigned to the shared spectrum and the aggregated spectrum only works as the supplemental downlink. The flexible traffic offloading of the E-CRNs can be achieved by the WF scheme by adjusting the two parameters δ_M and δ_N.

The E-CRNs' service based on the shared and aggregated spectrum is unavoidably affected by the PU networks and incumbent systems. According to their operation characteristics, the E-CRNs should dynamically assign their transmissions to the two spectrum. Therefore, there is a tradeoff between the system QoS and the system traffic offloading, which can be generally formulated as

$$\max \left\{ \bar{R}_{\text{E-CRNs}} \right\} \tag{48}$$

$$\text{s.t.} \quad Q_{\text{E-CRNs}} \leq \bar{Q}_{\text{E-CRNs}} \tag{49}$$

$$\xi_{\text{SE}}^{\text{E-CRNs}} \geq \bar{\xi}_{\text{SE}}^{\text{E-CRNs}}, \tag{50}$$

where the system outage probability should be less than a given threshold $\bar{Q}_{\text{E-CRNs}}$, and the system SE should be larger than a given threshold $\bar{\xi}_{\text{SE}}^{\text{E-CRNs}}$. Note that the main objective of the proposed E-CRNs is to maximize the system ergodic data-rate under two main constraints, spectrum efficiency and system outage defined in (43) and (44), respectively.

V. Numerical results and discussion

In this section, the numerical results and the corresponding theoretical analysis are presented to evaluate the performance of the proposed E-CRNs. The E-CRNs can jointly access the licensed white spectrum with the carrier frequency f_s and the unlicensed Industrial Scientific Medical (ISM) spectrum with the carrier frequency f_a. Note that both TVWS in 700 MHz and LTE TDD bands in 3500 MHz are considered as shared spectrum. The related simulation parameters are given in Table I. Note that the Okumura-Hata and COST 231-Hata channel models are also provided here to indicate the key channel parameters for the proposed E-CRNs.

The ShE vs. varying $\mathcal{P}_D$ and $\mathcal{P}_F$ under $\text{P}(\mathcal{H}_0)$, $\text{P}(\mathcal{H}_1)$ with different γ_F, γ_D is evaluated in Fig. 4, in which $\mathcal{P}_D = 0:0.1:1$ and $\mathcal{P}_F = 0:0.01:0.1$, $\text{P}(\mathcal{H}_0) + \text{P}(\mathcal{H}_1) = 1$. The function $\text{P}(z)$ denotes the probability of z. With

TABLE I: Simulation parameters.

Parameters	Value
Carrier frequency for SS, f_s	700 / 3500 MHz
Carrier frequency for SA, f_a	2400 MHz
Number of SS bands, M	100
Number of SA bands, N	100
Bandwidth of a band, B	0.2 MHz
Thermal noise power, N_o	-114 dBm/MHz
Number of SU transmission pairs, I	20
Number of PU transmission pairs, J	6
Number of WiFi transmission pairs, K	10
E-CRNs system period, T	100 ms
Sensing time for SS, τ_s	5 ms
Sensing time for SA, τ_s^A	5 ms
Idle time for SA, τ_i^A	10 ms
Path loss exponent, α	3
Channel models [46]	Okumura-Hata for SS
	COST 231-Hata for SA

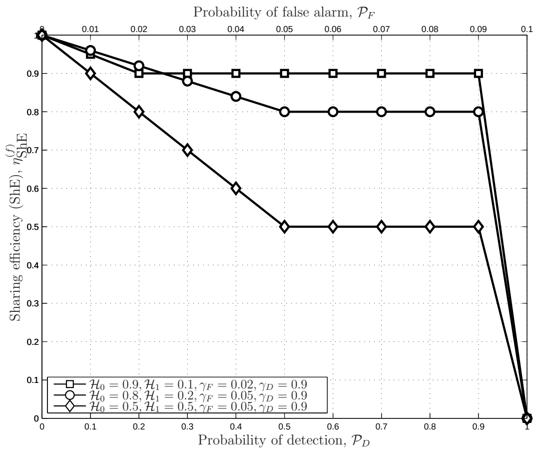

Fig. 4: The ShE vs. $\mathcal{P}_D$ and $\mathcal{P}_F$ under $\text{P}(\mathcal{H}_0)$, $\text{P}(\mathcal{H}_1)$ with different γ_F, γ_D.

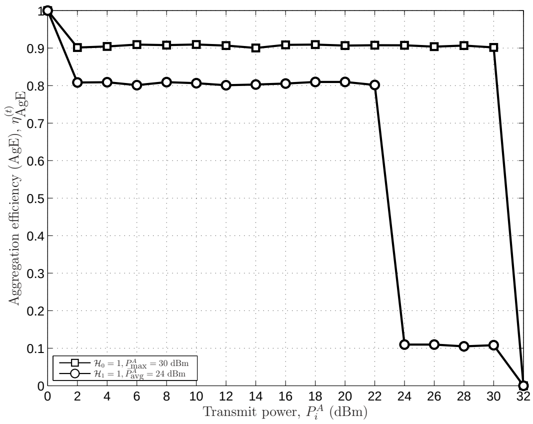

Fig. 5: The AgE vs. the transmit power P_i^A under $\text{P}(\mathcal{H}_0) = 1$ and $\text{P}(\mathcal{H}_1) = 1$ with the maximum transmit power constraint P_{max}^A and average transmit power constraint $\bar{P}_{\text{avg}}^A$.

the imperfect spectrum sensing ($\mathcal{P}_D < 1, \mathcal{P}_F > 0$), the ShE decreases with the increase of $\text{P}(\mathcal{H}_1)$ and the decrease of $\text{P}(\mathcal{H}_0)$, i.e., less licensed spectrum can be shared to the E-CRNs with more PU transmissions. Under the conditions of $\text{P}(\mathcal{H}_0) = 0.9, \text{P}(\mathcal{H}_1) = 0.1, \gamma_F = 0.02, \gamma_D = 0.9$, the ShE decreases from 1 to 0.9 when $\mathcal{P}_F \leq 0.02$ and $\mathcal{P}_D \leq 0.9$. If $0.02 < \mathcal{P}_F$ and $\mathcal{P}_D \leq 0.9$, the ShE is fixed to 0.9, i.e., 90% of the available spectrum can be shared to the E-CRNs. When $\mathcal{P}_D > 0.9$, the ShE sharply decreases to 0. From the results in Fig. 4, the ShE of the E-CRNs with imperfect spectrum sensing is mainly determined by the usage status of the target frequency bands and the thresholds γ_D and γ_F.

The AgE of the E-CRNs in the time domain $\eta_{\text{AgE}}^{(t)}$ is evaluated in Fig. 5, in which the transmit power is $P_i^A = 0:2:32$ dBm and the maximum transmit power constraint P_{max}^A under $\text{P}(\mathcal{H}_0) = 1$ and the average transmit power constraint $\bar{P}_{\text{avg}}^A$ under $\text{P}(\mathcal{H}_1) = 1$ are set to 30 dBm and 24 dBm [30], respectively. Under $\text{P}(\mathcal{H}_0) = 1$, the AgE $\eta_{\text{AgE}}^{(t)}$ is about 0.9 when $P_i^A \leq \bar{P}_{\text{max}}^A$ and it decreases fast to zero when the

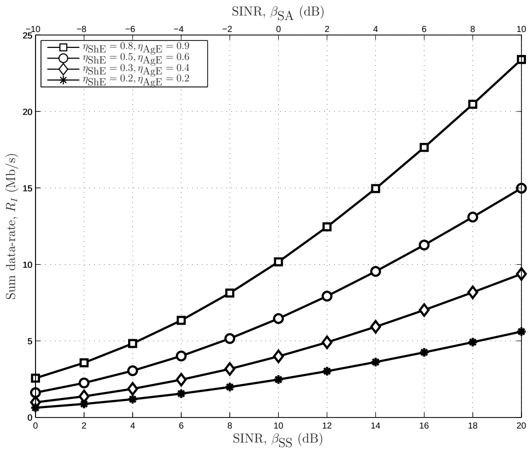

Fig. 6: The sum rate R_I vs. the SINRs β_{SS} and β_{SA} under different ShE η_{ShE} and AgE η_{AgE}.

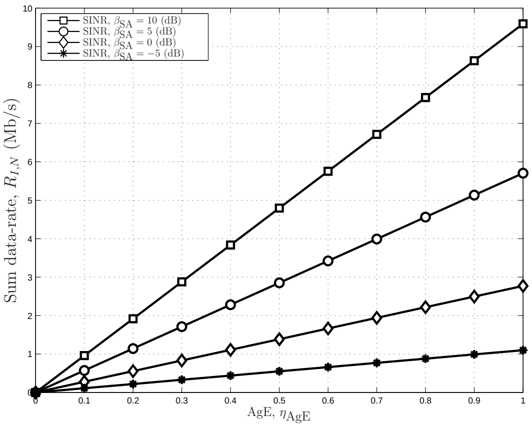

Fig. 7: The sum rate $R_{I,N}$ vs. the AgE η_{AgE} under different SINR β_{SA}.

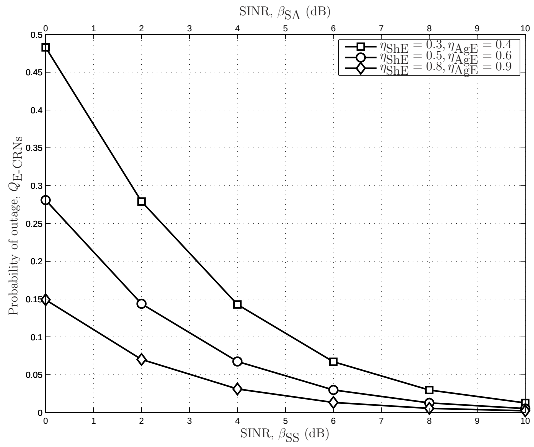

Fig. 8: The outage probability $Q_{\text{E-CRNs}}$ vs. the SINRs β_{SS} and β_{SA} under different ShE η_{ShE} and AgE η_{AgE}.

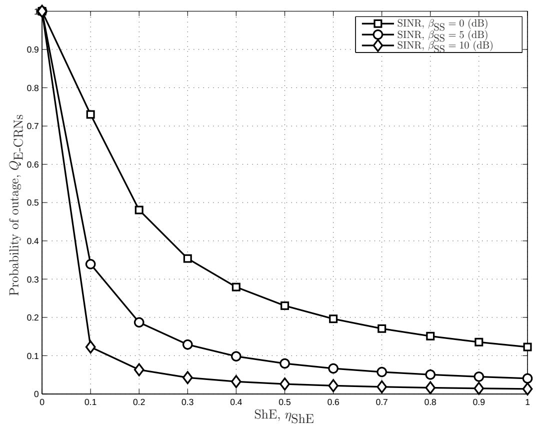

Fig. 9: The outage probability $Q_{\text{E-CRNs}}$ vs. the ShE η_{ShE} under different SINRs β_{SS}.

transmit power is larger than P^A_{max}. When the WiFi signals are present, i.e., $\mathrm{P}(\mathcal{H}_1)=1$, the AgE $\eta^{(t)}_{\text{AgE}}$ is about 0.8 if the transmit power is less than $\bar{P}^A_{\text{avg}}$. When the transmit power is $P^A_i \in [\bar{P}^A_{\text{avg}}, P^A_{\text{max}}]$, the unlicensed spectrum can still be aggregated by the E-CRNs with a low AgE. If the transmit power is larger than P^A_{max}, such spectrum cannot be aggregated, i.e., the AgE goes to zero. From the results in Fig. 5, we can observe that the unlicensed spectrum can be aggregated efficiently by the E-CRNs with the given transmit power constraints.

The sum rate of the E-CRNs is evaluated in Fig. 6, in which the SINRs β_{SS} and β_{SA} are set to $0:2:20$ dB and $-10:2:10$ dB, respectively. The E-CRNs can achieve larger data-rate when the SINR β_{SS} and SINR β_{SA} increase. Furthermore, the data-rate increases with larger ShE η_{ShE} and larger AgE η_{AgE}, i.e., there are more spectrum that can be exploited by the E-CRNs. When $\beta_{SS}=10$ dB and $\beta_{SA}=0$ dB under the condition that $\eta_{ShE}=0.8$ and $\eta_{AgE}=0.9$, the sum rate R_I is 10 Mb/s, which is about 4 Mb/s larger than the sum rate with $\eta_{ShE}=0.5$ and $\eta_{AgE}=0.6$.

The sum rate $R_{I,N}$ of the E-CRNs with varying η_{AgE} under different SINR β_{SA} is evaluated in Fig. 7, in which the data-rate in the aggregated unlicensed spectrum is presented. From this figure, we can observe that the sum rate increases with larger SINR β_{SA} and larger η_{AgE}, i.e., the E-CRNs can achieve high data-rate with more aggregated spectrum and larger transmit power. When $\eta_{AgE}=1$, i.e., all W_N is aggregated by the E-CRNS, the sum rate $R_{I,N}$ is about 9.7 Mb/s when $\beta_{SA}=10$ dB.

The outage probability of the E-CRNs is evaluated in Fig. 8, in which the SINR β_{SS} and SINR β_{SA} are both set to $0:1:10$ dB. We can observe that the system outage probability decreases when the SINRs increase with large ShE η_{ShE} and AgE η_{AgE}. When $\eta_{ShE}=0.5$, AgE $\eta_{AgE}=0.6$, and $\beta_{SS}=\beta_{SA}=4$ dB , the $Q_{\text{E-CRNs}}$ is about 0.06, which is about equal to the outage probability under the condition of $\eta_{ShE}=0.3$, $\eta_{AgE}=0.4$, and $\beta_{SS}=\beta_{SA}=6$ dB. In this case, there is about 2 dB gain of the outage probability when the ShE increases from 0.3 to 0.5 and AgE increases from 0.4 to

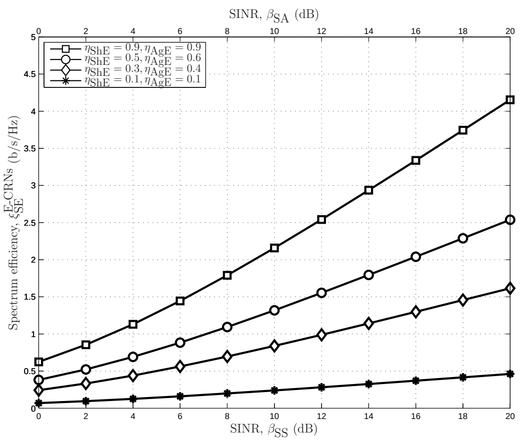

Fig. 10: The SE $\xi_{\text{SE}}^{\text{E-CRNs}}$ vs. the SINRs β_{SS} and β_{SA} under different ShE η_{ShE} and AgE η_{AgE}.

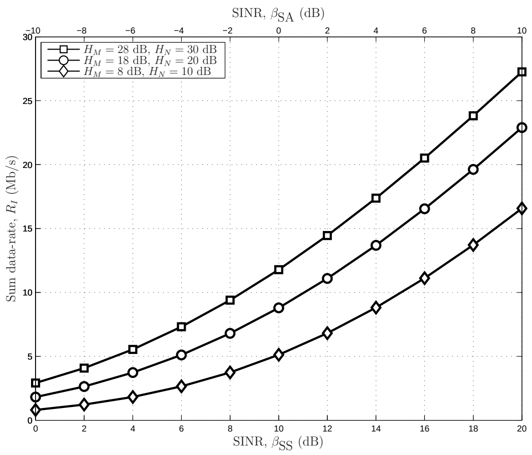

Fig. 11: The sum rate R_I vs. the SINRs β_{SS} and β_{SA} under different WLs H_M and H_N.

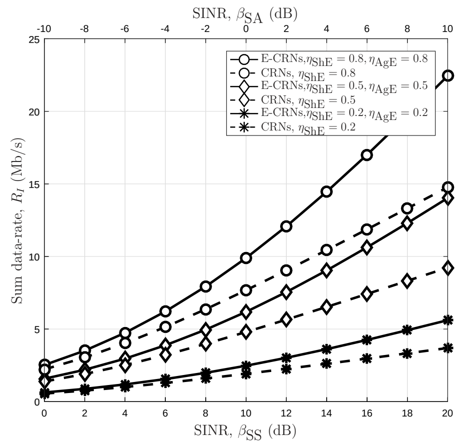

Fig. 12: The sum rate R_I vs. the SINRs β_{SS} and β_{SA} for E-CRNs and CRNs with different ShE η_{ShE} and AgE η_{AgE}.

0.6. It means that with more shared and aggregated spectrum, the E-CRNs can achieve better system performance in terms of outage probability.

The outage probability of the E-CRNs with only the shared spectrum is evaluated in Fig. 9, in which the ShE is set to $0 : 0.1 : 1$ and the SINR β_{SS} is set to 0 dB, 5 dB, and 10 dB. From the results, we can see that $Q_{\text{E-CRNs}}$ decreases with the increase of ShE and large SINR. However, for high SINR (say 10 dB), the outage probability does not decrease effectively with the increase of the ShE. It means that the outage probability of the E-CRNs on the shared spectrum is mainly affected by signal SINR.

The SE of the E-CRNs is evaluated in Fig. 10, in which the SINRs β_{SS} and β_{SA} are set to $0 : 2 : 20$ dB. The SE increases with high SINRs and high ShE and AgE, i.e., better spectrum efficiency can be achieved with more spectrum and higher SINRs. However, with low ShE and AgE, the high SE cannot be achieved for the E-CRNs because only a small part of the whole spectrum can be used by the E-CRNs.

The sum rate of the E-CRNs with different WLs H_M and H_N is evaluated in Fig. 11, in which the SINRs β_{SS} and β_{SA} are set to $0 : 2 : 20$ dB and $-10 : 2 : 10$ dB, respectively. The WLs H_M and H_N both in terms of dB are used to indicate the maximum transmission abilities of the shared and aggregated spectrum. In these simulations, the WL H_N is 2 dB larger than the WL H_M since we assume that the incumbent systems, e.g., WiFi networks, are more interference-resistant than the PU networks. Therefore, the E-CRNs can assign more traffic offloading to the aggregated spectrum W_N than the shared spectrum W_M under the conditions of equivalent ShE and AgE. From this simulation, we can observe that the sum rate can achieve about 28 Mb/s when the WLs are $H_M = 28$ dB, $H_N = 30$ dB and the SINRs are $\beta_{\text{SS}} = 20$ dB, $\beta_{\text{SA}} = 10$ dB. The E-CRNs can dynamically assign system traffic offloading to available spectrum by setting the appropriate WLs. Furthermore, the balance between system traffic offloading and system performance in terms of data-rate and outage probability can be achieved.

The sum rates of the E-CRNs and the CRNs with varying ShE η_{ShE} and AgE η_{AgE} are compared in Fig. 12, in which the SINRs β_{SS} and β_{SA} are set to $0 : 2 : 20$ dB and $-10 : 2 : 10$ dB, respectively. Note that only shared spectrum can be used by the CRNs, in which the ShE η_{ShE} is set to 0.8, 0.5, and 0.2. Compared with the conventional CRNs, the proposed E-CRNs can achieve higher system data rate. For example, there is about 8 Mb/s performance gain for E-CRNs with $\eta_{\text{ShE}} = \eta_{\text{AgE}} = 0.8$ and $\beta_{\text{SS}} = 20$ dB, $\beta_{\text{SA}} = 10$ dB. From Fig. 12, we can see that multiple spectrum can increase the performance gain of the proposed E-CRNs in terms of system data rate.

VI. Conclusions

In this paper, new E-CRNs have been proposed to jointly access the licensed white spectrum by SS and the unlicensed spectrum by SA. The E-CRNs framework has been designed. A SLM scheme has been proposed to manage the shared spectrum and aggregated spectrum. The WF algorithm has been proposed to dynamically assign system traffic offloading to shared spectrum and aggregated spectrum. The ShE, AgE, and SE have been included to evaluate the E-CRNs. Numerical results have verified that the proposed E-CRNs can achieve better performance in terms of sum rate, outage probability, and SE.

REFERENCES

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Sel. Area. Comm.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[2] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[3] X. Hong, J. Wang, C.-X. Wang, and J. Shi, "Cognitive radio in 5G : a perspective on energy-spectral efficiency trade-off," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 46–53, Jul. 2014.

[4] L. Lv, J. Chen, Q. Ni, and Z. Ding, "Design of cooperative non-orthogonal multicast cognitive multiple access for 5G systems: user scheduling and performance analysis" *IEEE Trans. Commun.*, vol. 65, no. 6, pp. 2641–2656, Jun. 2017.

[5] X. Ge, J. Chen, C.-X. Wang, J. S. Thompson, and J. Zhang, "5G green cellular networks considering power allocation schemes," *Sci China Inf Sci*, vol. 59, no. 2, Feb. 2016.

[6] X. Ge, Y. Qiu, J. Cheng, M. Huang, H. Xu, J. Xu, W. Zhang,Y. Yang, C.-X. Wang, and J. Thompson, "Wireless fractal cellular networks," *IEEE Wireless Commun. Mag.*, vol. 23, no. 5, pp. 110–119, Oct. 2016.

[7] C. Yang, J. Li, Q. Ni, A. Anpalagan, and M. Guizani, "Interference-aware energy efficiency maximization in 5G ultra-dense networks," *IEEE Trans. Commun.*, vol. 65, no. 2, pp.728–739, Feb. 2017.

[8] J. Si, H. Huang, Z. Li, B. Hao, and R. Gao, "Performance analysis of adaptive modulation in cognitive relay network with cooperative spectrum sensing," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2198–2211, Jul. 2014.

[9] Y. Gan, C. Jiang, N. C. Beaulieu, J. Wang, and Y. Ren, "Secure collaborative spectrum sensing: a peer-prediction method," *IEEE Trans. Commun.*, vol. 64, no. 10, pp. 4283–4294, Oct. 2016.

[10] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "Senseless: A database-driven white spaces network," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 189–203, Feb. 2012.

[11] W. Zhang, G. Abreu, M. Inamori, and Y. Sanada, "Spectrum sensing algorithms via finite random matrices," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 164–175, Jan. 2012.

[12] H. Sun, A. Nallanathan, C.-X. Wang, and Y. Chen, "Wideband spectrum sensing for cognitive radio networks: a survey," *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 74–81, Apr. 2013.

[13] "Microsoft White Spaces." [Online]. Available: http://whitespaces.microsoftspectrum.com/

[14] "Google Spectrum Database." [Online]. Available: https://www.google.com/get/spectrumdatabase

[15] A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: an information theoretic perspective," *Proc. of the IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.

[16] X. Kang, Y. C. Liang, H. Garg, and L. Zhang, "Sensing-based spectrum sharing in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 4649–4654, Oct. 2009.

[17] C. Zhai, H. Chen, X. Wang, and J. Liu, "Opportunistic spectrum sharing with wireless energy transfer in stochastic networks," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1296–1308, Aug. 2017.

[18] L. Zhang, G. Zhao, W. Zhou, L. Li, G. Wu, Y. C. Liang, and S. Li, "Primary channel gain estimation for spectrum sharing in cognitive radio networks," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4152–4162, Oct. 2017.

[19] L. Musavian and S. Aissa, "Capacity and power allocation for spectrum-sharing communications in fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 148–156, Jan. 2009.

[20] Z. Chen, X. Wang, and X. Zhang, "Continuous power allocation strategies for sensing-based multiband spectrum sharing," *IEEE J. Sel. Area. Comm.*, vol. 31, no. 11, pp. 2409–2419, Nov. 2013.

[21] R. Cai, J. K. Zhang, T. N. Davidson, W. Zhang, K. M. Wong, and P. C. Ching, "A power allocation strategy for multiple poisson spectrum-sharing networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 1785–1799, Apr. 2015.

[22] S. Dikmese, Z. Ilyas, P. C. Sofotasios, M. Renfors, and M. Valkama, "Sparse frequency domain spectrum sensing and sharing based on cyclic prefix autocorrelation," *IEEE J. Sel. Area. Comm.*, vol. 35, no. 1, pp. 159–172, Jan. 2017.

[23] A. Rabbachin, T. Q. S. Quek, H. Shin, and M. Z. Win, "Cognitive network interference," *IEEE J. Sel. Area. Comm.*, vol. 29, no. 2, pp. 480–493, Feb. 2011.

[24] J. Lee, J. G. Andrews, and D. Hong, "Spectrum-sharing transmission capacity with interference cancellation," *IEEE Trans. Commun.*, vol. 61, no. 1, pp. 76–86, Jan. 2013.

[25] M. Wildemeersch, T. Q. S. Quek, M. Kountouris, A. Rabbachin, and C. H. Slump, "Successive interference cancellation in heterogeneous networks," *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4440–4453, Dec. 2014.

[26] Intel, "Spectrum sharing: licensed shared access (LSA) and spectrum access system (SAS)," Oct. 2015.

[27] Ofcom, "A framework for spectrum sharing," Oct. 2015.

[28] ETSI TR 103 113 V1.1.1. (2013, Jul.) Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc); Mobile broadband services in the 2300 MHz - 2400 MHz frequency band under Licensed Shared Access regime.

[29] Federal Communications Commission, "FCC 15-47: Report and order and second further notice of proposed rulemaking," Apr. 2015.

[30] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, X. Shen, and L. L. Xie, "LTE-unlicensed: the future of spectrum aggregation for cellular networks," *IEEE Wirel. Commun.*, vol. 22, no. 3, pp. 150–159, Jun. 2015.

[31] C. Tsinos, F. Foukalas, and T. A. Tsiftsis, "Resource allocation for licensed/unlicensed carrier aggregation MIMO systems," *IEEE Trans. Commun.*, vol. 65, no. 9, pp.3765–3779, Sept. 2017.

[32] J. Zhang, X. Chen, K. P. Peppas, X. Li, and Y. Liu, "On high-order capacity statistics of spectrum aggregation systems over κ-μ and κ-μ shadowed fading channels," *IEEE Trans. Commun.*, vol. 65, no. 2, pp.935–944, Feb. 2017.

[33] Qualcomm, "Qualcomm research LTE in unlicensed spectrum: harmonious coexistence with WiFi," Jun. 2014.

[34] Nokia, "Nokia LTE for unlicensed spectrum," Jun. 2014.

[35] R. Zhang, Z. Zheng, M. Wang, X. Shen, and L. L. Xie, "Equivalent capacity in carrier aggregation-based LTE-A systems: A probabilistic analysis," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6444–6460, Nov. 2014.

[36] F. Liu, K. Zheng, W. Xiang, and H. Zhao, "Design and performance analysis of an energy-efficient uplink carrier aggregation scheme," *IEEE J. Sel. Area. Comm.*, vol. 32, no. 2, pp. 197–207, Feb. 2014.

[37] H. Lee, Y. Ko, S. Vahid, and K. Moessner, "Practical spectrum aggregation for secondary networks with imperfect sensing," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5474–5484, Jul. 2016.

[38] L. Jiao, I. A. M. Balapuwaduge, F. Y. Li, and V. Pla, "On the performance of channel assembling and fragmentation in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5661–5675, Oct. 2014.

[39] S. Ping, A. Aijaz, O. Holland, and A. H. Aghvami, "SACRP: A spectrum aggregation-based cooperative routing protocol for cognitive radio adhoc networks," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2015–2030, Jun. 2015.

[40] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, Apr. 2008.

[41] F. Wang, M. Krunz, and S. Cui, "Price-based spectrum management in cognitive radio networks," *IEEE J. Sel. Top. Sign. Proces.*, vol. 2, no. 1, pp. 74–87, Feb. 2008.

[42] S. Hayashi and Z. Q. Luo, "Spectrum management for interference-limited multiuser communication systems," *IEEE Trans. Inform. Theory*, vol. 55, no. 3, pp. 1153–1175, Mar. 2009.

[43] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, Jun. 2011.

[44] I. Ku, C.-X. Wang, and J. Thompson, "Spectral, energy and economic efficiency of relay-aided cellular networks," *IET Commun.*, vol. 7, no. 14, pp. 1476–1486, Sept. 2013.

[45] W. Zhang, C.-X. Wang, D. Chen, and H. Xiong, "Energy-spectral efficiency tradeoff in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2208–2218, Apr. 2016.

[46] M. Alotaibi, M. Sirbu, and J. Peha, "Impact of spectrum aggregation technology and frequency on cellular networks performance," in *Proc. IEEE DySPAN'15*, Stockholm, Sweden, Sept. 2015, pp. 326–335.

Wensheng Zhang (S'08-M'11) received the M.E. degree and Ph.D. degree both in electrical engineering from Shandong University, China, in 2005 and Keio University, Japan, in 2011, respectively. He has been an Assistant Professor in the School of Communication, Shandong Normal University, China, from 2005 to 2007. In 2011, he was a visiting researcher at Oulu University, Finland. In 2012, he joined the School of Information Science and Engineering at Shandong University, where he is currently an Associate Professor. His research interests lie in random matrix theory, cognitive radio networks, visible light communications, and 5G wireless communications.

Cheng-Xiang Wang (S'01-M'05-SM'08-F'17) received the BSc and MEng degrees in Communication and Information Systems from Shandong University, China, in 1997 and 2000, respectively, and the PhD degree in Wireless Communications from Aalborg University, Denmark, in 2004.

He was a Research Assistant with the Hamburg University of Technology, Hamburg, Germany, from 2000 to 2001, a Visiting Researcher with Siemens AG Mobile Phones, Munich, Germany, in 2004, and a Research Fellow with the University of Agder, Grimstad, Norway, from 2001 to 2005. He has been with Heriot-Watt University, Edinburgh, U.K., since 2005, where he was promoted to a Professor in 2011. In 2018, he joined Southeast University, China, as a Professor and Thousand Talent Plan Expert. He has authored 2 books, one book chapter, and over 330 papers in refereed journals and conference proceedings. His current research interests include wireless channel modeling and (B)5G wireless communication networks.

Dr. Wang is a Fellow of the IET and HEA, and is recognized as a Web of Science 2017 Highly Cited Researcher. He served or is currently serving as an Editor for nine international journals, including the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY since 2011, the IEEE TRANSACTIONSON COMMUNICATIONS since 2015, and the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2007 to 2009. He was the leading Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Special Issue on Vehicular Communications and Networks. He is also a Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Special Issue on Spectrum and Energy Efficient Design of Wireless Communication Networks, and the IEEE TRANSACTIONS ON BIG DATA, Special Issue on Wireless Big Data. He served or is serving as a TPC Member, TPC Chair, and General Chair of over 80 international conferences. He received nine Best Paper Awards from the IEEE Globecom 2010, the IEEE ICCT 2011, ITST 2012, the IEEE VTC 2013, IWCMC 2015, IWCMC 2016, the IEEE/CIC ICCC 2016, and the WPMC 2016.

Xiaohu Ge (M'09-SM'11) is currently a full Professor with the School of Electronic Information and Communications at Huazhong University of Science and Technology (HUST), China. He is an adjunct professor with with the Faculty of Engineering and Information Technology at University of Technology Sydney (UTS), Australia. He received his PhD degree in Communication and Information Engineering from HUST in 2003. He has worked at HUST since Nov. 2005. Prior to that, he worked as a researcher at Ajou University (Korea) and Politecnico Di Torino (Italy) from Jan. 2004 to Oct. 2005. His research interests are in the area of mobile communications, traffic modeling in wireless networks, green communications, and interference modeling in wireless communications. He has published more than 200 papers in refereed journals and conference proceedings and has been granted about 15 patents in China. He received the Best Paper Awards from IEEE Globecom 2010. Dr. Ge served as the general Chair for the 2015 IEEE International Conference on Green Computing and Communications (IEEE GreenCom 2015). He serves as an associate editor for IEEE Wireless Communications, IEEE Transactions on Vehicular Technology and IEEE ACCESS, etc.

Yunfei Chen (S'02-M'06-SM'10) received his B.E. and M.E. degrees in electronics engineering from Shanghai Jiaotong University, Shanghai, P.R.China, in 1998 and 2001, respectively. He received his Ph.D. degree from the University of Alberta in 2006. He is currently working as an Associate Professor at the University of Warwick, U.K. His research interests include wireless communications, cognitive radios, wireless relaying and energy harvesting.