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Research Article

Coexistence of Cognitive Small Cell and WiFi System: A Traffic Balancing Dual-Access Resource Allocation Scheme

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We consider a holistic approach for dual-access cognitive small cell (DACS) networks, which uses the LTE air interface in both licensed and unlicensed bands. In the licensed band, we consider a sensing-based power allocation scheme to maximize the sum data rate of DACSs by jointly optimizing the cell selection, the sensing operation, and the power allocation under the interference constraint to macrocell users. Due to intercell interference and the integer nature of the cell selection, the resulting optimization problems lead to a nonconvex integer programming. We reformulate the problem to a nonconvex power allocation game and find the relaxed equilibria, quasi-Nash equilibrium. Furthermore, in order to guarantee the fairness of the whole system, we propose a dynamic satisfaction-based dual-band traffic balancing (SDTB) algorithm over licensed and unlicensed bands for DACSs which aims at maximizing the overall satisfaction of the system. We obtain the optimal transmission time in the unlicensed band to ensure the proportional fair coexistence with WiFi while guaranteeing the traffic balancing of DACSs. Simulation results demonstrate that the SDTB algorithm could achieve a considerable performance improvement relative to the schemes in literature, while providing a tradeoff between maximizing the total data rate and achieving better fairness among networks.

1. Introduction

Recently, the rapid progress and pleasant experience of smart Internet based devices lead to an increasing demand for high data rate in wireless communication systems, which cause the growth of mobile traffic over thousands of times in the next decade [1]. However, since the licensed spectrum is limited, the new available licensed spectrum is becoming rare and expensive. To respond to increasing wireless communication capacity demand, new technologies have been proposed for cellular networks, such as small cells, microwave, massive *multiple-input multiple-output* (MIMO). Small cells as parts of the second tier in multitiered cellular networks have been considered as an effective means to boost the capacity and expand the coverage [2]. The incorporation of massive MIMO techniques into cellular networks can boost the channel throughput by transmitting independent data streams simultaneously over different antennas. However, the scarcity of the licensed spectrum is still the major block to further improve the data rate. The innovations that focus on the techniques that enable better utilization of the spectrum, including unlicensed bands, are an urgent issue. Specifically, it is assumed that up to 30% of the broadband access in cellular networks can be offloaded to the unlicensed spectrum occupied by WiFi networks [3].

Cognitive radio is able to enhance the spectrum efficiency by allowing cognitive radio users (CRs) to access the resources owned by primary users (PUs) in an opportunistic manner. In order to minimize the performance degradation caused to PUs, CRs perform spectrum sensing to determine the status of the spectrum [4]. In this paper, we define a dual-access cognitive small cell (DACS) network which takes the advantage of CRs and small cell networks. The DACS network could reuse the spectrum over small regions, which is regarded as one of the promising solutions for expanding the coverage and boosting the capacity of wireless networks. In addition, cognitive small cell base stations (CSBSs) can coexist with macrocell base stations (MBSs) by using the unoccupied licensed spectrum based on sensing results. One of the primary tasks of the DACS is to find a proper selection mechanism for cognitive small cell users (CSUs) and the associated CSBSs based on the sensing performance. However, the reliability of the sensing result is limited by several factors; thus the influence of the sensing accuracy should be taken into account.

Particularly, the unlicensed spectrum is considered as a solution of disposing the scarcity and valuableness of the licensed spectrum in Rel. 13, which supports the LTE system to offload the traffic to the unlicensed spectrum used by WiFi network, namely, LTE-*unlicensed* (LTE-U) [5]. The extension of LTE over 5 GHz spectrum requires providing fair coexistence of LTE-U with already existing WiFi systems. A feasible way to use both the licensed and unlicensed band simultaneously through the carrier aggregation feature (CA) is investigated in [6, 7]. On the one hand, allowing cellular networks to share the unlicensed band could mitigate spectrum scarcity in the licensed spectrum, while improving spectrum efficiency in the unlicensed band. Literature [8] investigated traffic load offloading from LTE-U to WiFi and aims to maximize the throughput of LTE-U with the minimum throughput requirement of WiFi networks. On the other hand, the impact of the cellular network on the WiFi system is not negligible; for example, the transmission of LTE users could increase the collision probability to WiFi systems. Therefore, there comes a critical challenge for designers to ensure that the LTE-U can coexist with WiFi fairly and friendly in the unlicensed band while guaranteeing regulatory requirement of the local government policy.

1.1. Related Work. In the licensed band, resource allocation problems are discussed in [9–13]. The power allocation problem in cognitive small cell networks (CSNs) leads to a noncooperative game (NCG) which was discussed in [11]. In addition, the sensing information was addressed in [12] as a part of the game, and the analysis of the equilibria is based on a concept called quasi-Nash equilibrium (QNE) [13].

The current researches focus on the coexistence of LTE-U and WiFi in the unlicensed band based on different deployment scenarios [14–18]. In [14], the authors proposed a time-domain resource separation method based on almost blank subframes (ABSs). In this scenario, LTE users stop transmitting in ABSs, whereas WiFi users have the opportunity to access the channel without interference. A similar coexistence scheme was proposed in [15], where LTE users allocate silent gaps with a predefined duty cycle to facilitate better coexistence with WiFi users. However, those schemes cannot achieve the optimal performance of LTE-U operation due to its discontinuous transmission. In [16], Zhang et al. proposed an enhanced static ABSs scheme to mitigate the cochannel interference between small cells and WiFi systems. The authors in [17] specially aim to optimize the transmission QoS of LTE users with the minimum transmission requirement of WiFi users, while it does not meet QoS requirement of all the LTE users by the designed mechanism. Based on the decision tree and the game theory, [18] presented a flexible architecture decoupling control plane from data plane which could improve throughput and spectrum efficiency.

Listen-before-talk (LBT) scheme is a another way to enable the coexistence of LTE-U and WiFi in the unlicensed band [19–22]. In [19], the authors proposed a LBT scheme by enabling carrier sensing at each LTE-eNB. Although the scheme can enable fair coexistence between LTE-U and WiFi, it results in spectrum underutilization due to the carrier sense operation in the LBT scheme. The fair coexistence between LTE-U and WiFi in the unlicensed band has been investigated by a stochastic geometry modeling approach where the LBT scheme is applied at SBSs [20]. A channel access framework based on LBT mechanism in LTE-U systems was proposed in [21], without the consideration of the licensed and the unlicensed spectrum management. In [22], the authors introduced a new time-frequency structure with a modified LBT scheme.

Traffic balancing scheme between licensed and unlicensed bands was proposed in [23–25]. The authors in [23] presented traffic balancing scheme in the licensed and unlicensed band by controlling the transmission power in the licensed band and the fraction of transmission time in the unlicensed band, respectively. However, the analysis in [23] was limited to the single user case, which can not be easily extended to the case with multiple users. For the downlink traffic balancing between licensed and unlicensed bands, [24] proposed a regret-based learning aided downlink traffic balancing scheme to ensure fair coexistence between LTE-U and WiFi. Jointly considering the power control and spectrum allocation in licensed/unlicensed bands to maximize the spectrum efficiency while guaranteeing the QoS of small cell users and WiFi users was discussed in [25].

1.2. Contributions. In this study, dual-access cognitive small cell (DACS) refers to the cognitive small cell with LTE technologies which can access both licensed and unlicensed bands simultaneously. The transmission model is based on the current wireless transmission system, in which the licensed spectrum is scarce and UEs have ever increasing data rate requirements, especially for downlink transmission. Thus, the supplemental downlink (SDL) model is suggested in [17, 26]; in this model LTE could offload parts of the traffic load to the unlicensed band and coexist with the WiFi user while taking into account the WiFi transmission requirements. In addition, in order to ensure the transmission QoS, the control information will still use the licensed band. Therefore, we use the licensed band to support the uplink transmission and use the unlicensed band to support the downlink transmission. Assume there are two sets of antennas for each CSBS; A_L is used for the licensed band and A_u for the unlicensed band. The DACS can access both licensed and unlicensed bands simultaneously; in the licensed band, CSUs are considered as the secondary users which work based on the mechanism of cognitive radio (CR) technologies. It could reuse the licensed spectrum when the macrocell users (MUs) are absent. In the unlicensed band, CSUs share the unlicensed spectrum with WiFi users by adjusting the transmission time. The objective is to maximize the utility of the whole system (including macrocell system, DACS system, and WiFi system), which could evaluate the satisfaction of the whole system, while guaranteeing the coexistence between CSUs and WiFi users in the unlicensed band. The main contributions can be summarized as follows:

(i) Firstly, CSU defined in this paper is based on CR technologies in which the licensed band could be reused when the MBS is absent. In addition, SDL model is considered for the transmission scheme, and parts of the downlink traffic load could be offloaded to the unlicensed band while the control information still uses the licensed band to ensure the transmission QoS. We propose a sensing-based power allocation scheme to maximize the total data rate of the whole network (LTE and WiFi) by jointly optimizing the cell selection, the sensing operation, and the power allocation as well as the unlicensed band transmission time.

(ii) Secondly, in the licensed band, we aim at maximizing the total data rate of DACSs by jointly optimizing the CSU-CSBS assignment, the detection operation, and the power allocation under the interference constraint to MUs. Due to the nonconvexity of the optimization problem, we reformulate the problem to a nonconvex power allocation game and find the quasi-Nash equilibrium (QNE) of the nonconvex game. The sufficient conditions for the existence and the uniqueness of a QNE are given by theoretical prove.

(iii) Thirdly, in the unlicensed band, taking into account the dynamic WiFi traffic load with varying transmission probability, we propose a dynamic channel access scheme for CSUs based on enhanced-LBT (E-LBT) scheme which could increase the spectrum efficiency and guarantee the transmission QoS of WiFi networks in the unlicensed band. Specifically, we analyze the WiFi traffic load by a statistical method, which could calculate the optimal transmission time of CSU based on the transmission probability of WiFi users.

(iv) Finally, we propose a satisfaction-based dual-band traffic balancing (SDTB) algorithm over the licensed and the unlicensed band which aims at maximizing the overall utility of DACSs and WiFi networks by jointly optimizing the cell selection, detection operation, and power allocation in the licensed band and transmission time in the unlicensed band. Furthermore, we calculate the computation complexity and evaluate the performance of the proposed SDTB scheme in the realistic channel status with multi-CSBS and multi-AP.

In the rest of this paper, we describe the system model in Section 2 and formulate the optimization problem in Section 3. The optimal satisfaction-based dual-band traffic balancing scheme is shown in Section 4. The simulation results are discussed in Section 5 and Section 6 finally concludes the paper.

Notations. Matrices and vectors are indicated in boldface. $\mathbb{C}^{m\times n}$ denotes that the space size of matrix is $m\times n$. $\mathrm{Tr}(\cdot)$ and $(\cdot)^H$ stand for trace and Hermitian transpose, respectively. $[\cdot]^+$ denotes $\max(0,\cdot)$. $\nabla^2_{\mathbf{x}}R(\mathbf{x})$ is the Hessian matrix of function $R(\mathbf{x})$; $\nabla_{\mathbf{x}}R(\mathbf{x})$ is the gradient of function $R(\mathbf{x})$ at point $\mathbf{x}$.

2. System Model

As shown in Figure 1, we consider a DACS system which could transmit and receive signals in both licensed and unlicensed bands simultaneously. There are M CSBSs, J CSUs, one MBS, K MUs, one WiFi-AP, and N WiFi users. In the licensed band, we consider the uplink transmission of CSBSs based on sensing results from antennas A_L while sharing the unlicensed band with WiFi systems for downlink transmission based on sensing results from antennas A_u. Due to the limited coverage radius of CSBSs, the number of CSUs and CSBSs is in an order of magnitude. Assuming both the CSBSs and the MBS are equipped with N_r antennas (including A_L and A_u), WiFi-AP and various users (CSUs, MUs, and WiFi users) are equipped with N_t antennas (including A_L and A_u). There is no cooperation within the heterogeneous network (macrocell network, DACS network, and WiFi network). Each user can simultaneously communicate over multiple channels; thus, multiuser interference (MUI) in the same channel must be taken into account.

2.1. Resource Allocation for CSUs with MUs in the Licensed Band. In the licensed band, we consider the uplink transmission under OFDMA technology where CSUs could control the emitted antenna pattern and the power allocation of each subchannel through the precoding matrices. We aim at maximizing the sum rate of overall DACSs with proper precoding matrix, as well as the best assignment between CSU j $(j=1,2,\ldots,J)$ and the associated CSBS i $(i=1,2,\ldots,M)$. The binary incidence matrix is $\mathbf{A}$, whose coefficients a^{ij} shows the status between CSBS i and CSU j. If $a^{ij}=1$, it denotes that CSU j and CSBS i are associated; otherwise $a^{ij}=0$. The binary incidence matrix a^{ij} should satisfy the following conditions:

(1) For CSU j, $\sum_{i=1}^{M}a^{ij}=1$ means that CSU j can only connect to one CSBS;

(2) For CSBS i, $\sum_{j=1}^{J}a^{ij}\le D$, where D is the maximum acceptable number of CSUs for CSBS i.

The value D is derived from zero-forcing (ZF) decoding to eliminate the interference; thus, $D \le N_r/N_t$. Based on this assumption, CSUs connected to the same CSBS do not have interference, while there is intercell interference between DACSs and macrocell networks. The frame structure of CSU j consists of a sensing slot of duration t_s and a data transmission slot of duration $T_L - t_s$ over k $(k=1,2,\ldots,K)$ spatial subchannels. In the sensing slot, if MU is detected absent, CSUs start transmitting in the transmission slot. We assume that simultaneous spectrum sensing of each licensed subchannel is performed by the set of antennas A_L at each CSBS under energy detection scheme, where the MU signal is modeled as a complex Gaussian random signal in the presence of an additive white Gaussian noise. The detection problem on subchannel k can be formulated as a hypothesis test, where hypothesis $H_{0,k}$ represents the absence of a MU in subchannel k, and hypothesis $H_{1,k}$ represents the presence of

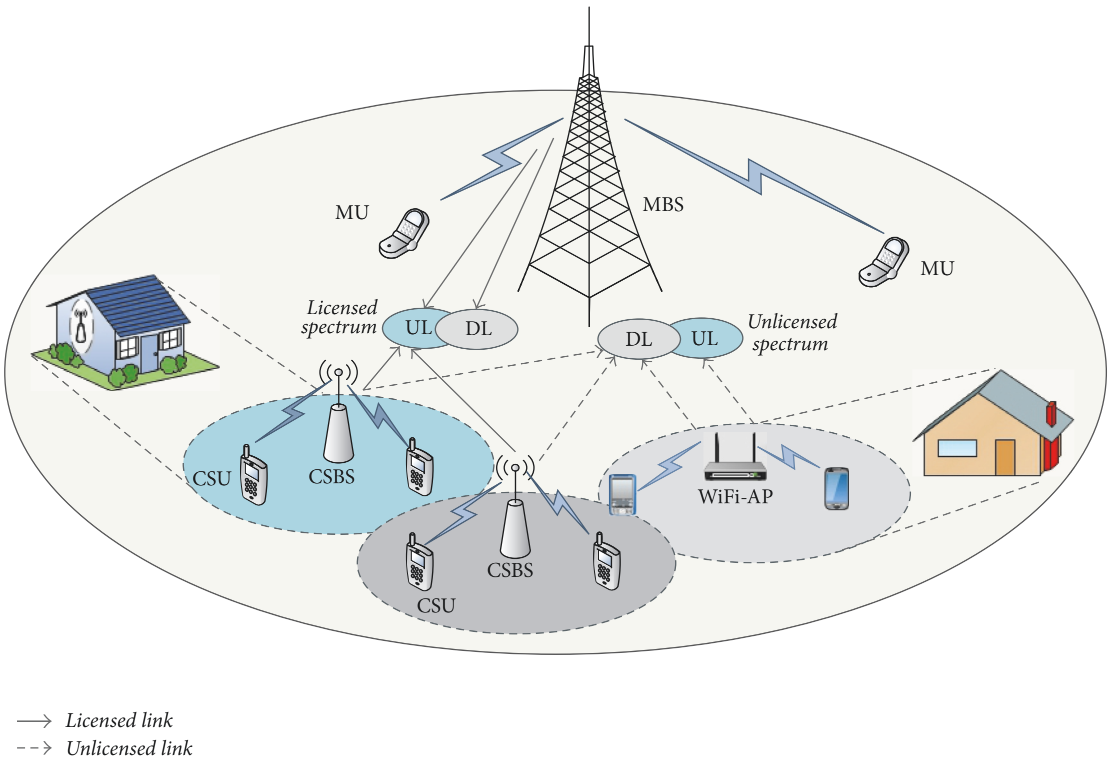

Figure 1: Network model. Illustration of DACSs shares licensed bands with the macrocell network and unlicensed bands with the WiFi network.

a MU in subchannel k. Specifically, for channel k, the received signal $\mathbf{y}_k^i$ at CSBS i can be formulated as

$$\begin{aligned} H_{0,k} &: \mathbf{y}_k^i(t) = \mathbf{n}_k(t) \\ H_{1,k} &: \mathbf{y}_k^i(t) = \mathbf{S}_k^i(t) + \mathbf{n}_k(t), \end{aligned} \tag{1}$$

where $\mathbf{y}_k^i(t) \in \mathbb{C}^{N_r \times 1}$ denotes the received signal, $\mathbf{n}_k(t) \in \mathbb{C}^{N_r \times 1}$ denotes the i.i.d noise on subchannel k with zero mean and variance $(\delta_{k,n}^i)^2$, that is, $\mathcal{N}(0, (\delta_{k,n}^i)^2 \mathbf{I})$, and $\mathbf{S}_k^i(t) = \mathbf{G}_k^i \mathbf{s}_k(t)$ stands for MU signals on subchannel k, where $\mathbf{s}_k(t) \in \mathbb{C}^{N_t \times 1} \sim \mathcal{N}(0, \gamma_k \mathbf{I})$ is a column vector of N_t information symbols, γ_k is the variance of symbol $\mathbf{s}_k$, and $\mathbf{G}_k^i \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix on subchannel k between MU and CSBS i. $L_s = t_s f_s$ denotes the number of detection samples. Under an energy detection scheme the decision is based on [27]:

$$\sum_{l=1}^{L_s} \mathrm{Tr}\left(\mathbf{Y}_k^i\right) \gtrless_{H_{0,k}}^{H_{1,k}} \tau_k, \quad k = 1, 2, \ldots, K, \tag{2}$$

where τ_k denote the decision thresholds. According to the Central Limit Theorem, for large L_s, $\mathbf{Y}_k$ are approximately normally distributed: $\mathbf{Y}_k^i \sim \mathcal{N}(\mu_{k,0}^i, (\sigma_{k,0}^i)^2)$ for $H_{0,k}$, and $\mathbf{Y}_k^i \sim \mathcal{N}(\mu_{k,1}^i, (\sigma_{k,1}^i)^2)$ for $H_{1,k}$, where

$$\begin{aligned} \mu_{k,0}^i &= L_s N_r \left(\delta_{k,n}^i\right)^2 \\ \left(\delta_{k,0}^i\right)^2 &= L_s N_r^2 \left(\delta_{k,n}^i\right)^4 \\ \mu_{k,1}^i &= L_s \left(N_r \left(\delta_{k,n}^i\right)^2 + \gamma_k \mathrm{Tr}\left(\mathbf{G}_k^i \left(\mathbf{G}_k^i\right)^H\right)\right) \\ \left(\delta_{k,1}^i\right)^2 &= L_s \left(N_r \left(\delta_{k,n}^i\right)^2 + \gamma_k \mathrm{Tr}\left(\mathbf{G}_k^i \left(\mathbf{G}_k^i\right)^H\right)\right)^2. \end{aligned} \tag{3}$$

The probabilities of detection $\mathcal{P}_{k,d}^i$ and false alarm $\mathcal{P}_{k,\mathrm{fa}}^i$ for the kth channel for CSBS i are expressed in closed forms as

$$\begin{aligned} \mathcal{P}_{k,\mathrm{fa}}^i(\tau_k, t_s) &= \mathcal{Q}\left(\frac{\left(\tau_k - \mu_{k,0}^i\right)}{\delta_{k,0}^i}\right) \\ \mathcal{P}_{k,d}^i(\tau_k, t_s) &= \mathcal{Q}\left(\frac{\left(\tau_k - \mu_{k,1}^i\right)}{\delta_{k,1}^i}\right). \end{aligned} \tag{4}$$

2.2. Resource Allocation for CSUs with WiFi Users in the Unlicensed Band. In the unlicensed band, the coexistence of DACS and WiFi is based on LTE-Release 10–12 by using specific techniques such as Carrier Sense Adaptive Transmission (CSAT) with LTE air interface protocol, which performs Clear Channel Assessment (CCA) before transmitting data [5]. CCA may potentially degrade the channel utilization and lose the access opportunities in unlicensed spectrum channel to other systems. In LTE-Release 13, LBT mechanism is required which needs to change LTE air interface [22]. The performance of WiFi systems will be significantly affected due to the CSMA/CA mechanism, while the performance of DACS system was almost unchanged based on the LTE protocol. The main challenge for the coexistence of DACS and WiFi is to ensure the fairness between two systems.

Two guidelines are followed in the design of the access scheme in the unlicensed band: (1) the CSBS senses the unlicensed band in order to avoid interference from ongoing transmission by other users; (2) the access scheme aligns with LTE frame structure.

In order to access the unlicensed band while guaranteeing the fairness for WiFi users, in this paper, we develop a channel access scheme that aligns with LTE frame structure, namely, Enhanced-LBT (E-LBT) scheme. The proposed E-LBT is based on the 3GPP definition. Instead of fixing the data transmission and detection duration, the transmission duration for DACSs will be adaptively adjusted with respected to the available licensed bandwidth as well as the WiFi traffic load. The frame structure of CSBS i consists of the detection duration and the data transmission duration in the unlicensed band.

Assume that spectrum sensing in the unlicensed band is performed by the set of antennas A_u at each CSBS by energy detection scheme. If the unlicensed band is regarded as clear (no WiFi users or other CSBSs occupying the band), the CSBS i will start transmitting for time duration T^i according to the channel condition as well as the WiFi traffic load.

Due to the randomness of the locations of WiFi-AP/CSBS, as well as the time-varying channel conditions, the detection results depended on the current traffic load of WiFi users. For the simplicity and without loss of generality, we define the probability of a WiFi user continuing to transmit data in the next slot (after accessing the unlicensed band) as λ.

In the E-LBT scheme, there are the five following cases in the unlicensed band transmission.

Case 1. WiFi and CSBS i occupy the unlicensed band simultaneously with cochannel interference. For instance, the WiFi user is transmitting in the unlicensed band while CSBS i accesses the band under error detection results, namely, miss detection with probability $1 - \mathscr{P}_d^i$.

Case 2. CSBS i and CSBS $i+1$ are transmitting in the unlicensed band simultaneously with cochannel interference. For instance, CSBS i decides to access the unlicensed band which is occupied by other CSBSs due to miss detection results.

Case 3. WiFi is absent, and CSBS i occupies the unlicensed band without false alarm.

Case 4. WiFi occupies the unlicensed band, without interference from CSBSs. For instance, all the CSBSs detect the WiFi signal correctly.

Case 5. WiFi and all the CSBSs are absent; thus the channel is idle.

The details of E-LBT scheme are shown in Figure 2. According to above cases, the detection problem in the unlicensed band can be formulated as a hypothesis test. We denote the hypotheses as H_{XY}, where $X \in \{0, 1, 2\}$, $Y \in \{0, 1\}$ represent the activity of CSBSs and WiFi users, respectively. $X = 0$ represents all the CSBSs being absent; $X = 1$ represents only one CSBS transmitting; $X = 2$ represents more than one CSBS transmitting at the same time. Similarly, $Y = 0$ represents the WiFi user being absent, while $Y = 1$ represents the WiFi user transmitting. For instance, hypothesis H_{20} represents more than one CSBS occupying the channel without the WiFi user; thus there is interference between CSBSs in the unlicensed band. Specifically, the received signal at CSBS i under each hypothesis can be written as

$$\mathbf{y}^i(t) = \begin{cases} \mathbf{S}^i(t) + \mathbf{n}(t) & H_{10} \\ \mathbf{S}^i(t) + \mathbf{W}^i(t) + \mathbf{n}(t) & H_{11} \\ \mathbf{S}^{i+1}(t) + \mathbf{n}(t) & H_{20} \\ \mathbf{W}^i(t) + \mathbf{n}(t) & H_{01} \\ \mathbf{n}(t) & H_{00}, \end{cases} \quad (5)$$

where $\mathbf{y}^i(t) \in \mathbb{C}^{N_r \times 1}$ denotes the received signal, $\mathbf{n}(t) \in \mathbb{C}^{N_r \times 1}$ denotes the additive background noise with zero mean and variance $(\delta_n)^2$, that is, $\mathcal{N}(0, (\delta_n)^2\mathbf{I})$, $\{\mathbf{S}^i(t) = \mathbf{H}_u^i \mathbf{s}(t), \mathbf{W}^i(t) = \mathbf{G}_w^i \mathbf{w}(t)\} \in \mathbb{C}^{N_r \times 1}$ stand for the receive signals at CSBS i from other CSBSs, and WiFi in the unlicensed band, respectively. Specially, for H_{20}, $\mathbf{S}^{i+1}(t)$ represents the received signals from multi-CSBSs. $\mathbf{s}(t) \in \mathbb{C}^{N_r \times 1} \sim \mathcal{N}(0, \gamma_u \mathbf{I})$ is a column vector of N_r information symbols, γ_u is the variance of $\mathbf{s}(t)$, and $\mathbf{H}_u^i \in \mathbb{C}^{N_r \times N_r}$ is the channel matrix in the unlicensed band from other CSBSs to CSBS i. $\mathbf{w}(t) \in \mathbb{C}^{N_t \times 1}$ is a column vector of N_t information symbols, and $\mathbf{G}_w^i \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix in the unlicensed band from WiFi user to CSBS i. By the similar process to (4), the probabilities of detection $\mathscr{P}_d^i$ and false alarm $\mathscr{P}_{\mathrm{fa}}^i$, with the threshold τ_u in the unlicensed band are given, respectively, by

$$\begin{aligned} \mathscr{P}_{\mathrm{fa}}^i(\tau_u, t_u) &= \mathcal{Q}\left(\frac{(\tau_u - \mu_0^i)}{\delta_0^i}\right) \\ \mathscr{P}_d^i(\tau_u, t_u) &= \mathcal{Q}\left(\frac{(\tau_u - \mu_1^i)}{\delta_1^i}\right), \end{aligned} \quad (6)$$

where

$$\begin{aligned} \mu_0^i &= L_u N_r (\delta_n)^2 \\ (\delta_0^i)^2 &= L_u N_r^2 (\delta_n)^4 \\ \mu_1^i &= L_u \Big(N_r (\delta_n)^2 \\ &\quad + \gamma_u \Big(\mathrm{Tr}\big(\mathbf{G}_w^i (\mathbf{G}_w^i)^H\big) + \mathrm{Tr}\big(\mathbf{H}_u^i (\mathbf{H}_u^i)^H\big)\Big)\Big) \\ (\delta_1^i)^2 &= L_u \Big(N_r (\delta_n)^2 \\ &\quad + \gamma_u \Big(\mathrm{Tr}\big(\mathbf{G}_w^i (\mathbf{G}_w^i)^H\big) + \mathrm{Tr}\big(\mathbf{H}_u^i (\mathbf{H}_u^i)^H\big)\Big)\Big)^2. \end{aligned} \quad (7)$$

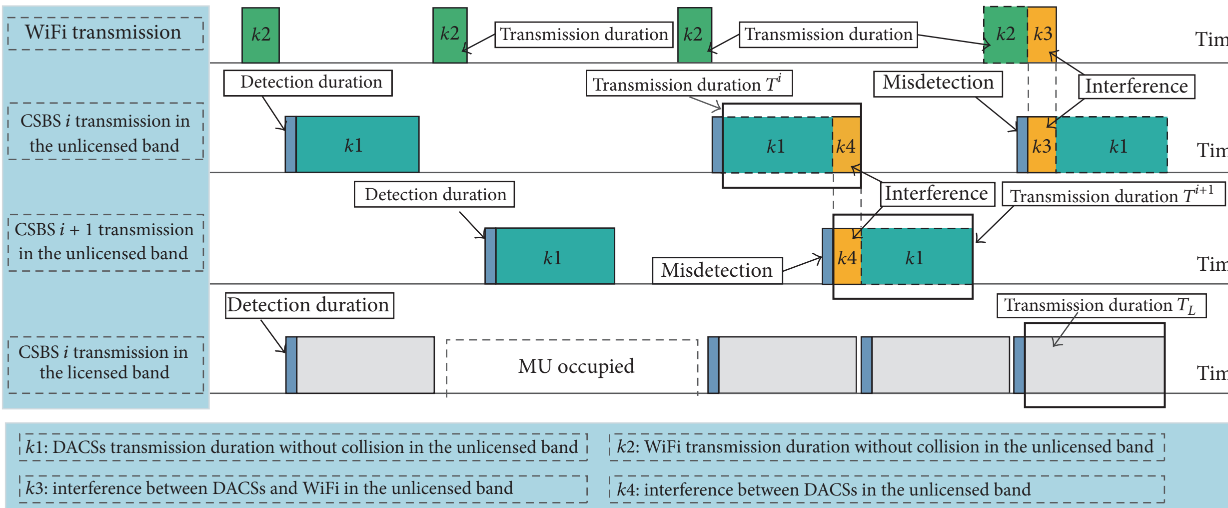

FIGURE 2: Data transmission in the unlicensed band.

Based on the above discussion, there is cochannel interference in Cases 1 and 2, whereas Cases 3 and 4 referred to the scene without cochannel interference; if the unlicensed band is idle, we obtain Case 5. Before discussion, we give the definition of the following parameters. In Figure 2, k_1 represents the average transmission time of DACSs without interference; k_2 represents the average transmission time of WiFi without interference; k_3 represents the average interference time between DACSs and WiFi; k_4 represents the average interference time between DACSs under miss detection; k_t represents the average backoff time and detection time.

(i) Cases with Interference

Case 1 (t_1). Let $t_1 = k_3/k_{\text{tol}}$ denote the final interference ratio between DACSs and WiFi in the unlicensed band, where $k_{\text{tol}} = k_L + k_w + k_t$ is the total available transmission time, including the average transmission time of DACSs, $k_L = (1-\mathscr{P}^i_{\text{fa}})T^i$, and the average transmission time of WiFi based on the traffic load λ (k represents the time slot index), $k_w = \sum_{k=1}^{\infty} k\cdot\lambda^{k-1} = 1/(1-\lambda)^2$. Furthermore, taking into account the idle time, we have $k_t = d\cdot(k_L+k_w)$, which depends on the detection and backoff time before occupying the unlicensed band, where d is idle time factor. $k_3 = (1-(\mathscr{P}^i_d)^M)(k_w-k_2)$ is the average interference time between DACSs and WiFi, where $k_2 = \sum_{k=1}^{\infty} k\cdot(\lambda\mathscr{P}^i_d)^{k-1} = 1/(1-\lambda\mathscr{P}^i_d)^2$ represents the WiFi average transmission time without interference.

Case 2 (t_2). The interference ratio between DACSs is denoted as $t_2 = k_4/k_{\text{tol}}$, where $k_4 = k_L\cdot(1-(\mathscr{P}^i_d)^{M-1})$ is the average interference time between DACSs, under miss detection.

(ii) Cases without Interference

Case 3 (t_3). The transmission ratio of DACSs in the unlicensed band without interference is denoted as $t_3 = k_1/k_{\text{tol}}$, where $k_1 = k_L\cdot(\mathscr{P}^i_d)^{M-1}$ is the average transmission time without interference.

Case 4 (t_4). The WiFi transmission ratio is given by $t_4 = k_2/k_{\text{tol}}$.

(iii) Spectrum Idle

Case 5 (t_5). Due to the backoff time and detection time before accessing the channel, the idle ratio is $t_5 = k_t/k_{\text{tol}}$.

According to the above analysis, we obtain that the transmission ratio of DACSs and WiFi in the unlicensed band can be represented as η and Φ, respectively:

$$\begin{aligned}\eta &= t_1 + t_2 + t_3\\ \Phi &= t_1 + t_4.\end{aligned} \tag{8}$$

3. Problem Formulation

Table 1 describes the users' transmission data rate in the licensed and unlicensed band. The transmission data rate of DACSs consists of the uplink transmission rate R_L in the licensed band and the downlink transmission rate R_u in the unlicensed band, and the transmission data rate of WiFi user n ($n = 1, 2, \ldots, N$) is expressed as $R_{w,n}$.

3.1. In the Licensed Band. In this work, the data rate of the DACS consists of two parts: uplink transmission in the licensed band and downlink transmission in the unlicensed band. In the licensed subchannel k, the received signal $\mathbf{z}^i_k \in \mathbb{C}^{N_r\times 1}$ at the CSBS i from CSU j is given by

$$\mathbf{z}^i_k = \sum_{j=1}^{J} a^{ij}\mathbf{H}^{ij}_k\mathbf{q}^j_k + \sum_{j=1}^{J}\left(1-a^{ij}\right)\mathbf{H}^{ij}_k\mathbf{q}^j_k + \mathbf{n}_k, \tag{9}$$

Table 1: The relationship between five cases and transmission data rate.

User type	Cases	1	2	3	4	5	Average transmission rate
	Hypothesis	H_{11}	H_{20}	H_{10}	H_{01}	H_{00}	
	Transmission ratio	t_1	t_2	t_3	t_4	t_5	
DACS	Licensed band			R_L			R_L
	Unlicensed band	R_U^{01}	R_U^{10}	R_U^{00}			$R_U = t_1 R_U^{01} + t_2 R_U^{10} + t_3 R_U^{00}$
WiFi		$R_{w,n}^{01}$			$R_{w,n}^{11}$		$R_{w,n} = t_4 R_{w,n}^{11} + t_1 R_{w,n}^{01}$

where $\mathbf{q}_k^j$ denotes the transmission data from CSU j; $\mathbf{H}_k^{ij} \in \mathbb{C}^{N_r \times N_t}$ is the cross-channel matrix on channel k from CSU j to CSBS i. The first term on the right-hand side is the desired signals sent from intracell CSU j; the second term represents the intercell interference from other CSUs that share the subchannel k. The achievable sum rate of DACS i for a given set of user's covariance matrices $\mathbf{Q}_{L,k}^1, \mathbf{Q}_{L,k}^2, \dots, \mathbf{Q}_{L,k}^J$, is denoted as $R_L^i(\mathbf{Q}_L^j, \mathbf{a}^j, \boldsymbol{\tau}, t_s)$, $\mathbf{Q}_L^j = (\mathbf{Q}_{L,k}^j)_{k=1}^K$, $\mathbf{a}^j = (a^{ij})_{i=1}^M$, and $\boldsymbol{\tau} = (\tau_k)_{k=1}^K$ and formulated as

$$R_L^i\left(\mathbf{Q}_L^j, \mathbf{a}^j, \boldsymbol{\tau}, t_s\right) = T_s \sum_{k=1}^{K} \left(1 - \mathscr{P}_{k,\mathrm{fa}}^i\left(\tau_k, t_s\right)\right) B_{L,k} \cdot \log\det\left(\mathbf{I} + \left(\mathbf{C}_k^j\right)^{-1} \sum_{j=1}^{J} a^{ij} \mathbf{Q}_{L,k}^{j,H}\right), \quad (10)$$

where $B_{L,k} = B_L/K$ is the bandwidth, $\mathbf{Q}_{L,k}^{j,H} = \mathbf{H}_k^{ij} \mathbf{Q}_{L,k}^j (\mathbf{H}_k^{ij})^H$, $T_s = 1 - t_s/T_L$, and $\mathbf{Q}_{L,k}^j$ denote the covariance matrix of the symbols transmitted by CSU j in subchannel k. $\mathbf{C}_k^j$ is the noise-plus-interference covariance:

$$\mathbf{C}_k^j = \mathbf{I} + \sum_{j=1}^{J} \left(1 - a^{ij}\right) \mathbf{H}_k^{ij} \mathbf{Q}_{L,k}^j \left(\mathbf{H}_k^{ij}\right)^H. \quad (11)$$

For CSU j, the total transmission power over all licensed subchannels should not exceed its budget power $P_{\max}^j$. Consequently, the power budget constraint is denoted as

$$\sum_{k=1}^{K} \mathrm{Tr}\left(\mathbf{Q}_{L,k}^j\right) \le P_{\max}^j. \quad (12)$$

Considering that the sensing information is not always reliable, to guarantee the QoS of MUs, the cochannel interference from CSUs should not exceed an interference mask. Thus the individual soft-shaping constraint to effectively protect the MU is denoted as

$$\left(1 - \mathscr{P}_{k,d}^i\left(\tau_k, t_s\right)\right) \mathrm{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^j \left(\mathbf{G}_k^j\right)^H\right) \le P_{\mathrm{mask},k}, \quad (13)$$

where $\mathbf{G}_k^j \in \mathbb{C}^{N_t \times N_t}$ is the channel matrix from CSU j to the MU in subchannel k and $\mathbf{P}_{\mathrm{mask}} = [P_{\mathrm{mask},k}]_{k=1}^K$ denotes the interference mask on all subchannels. In addition, from the target sensing accuracy, the following linear constraint should be satisfied:

$$\tau_{k,\min} \le \tau_k \le \tau_{k,\max}, \quad (14)$$

where $\tau_{k,\min} = (\mu_{k,0}^i)_{\max}$ and $\tau_{k,\max} = (\mu_{k,1}^i)_{\min}$, denoted as $\boldsymbol{\tau} \in \mathscr{T}$. For the convenience of reading, we enable the a^{ij} to the following convex set:

$$\mathscr{A} = \left\{\sum_{i=1}^{M} a^{ij} = 1, \sum_{j=1}^{J} a^{ij} \le D, a^{ij} \in \{0, 1\}\right\}. \quad (15)$$

Therefore, the sum data rate of DACSs over all licensed subchannels can be written as

$$R_L = \sum_{i \in M} R_L^i. \quad (16)$$

3.2. In the Unlicensed Band. DACSs and WiFi coexist in the unlicensed band, sharing the unlicensed band under the E-LBT mechanism. Based on the E-LBT, the CSBS detects the channel condition before transmitting data and determines the transmission time according to the channel condition (e.g., WiFi traffic load). Thus, DACSs transmission data rate is associated with WiFi real-time traffic load. According to Table 1, the data rate of DACSs and WiFi networks is composed of several parts:

(i) For Case 1 $(R_u^{01}, R_{w,n}^{01})$, the data rate of DACS i with interference from WiFi is given by

$$R_u^{01} = \sum_{j=1}^{J} B_u \log\det\left(\mathbf{I} + \left(\mathbf{C}_u^{j,1}\right)^{-1} \mathbf{H}_u^{ij} \mathbf{Q}_u^i \left(\mathbf{H}_u^{ij}\right)^H\right), \quad (17)$$

where B_u is the unlicensed bandwidth, $\mathbf{H}_u^{ij}$ is the channel matrix in the unlicensed band from CSBS i to CSU j, and $\mathbf{Q}_u^i$ represents the covariance matrix of CSBS i in the unlicensed band. $\mathbf{C}_u^{j,1} = \delta_n^2 \mathbf{I} + \mathbf{G}_u^j \mathbf{Q}_w (\mathbf{G}_u^j)^H$ denotes the noise-plus-interference covariance matrix of WiFi networks, $\mathbf{G}_u^j$ is the channel matrix in the unlicensed band of CSU j, and $\mathbf{Q}_w$ is the covariance matrix of WiFi networks. Moreover, the data rate of WiFi user n with interference from DACSs is given by

$$R_{w,n}^{01} = B_u \log\det\left(\mathbf{I} + \left(\mathbf{C}_u^0\right)^{-1} \mathbf{H}_w \mathbf{Q}_w \left(\mathbf{H}_w\right)^H\right) \quad (18)$$

where $\mathbf{C}_u^0 = \delta_n^2 \mathbf{I} + \mathbf{G}_u^i \mathbf{Q}_u^i (\mathbf{G}_u^i)^H$ denotes the noise-plus-interference covariance matrix from DACSs in the unlicensed band; $\mathbf{G}_u^i$ represents the channel matrix in the unlicensed band from DACS i to WiFi users.

(ii) For Case 2 (R_u^{10}), the data rate of DACS i with interference from other DACSs is given by

$$R_u^{10} = \sum_{j=1}^{J} B_u \log\det\left(\mathbf{I} + \left(\mathbf{C}_u^{j,2}\right)^{-1} \mathbf{H}_u^{ij}\mathbf{Q}_u^{i}\left(\mathbf{H}_u^{ij}\right)^{H}\right), \quad (19)$$

where $\mathbf{C}_u^{j,2} = \delta_n^2\mathbf{I} + \sum_{i=1}^{M}(1 - a^{ij})\mathbf{H}_u^{ij}\mathbf{Q}_u^{i}(\mathbf{H}_u^{ij})^H$ denotes the noise-plus-interference covariance matrix from nonassociated DACSs in the unlicensed band.

(iii) For Case 3 (R_u^{00}), the data rate of DACS i without interference from other users is given by

$$R_u^{00} = \sum_{j=1}^{J} B_u \log\det\left(\mathbf{I} + \left(\mathbf{C}_u^{j,0}\right)^{-1} \mathbf{H}_u^{ij}\mathbf{Q}_u^{i}\left(\mathbf{H}_u^{ij}\right)^{H}\right), \quad (20)$$

where $\mathbf{C}_u^{j,0} = \delta_n^2\mathbf{I}$ is the additive background noise covariance matrix in the unlicensed band.

(iv) For Case 4 ($R_{w,n}^{11}$), the data rate of WiFi user n is denoted as

$$R_{w,n}^{11} = B_u \log\det\left(\mathbf{I} + \frac{\mathbf{H}_w\mathbf{Q}_w\left(\mathbf{H}_w\right)^{H}}{\delta_n^2}\right), \quad (21)$$

where $\mathbf{H}_w$ is the WiFi channel matrix in the unlicensed band.

Consequently, we obtain the achievable total data rate of DACSs in the unlicensed band as

$$R_u = t_1 R_u^{01} + t_2 R_u^{10} + t_3 R_u^{00} \quad (22)$$

and the achievable data rate of WiFi user n as

$$R_{w,n} = t_1 R_{w,n}^{01} + t_4 R_{w,n}^{11}. \quad (23)$$

In the unlicensed band, all the CSUs and WiFi users share the same spectrum band. Therefore, there is not only the interference between CSUs, but also the interference between CSUs and WiFi users. According to Figure 2, CSUs decide to access the unlicensed band based on the results from E-LBT scheme. However, due to the variable channel state, the detection accuracy of a DACS is fluctuant; thus the detection results are not always reliable: (1) WiFi user is transmitting in the channel, but DACSs detect that the channel is idle (with misdetection). Consequently, there is interference between CSUs and WiFi users due to misdetection. Specially, when users are closer to each other, the interference is serious. (2) WiFi users are not transmitting in the channel, but DACSs detect that the channel is busy (with false alarm), resulting in a waste of available spectrum resource.

In the licensed band, in order to share the spectrum with MUs, power control for CSUs is needed to ensure the interference from CSUs to MUs below a given interference mask. Due to different government regulation requirements, we assign separated power budgets to the licensed and unlicensed band.

We adopt a utility function $U(R)$ to evaluate user's satisfaction about an achieved data rate R. The widely used logarithmic utility function is considered to guarantee the proportional fair coexistence between CSUs and WiFi,

$$U(R) = \ln(R), \quad (24)$$

where $\ln(\cdot)$ is natural logarithm function. It could capture the typical user satisfaction about data rate—as data rate increases, user utility grows faster when data rate is low than when it is high.

Since CSUs have the ability to access both the licensed and unlicensed bands simultaneously, the CSUs will generate interference to the cochannel users (MUs, WiFi users) during the transmission process. Therefore, in this paper, we focus on the harmonious coexistence mechanism between CSUs and WiFi users, while ensuring the communication performances of MUs and WiFi users in the licensed and unlicensed band, respectively. According to the above analysis, the optimization problem of maximizing the total utility of DACSs and WiFi networks by jointly optimizing the cell selection, detection operation, power allocation, and transmission time in the licensed and unlicensed band can be formulated as $P1$:

$$\begin{aligned}
\max_{\mathbf{Q}_L^j,\mathbf{a}^j,\boldsymbol{\tau},t_s,T^i} \quad & U\left(\mathbf{Q}_L^j, \mathbf{a}^j, \boldsymbol{\tau}, t_s, T^i\right) \\
& = \ln\left(R_L\left(\mathbf{Q}_L^j, \mathbf{a}^j, \boldsymbol{\tau}, t_s\right) + R_u\left(T^i\right)\right) \\
& \quad + \sum_{n=1}^{N} \ln\left(R_{w,n}\left(T^i\right)\right) \\
\text{s.t.} \quad & (c1)\left(1 - \mathscr{P}_{k,d}^{i}\left(\tau_k, t_s\right)\right)\operatorname{Tr}\left(\mathbf{G}_k^j\mathbf{Q}_{L,k}^j\left(\mathbf{G}_k^j\right)^H\right) \\
& \leq P_{\mathrm{mask},k} \\
& (c2)\sum_{k=1}^{K}\operatorname{Tr}\left(\mathbf{Q}_{L,k}^j\right) \leq P_{\max}^j \\
& (c3)\,\mathbf{a} \in \mathscr{A} \\
& (c4)\,\boldsymbol{\tau} \in \mathscr{T} \\
& (c5)\,0 \leq t_s \leq T_L \\
& (c6)\,0 \leq T^i \leq \frac{\left(k_{\mathrm{tol}} - k_w\right)}{\left(1 - \mathscr{P}_{\mathrm{fa}}^{i}\right)}, \quad \forall i, j, k,
\end{aligned} \quad (25)$$

where $(c1)$ is the nonconvex individual soft-shaping constraint to effectively protect MUs from harmful interference by CSUs transmission. $(c2)$–$(c6)$ are the convex constraint sets. $(c2)$ ensures that the total transmission power of CSU j should not exceed its power budget. In addition, due to the integer nature of the element a^{ij} of the incidence matrix, the problem $P1$ is an integer programming which is NP-hard. Furthermore, constraint $(c6)$ shows that the transmission time of CSUs in the unlicensed band must be no more than the total transmission time except the WiFi transmission time based on the correct detection, so that the harmonious coexistence between CSUs and WiFi users can be achieved. In order to find the optimal solution of problem $P1$, we propose a dual-band (licensed and unlicensed bands) traffic balancing scheme to simplify the original problem and find equivalent solutions.

4. Satisfaction-Based Dual-Band Traffic Balancing Scheme

The optimization problem can be divided into two sub-optimization problems and solved separately. Firstly, we maximize the data rate R_L of CSU in the licensed band by optimizing the cell selection, detection operation, and power allocation, which results in the maximum utility of the licensed band. Secondly, we maximize the utility $U(\cdot)$ of whole networks by optimizing the transmission time in the unlicensed band. Specifically, the alternative direction optimization method is used to obtain the optimal solution of $P1$:

(i) Suboptimization 1: sensing-based power allocation (SBPA): for CSU j, the status a^{ij} can be considered as a constant with the initial assignment and the optimal sensing time t_s can be found by exhaustive search. Thus, we start from the two multidimensional variables $\mathbf{Q}_L^j$ and τ_k to maximize the data rata $R_L^\star$ of DACSs. Due to the inherently competitive nature of distributed multiuser DACSs, we adopt the game theory to solve the nonconvex noncooperative problem for DACSs.

(ii) Suboptimization 2: dual-band traffic balancing (DBTB): based on the solution from SBPA, we obtained the optimal $R_L^\star$ in the licensed band. In the following step, the $R_L^\star$ as well as the associated parameters $\mathbf{Q}_L^{j\star}, \mathbf{a}^{j\star}, \boldsymbol{\tau}^\star, t_s^\star$ are considered as constant and the original optimization problem can be formulated as maximizing the utility $U(\cdot)$ in (25). The suboptimization problem DBTB aims at optimizing the transmission time T^i based on WiFi real-time traffic load, that is, λ, to maximize the total utility of whole networks, while guaranteeing the coexistence between CSUs and WiFi users.

4.1. Suboptimization Problem 1: SBPA. According to the inherently competitive nature of distributed multiuser DACSs, game theory is adopted to solve the nonconvex noncooperative problem for DACSs. The resource allocation problem among CSUs is reformulated as a strategic noncooperative game. In order to simplify the game, we consider the problem equal to maximizing the individual rate of CSU j. For CSU j, the variable $\mathbf{a}^j$ can be considered as a constant and the optimal sensing time t_s can be finally optimized by exhaustive search. Collaborative spectrum sensing can improve the performance of spectrum sensing in cognitive radio networks [28]. Furthermore, we assume that the sensing results from CSBS i are shared with CSU j in this cell, with the initial assignment based $\mathbf{a}^j$, we have $\mathcal{P}_{k,\mathrm{fa}}^j = \mathcal{P}_{k,\mathrm{fa}}^i$ and $\mathcal{P}_{k,d}^j = \mathcal{P}_{k,d}^i$. We start from the two multidimensional variables case, that is, $\mathbf{Q}_L^j$ and $\boldsymbol{\tau}$. Assume that there are J players, corresponding to the J CSUs, each one controlling the variables $\mathbf{x}^j = (\mathbf{Q}^j, \boldsymbol{\tau})$, $j = 1, \ldots, J$. Let $\mathbf{x}^{-j} = (\mathbf{x}^1, \ldots, \mathbf{x}^{j-1}, \mathbf{x}^{j+1}, \ldots, \mathbf{x}^J)$ be the set of strategies from all the CSUs, except CSU j. The optimization function $R_L^j(\mathbf{Q}_L^j, \boldsymbol{\tau})$ for CSU j is the data rate over channels, given by

$$R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) = T_s \sum_{k=1}^{K} \left(1 - \mathcal{P}_{k,\mathrm{fa}}^j B_{L,k}\left(\tau_k\right)\right) \cdot \log\det\left(\mathbf{I} + \left(\mathbf{C}_k^j\right)^{-1} \mathbf{Q}_{L,k}^{j,H}\right), \tag{26}$$

where T_s is considered as a constant to be optimized at a later step. Each CSU competes against the others by choosing the transmit covariance matrix $\mathbf{Q}^j$ and the associated threshold $\boldsymbol{\tau}$ to maximize its own rate with the given certain constraints. The noncooperative power allocation game of CSU j can be formulated as problem $P2$:

$$\begin{aligned} \max_{\mathbf{Q}_L^j, \boldsymbol{\tau}} \quad & R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) \\ \text{s.t.} \quad & \left(1 - \mathcal{P}_{k,d}^j\left(\tau_k\right)\right) \operatorname{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^j \left(\mathbf{G}_k^j\right)^H\right) \le P_{\mathrm{mask},k}, \\ & \sum_{k=1}^{K} \operatorname{Tr}\left(\mathbf{Q}_{L,k}^j\right) \le P_{\max}^j, \\ & \boldsymbol{\tau} \in \mathcal{T}, \ \forall i, j, k. \end{aligned} \tag{27}$$

The resulting game $P2$ is nonconvex, we analyze the proposed nonconvex game based on a relaxed equilibrium concept introduced in [13], namely, the QNE, and prove that the proposed nonconvex game in DACSs always admits a unique QNE, which coincides with the NE. We denote the non-convex individual constraints $(c1)$ as $\mathbf{H}_{\mathbb{C}}(\mathbf{x}) = [h_{\mathbb{C}}^j(\mathbf{x}^j)]_{j=1}^J$. The convex individual constraints $(c2)$–$(c5)$ are denoted as $\widetilde{\mathbf{G}}_{\mathbb{C}}(\mathbf{x}) = [(\widetilde{g}_k^j(\mathbf{x}^j))_{k=1}^K]_{j=1}^J$, and embedded in the definition set of $\mathbf{x}^j = [\mathbf{Q}_L^j, \boldsymbol{\tau}]$, denoted as $\mathbf{X}_{\mathbb{C}}^j$. Thus, we can formulate the nonconvex game $\mathcal{G}_{\mathbb{C}}(\mathbf{H}_{\mathbb{C}}, \widetilde{\mathbf{G}}_{\mathbb{C}})$ as problem $P3$:

$$\begin{aligned} \max_{\mathbf{x}^j} \quad & R_L^j\left(\mathbf{x}^j\right) \\ \text{s.t.} \quad & h_{\mathbb{C}}^j\left(\mathbf{x}^j\right) \le 0, \quad \mathbf{x}^j \in \mathbf{X}_{\mathbb{C}}^j. \end{aligned} \tag{28}$$

Let $\mathcal{Y}_{\mathbb{C}}^j$ denote the feasible strategy set of CSU j, written as

$$\mathcal{Y}_{\mathbb{C}}^j = \left\{\mathbf{x}^j \in \mathbf{X}_{\mathbb{C}}^j \mid h_{\mathbb{C}}^j\left(\mathbf{x}^j\right) \le 0\right\}, \quad 1 \le k \le K. \tag{29}$$

Denoting by α_k^j the multipliers associated with the nonconvex constraints $h_{\mathbb{C}}^j(\mathbf{x}^j) \le 0$ of CSU j, the Lagrange function of the problem $P3$ can be written as

$$L^j\left(\mathbf{x}^j, \boldsymbol{\alpha}^j\right) = -R_L^j\left(\mathbf{x}^j\right) + \boldsymbol{\alpha}^j h_{\mathbb{C}}^j\left(\mathbf{x}^j\right). \tag{30}$$

The KKT conditions of CSU j are given by

$$\begin{aligned}
&\nabla_{\mathbf{Q}_L^j} R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) - \alpha_k^j\left(1 - \mathscr{P}_{k,d}^j\left(\tau_k\right)\right) \operatorname{Tr}\left(\mathbf{G}_k^j\left(\mathbf{G}_k^j\right)^H\right) \\
&\quad = 0 \\
&\nabla_{\boldsymbol{\tau}} R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) + \alpha_k^j \nabla_{\tau_k} \mathscr{P}_{k,d}^j\left(\tau_k\right) \operatorname{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^i\left(\mathbf{G}_k^j\right)^H\right) \\
&\quad = 0 \\
&\alpha_k^j\left[\left(1 - \mathscr{P}_{k,d}^j\left(\tau_k\right)\right) \operatorname{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^j\left(\mathbf{G}_k^j\right)^H\right) - P_{\text{mask},k}\right] \\
&\quad = 0,
\end{aligned} \tag{31}$$

where $\nabla_{\mathbf{Q}_L^j} R_L^j(\mathbf{Q}_L^j, \boldsymbol{\tau}), \nabla_{\boldsymbol{\tau}} R_L^j(\mathbf{Q}_L^j, \boldsymbol{\tau})$ denote the complex matrix derivative of $R_L^j(\mathbf{x}^j)$ with respect to $\mathbf{Q}_L^j$ and $\boldsymbol{\tau}$, respectively. More specifically, if $\mathbf{x}^\star$ are the stationary solutions of game $\mathscr{G}_{\mathbb{C}}(\mathbf{H}_{\mathbb{C}}, \widetilde{\mathbf{G}}_{\mathbb{C}})$, the KKT conditions (31) can be reformulated to the equivalent form:

$$\begin{aligned}
&\left(\mathbf{x}^\star, \boldsymbol{\alpha}^\star\right)^{T_L} \\
&\cdot \underbrace{\begin{pmatrix}
\nabla_{\mathbf{Q}_L^j} R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) - \alpha_k^j\left(1 - \mathscr{P}_{k,d}^j\left(\tau_k\right)\right) \operatorname{Tr}\left(\mathbf{G}_k^j\left(\mathbf{G}_k^j\right)^H\right) \\
\nabla_{\boldsymbol{\tau}} R_L^j\left(\mathbf{Q}_L^j, \boldsymbol{\tau}\right) + \alpha_k^j \nabla_{\tau_k} \mathscr{P}_{k,d}^j\left(\tau_k\right) \operatorname{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^j\left(\mathbf{G}_k^j\right)^H\right) \\
-P_{\text{mask},k} + \left(1 - \mathscr{P}_{k,d}^j\left(\tau_k\right)\right) \operatorname{Tr}\left(\mathbf{G}_k^j \mathbf{Q}_{L,k}^j\left(\mathbf{G}_k^j\right)^H\right)
\end{pmatrix}_{j=1}^{J}}_{\boldsymbol{\Gamma}_{\mathbb{C}}\left(\mathbf{x}^\star, \boldsymbol{\alpha}^\star\right)} \\
&\leq 0, \quad \left(\mathbf{x}^j, \boldsymbol{\alpha}^j\right) \in \mathbf{Y}_{\mathbb{C}}.
\end{aligned} \tag{32}$$

Inequalities (32) define a VI problem with variables $(\mathbf{x}, \boldsymbol{\alpha})$, denoted as $\mathrm{VI}_{\mathbb{C}}(\mathbf{Y}_{\mathbb{C}}, \boldsymbol{\Gamma}_{\mathbb{C}})$, where the vector function $\boldsymbol{\Gamma}_{\mathbb{C}}$ is defined in (32), and feasible set $\mathbf{Y}_{\mathbb{C}} = \prod_{j=1}^{J} \mathbf{X}_{\mathbb{C}}^j \times \mathbb{R}_+^r$. The $\mathrm{VI}_{\mathbb{C}}(\mathbf{Y}_{\mathbb{C}}, \boldsymbol{\Gamma}_{\mathbb{C}})$ is an equivalent reformulation of the KKT conditions (31). The convex constraints $(c2)$–$(c5)$ are embedded in the complex defining set $\mathbf{Y}_{\mathbb{C}}$, $\mathbf{Y}_{\mathbb{C}} = \prod_{j=1}^{J} \mathbf{X}_{\mathbb{C}}^j \times \mathbb{R}_+^r$, where $\mathbf{X}_{\mathbb{C}}^j$ stands for the complex convex constraints $(c2)$–$(c5)$ defined in the problem $P1$, and r is the total number of multipliers $\boldsymbol{\alpha}$.

Definition 1. A quasi-Nash equilibrium of the game $\mathscr{G}_{\mathbb{C}}(\mathbf{H}_{\mathbb{C}}, \widetilde{\mathbf{G}}_{\mathbb{C}})$ is defined and formed by the solution tuple $(\mathbf{x}^\star, \boldsymbol{\alpha}^\star)$ of the equivalent $\mathrm{VI}_{\mathbb{C}}(\mathbf{Y}_{\mathbb{C}}, \boldsymbol{\Gamma}_{\mathbb{C}})$, which is obtained under the first-order optimality conditions of each player's problems, while retaining the convex constraints in the defined set $\mathbf{X}_{\mathbb{C}}^j$ [13].

Theorem 2. *The $VI_{\mathbb{C}}(\mathbf{Y}_{\mathbb{C}}, \boldsymbol{\Gamma}_{\mathbb{C}})$ has a solution; thus the game $\mathscr{G}_{\mathbb{C}}(\mathbf{H}_{\mathbb{C}}, \widetilde{\mathbf{G}}_{\mathbb{C}})$ has a QNE, which is nontrivial.*

The similar proof can be found in [12]. The uniqueness of the QNE for the problem $P3$ needs an appropriate second-order sufficiency condition. We provide the following theorem.

Theorem 3. *If the Hessian matrix of (30), denoted as $\nabla_{\mathbf{x}^i}^2 L^i(\mathbf{x}^i, \boldsymbol{\alpha}^i)$, is positive definite for all $\mathbf{x}^j \in \mathbf{X}_{\mathbb{C}}^j$ and $\boldsymbol{\alpha}^j \in \mathbb{R}_+^r$, then the nonconvex optimization problem $P3$ for each CSU j has a unique optimal solution $\mathbf{x}^{j,\star} \in \mathbf{X}_{\mathbb{C}}^j$. In addition, the $\nabla_{\mathbf{x}^j}^2 L^j(\mathbf{x}^j, \boldsymbol{\alpha}^j)$ is positive definite, if the following sufficient condition is satisfied:*

$$\begin{aligned}
&\frac{\max_{k=1,\ldots,K}\left(\boldsymbol{\alpha}^j / \sqrt{2\pi}\right) \operatorname{Tr}\left(\mathbf{G}_k^j\left(\mathbf{G}_k^j\right)^H\right)}{\min\left(\operatorname{Re}\left(\xi_{\min}\left(-\nabla_{\mathbf{Q}_L^j}^2 R_L^i\left(\mathbf{x}^j\right)\right), \xi_{\min}\left(-\nabla_{\boldsymbol{\tau}}^2 R_L^j\left(\mathbf{x}^j\right)\right)\right)\right)} \\
&\quad < 1.
\end{aligned} \tag{33}$$

Proof. The proof is provided in [29]. □

$\xi_{\min}(-\nabla_{\mathbf{Q}_L^j}^2 R_L^j(\mathbf{x}^j))$ and $\xi_{\min}(-\nabla_{\boldsymbol{\tau}}^2 R_L^j(\mathbf{x}^j))$ denote the minimum eigenvalues of matrices $-\nabla_{\mathbf{Q}_L^j}^2 R_L^j(\mathbf{x}^j)$ and $-\nabla_{\boldsymbol{\tau}}^2 R_L^j(\mathbf{x}^j)$, respectively. This condition quantifies how much MUI can be tolerated by the systems to guarantee the existence and the uniqueness of the QNE, meaning that when the interference from the CSU to the MU is sufficiently small (satisfying the condition (33)), the nonconvex problem $P3$ has a unique solution QNE, which coincides with the NE.

4.2. Suboptimization Problem 2: DBTB. Based on the optimal results $\mathbf{Q}_L^{j\star}, \mathbf{a}^{j\star}, \boldsymbol{\tau}^\star, t_s^\star$ obtained from SBPA, we obtain the achievable maximum sum data rate $R_L^\star$ of DACSs in the licensed band. In DBTB, we focus on maximizing the utility of whole networks while ensuring the traffic balancing between CSUs and WiFi users in the licensed and unlicensed band. Consequently, the original problem can be formulated as

$$\begin{aligned}
\max_{T^i} \quad & U\left(T^i\right) \\
& = \ln\left(R_L^\star + R_u\left(T^i\right)\right) + \sum_{n=1}^{N} \ln\left(R_{w,n}\left(T^i\right)\right)
\end{aligned} \tag{34}$$

$$\text{s.t.} \quad 0 \leq T^i \leq \frac{k_{\text{tol}} - k_w}{1 - \mathscr{P}_{\text{fa}}^i}, \quad \forall i, j, k. \tag{35}$$

The objective function of the above DBTB is only related to the DACS transmission time T^i in the unlicensed band. By the characteristics of the natural logarithm equation, when T^i is large, there are higher data rate and satisfaction of DACS, with lower WiFi users data rate and satisfaction; on the contrary, when T^i is small, the CSUs' data rate and satisfaction are lower, but those of WiFi users are higher.

Since the overall utility is composed of two parts: DACSs utility and WiFi networks utility, to achieve the maximum utility of whole networks, we need to balance the tradeoff between them. Therefore, we maximize the whole network utility by maximizing the data rate of DACSs while guaranteeing the WiFi users transmission quality. Equation (34) is a linear equation with respect to T^i. To get the optimal T^i, take the derivative of (34) with respect to T^i and set it to zero; we obtain that

$$T^\star = \frac{\widetilde{e} \cdot \widetilde{g} + \widetilde{f} - N \cdot \widetilde{g} \cdot \widetilde{b}}{2N \cdot \widetilde{g} \cdot \widetilde{a}}, \tag{36}$$

where the $\widetilde{a}, \widetilde{b}, \widetilde{c}, \widetilde{e}, \widetilde{f}, \widetilde{g}$ are expressed as follows:

$$\begin{aligned}
\widetilde{a} &= (1+d)\left(1-\mathscr{P}_{\text{fa}}^{i}\right)^{2}(1-\lambda)^{4}T^{2}\left[(1+d)R_{L}^{\star} + R_{u}^{0.0}\left(\mathscr{P}_{d}^{i}\right)^{n-1} + R_{u}^{1.0}\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n-1}\right)\right] \\
\widetilde{b} &= \left(1-\mathscr{P}_{\text{fa}}^{i}\right)(1-\lambda)^{2}T\left[2R_{L}^{\star}(1+d)^{2} + R_{u}^{0.1}(1+d)\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n}\right)\left(1-\frac{(1-\lambda)^{2}}{\left(1-\lambda\mathscr{P}_{d}^{i}\right)^{2}}\right) + R_{u}^{0.0}\left(\mathscr{P}_{d}^{i}\right)^{n-1} + R_{u}^{1.0}\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n-1}\right)\right] \\
\widetilde{c} &= R_{L}^{\star}(1+d)^{2} + R_{u}^{0.1}\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n}\right)\left(1-\frac{(1-\lambda)^{2}}{\left(1-\lambda\mathscr{P}_{d}^{i}\right)^{2}}\right) \\
\widetilde{e} &= \left(1-\mathscr{P}_{\text{fa}}^{i}\right)(1-\lambda)^{2}(1+d)\left[R_{u}^{0.0}\left(\mathscr{P}_{d}^{i}\right)^{n-1} + R_{u}^{1.0}\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n-1}\right) - \left(1-\frac{(1-\lambda)^{2}}{\left(1-\lambda\mathscr{P}_{d}^{i}\right)^{2}}\right)R_{u}^{0.1}\left(1-\left(\mathscr{P}_{d}^{i}\right)^{n}\right)\right] \\
\widetilde{f} &= \sqrt{\left(\widetilde{e}\cdot\widetilde{g} - N\widetilde{g}\cdot\widetilde{b}\right)^{2} - 4N\widetilde{g}\cdot\widetilde{a}\left(N\widetilde{g}\cdot\widetilde{c} - \widetilde{e}\right)} \\
\widetilde{g} &= \left(1-\mathscr{P}_{\text{fa}}^{i}\right)(1-\lambda)^{2}.
\end{aligned} \tag{37}$$

Considering the constraint (35) which restricts the transmission time T^{i} of DACS, we have

$$T^{\star} = \min\left(\left(\frac{\widetilde{e}\cdot\widetilde{g} + \widetilde{f} - N\cdot\widetilde{g}\cdot\widetilde{b}}{2N\cdot\widetilde{g}\cdot\widetilde{a}}\right)^{+}, \frac{k_{\text{tol}} - k_{w}}{1-\mathscr{P}_{\text{fa}}^{i}}\right), \tag{38}$$

where $(x)^{+} = \max(0, x)$. The optimal solutions (38) show that DACSs can adjust the transmission time based on the real-time WiFi users traffic load.

According to the above analysis, based on the SBPA, DACSs could get the maximum data rate $R_{L}^{\star}$ in the licensed band by optimizing the cell selection, detection operation, and power allocation. Furthermore, based on the DBTB, DACSs could adjust the amount of traffic assigned to the unlicensed band to decide the transmission time T^{i} in the unlicensed band.

Due to the nonconvexity of the problem, we propose a satisfaction-based dual-band traffic balancing (SDTB) algorithm for DACSs based on the IP method [30, 31], which is composed of two suboptimization problems: SBPA and DBTB. Suboptimization problem SBPA is composed of two steps: line search step and trust region step. We start from line searching to ensure that the search direction is a descent direction for the merit function, turning to the trust region step otherwise. The merit function of our problem is composed of an objective function component and a component comprising constraints of the problem. We outline the main steps of SDTB algorithm in Algorithm 1, where N_b is the maximum number of backtracking search steps. For our problem, we choose $\varepsilon = 10^{-7}$ and $N_b = 3$. The resulting algorithm is ensured to have global convergence, thus achieving a QNE of the game $P3$. For more details, we refer to [12, 29–31].

The complexity of the iterative SDTB algorithm relates to the procedure of line search iteration steps and trust region iteration steps, as well as the size of the DACS. The total complexity of the SDTB algorithm is given by $O_{\text{SDTB}} = O(\ln(1/\varepsilon)J\sqrt{L(2K+J)}) \sim O(\ln(1/\varepsilon)J((N_b+1)\sqrt{L(2K+J)} + L(2K+J)))$.

5. Simulation Results

In this section, we evaluate the proposed satisfaction-based dual-band traffic balancing (SDTB) algorithm in practical deployment scenarios. We consider a DACS network with $M = 3$ CSBSs, $J = 8$ CSUs, and $K = 2$ MUs. All the MUs and CSUs are randomly placed in a 50 m × 50 m square. Assume CSBS, MU, and CSU are equipped with $N_r = 10$ and $N_t = 2$ antennas, respectively. All involved channels between CSUs, CSBSs, and MUs obey Rayleigh distribution as well as the channel gains being associated with distance.

Table 2 summarizes the path loss model and parameter used in the simulations. The path loss is based on the 3GPP Indoor scenario for LTE [32], where path loss (PL) is in dB, d_{ij} is the distances between user j and station i, and L_{ow} is the outer wall penetration loss. Log-normal shadowing is with variance 3 dB, $T_L = 50$ ms, $f_{\text{ls}} = 2$ MHz in the licensed band, $f_{\text{us}} = 5$ GHz in the unlicensed band, and $(\delta_{k,n}^{i})^{2} = 1$, according to [33]. $P_{\text{mu}} = 10$ dB is the transmission power of MU. The maximum power of CSU j is $P_{\max}^{j} = 5$ dB. LTE-Advanced is adopted as the cellular air interface while 802.11 with a frame aggregation level of 15 k Bytes is used for the WiFi air interface. The unlicensed bandwidth is set to 20 MHz. The calculated utility function described in Section 3 is used in the simulations.

Figure 3 represents the total data rate of DACSs in the licensed band R_L versus the sensing time $t_s^{\star}$ for different D. We can observe the optimal sensing time t_s from the figure. Based on the result, there exists a maximum data rate at the optimal sensing time $t_s^{\star}$ for different D. $D = 2$ represents the case without optimization, leading to the lower total data rate due to the CSBSs and CSUs being randomly associated compared with the proposed SDTB algorithm, in which CSUs could select the best CSBSs to maximize the total data rate. Notice that, for $D = 4$ and $D = 5$, the curves are overlapped, which means that there is no rate gain for $D \geq 4$; thus DACSs achieve the best performance.

Figure 4 shows the total utility of CSUs and WiFi users versus the WiFi traffic load λ for different DACS transmission

(1) Initialize $\mathbf{x}^j = (\mathbf{Q}_L^j, \boldsymbol{\tau})$, $\mathbf{z}^j = (\mathbf{x}^j, \mathbf{s}^j)$, λ. $\boldsymbol{\Psi}^j = (\boldsymbol{\alpha}^j, \boldsymbol{\beta}^j)$, T^i, Trust region radius $\Upsilon^j > 0$ and $\mathbf{v}^j > 0$.
(i) sub-optimal algorithm 1: SBPA
(2) **repeat**
(3) **for** $j = 1 : J$
(4) **repeat; repeat**
(5) Compute the number N_e^j, set LS = 0
(6) **if** $N_e^j \leq 3K$
(7) Get direction $\overrightarrow{dr}$ and step size ρ for $\mathbf{z}^j$ and $\boldsymbol{\Psi}^j$ by Newtons's method
(8) **if** Step size $\rho_{\min}^j > \varepsilon$, set $i = 0$, $\rho_{T_L}^j = 1$
(9) **repeat**
(10) **if** The merit function in search direction $\overrightarrow{dr}$ for
(11) $\boldsymbol{\Psi}^j$ this step ρ^j is decreased update ρ^j, $\mathbf{z}^j$
(12) Update Υ^j and set LS = 1
(13) **else** Update $i = i + 1$, choose a smaller $\rho_{T_L}^j$
(14) **endif**
(15) **until** $i > N_b$ Or $\rho_{T_L}^j < \varepsilon$ Or LS == 1
(16) **endif; endif**
(17) **if** LS == 0
(18) Compute $\mathbf{z}^j$, $\boldsymbol{\Psi}^j \Upsilon^j$ using the trust region method
(19) **endif**, Update $\mathbf{v}^j$
(20) **until** $\mathbf{x}^j$ and $\boldsymbol{\Psi}^j$ satisfy the stopping test
(21) Reset the barrier parameters, so that $\mathbf{v}^j$ is decreasing
(22) **until** $\mathbf{x}^j$ and $\boldsymbol{\Psi}^j$ satisfy the stopping test
(23) Update $\mathbf{x}^j$
(24) **endfor**
(25) **until** $\mathbf{x}^j$ achieve convergence
(ii) sub-optimal algorithm 2: DBTB
(26) Based on the optimal result $R_L^\star$
(27) Take the derivative of (34), set to zero, obtain T^i in (36)
(28) **if** $T^i < (k_{\text{tol}} - k_w)/(1 - \mathscr{P}_{\text{fa}}^i)$, then get optimal $T^\star$ in (36)
(29) **else** get the optimal $T^\star = (k_{\text{tol}} - k_w)/(1 - \mathscr{P}_{\text{fa}}^i)$
(30) **endif**
(31) End the SDTB algorithm

Algorithm 1: Satisfaction-based dual-band traffic balancing algorithm.

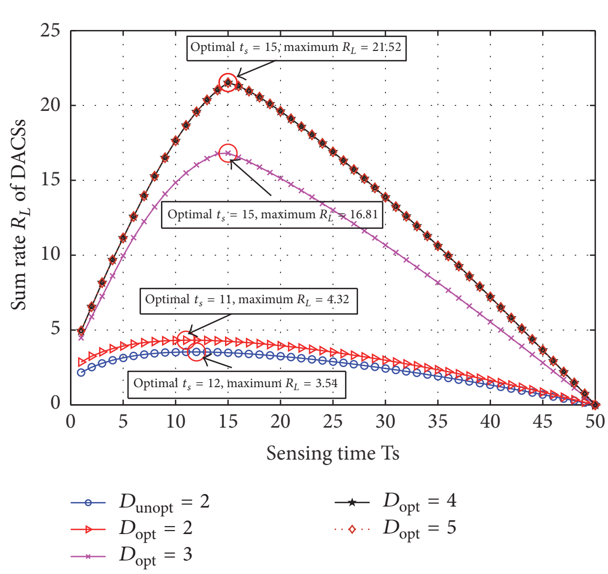

Figure 3: The sum rate R_L versus sensing time t for different D.

time T. We assume that the licensed bandwidth B_L = 1.4 MHZ and the WiFi users number $N = 1$. In this figure, we could observe that, with fixed T, the overall utility is not maximized with variational WiFi traffic load λ. The total utility increases with increasing λ at the beginning, that is, because the data rate of WiFi increases with increasing λ whereas there is only tiny influence on DACSs. The utility of whole networks achieves the maximum value at different T with dynamic traffic load λ, namely, traffic balance turning point, (e.g., $T = 5$, $\lambda = 0.56$, $R_L = 21.52$). After this point, the utility of whole networks decreases owing to the fact that the utility descending from DACSs is more than the utility ascending from WiFi with respect to the increasing traffic load λ. For larger T, the traffic balance turning point appears with larger λ. Furthermore, we compare the proposed SDTB algorithm with the ordinary scheme for fixed transmission time T. It is clear from the result that the proposed SDTB algorithm can obtain the optimal T under different WiFi traffic load λ and achieve the maximum utility of whole networks.

Table 2: Simulation parameters.

Parameter	Value
CSBS number	$M = 3$
CSU number	$J = 8$
CSU transmission duration in licensed bands	$T_L = 50$ ms
CSU transmission duration in unlicensed bands	$T \in (0, 30)$ ms
Licensed frequency	$f_{ls} = 2$ MHz
Unlicensed frequency	$f_{us} = 5$ GHz
Unlicensed bandwidth	$B_u = 20$ MHz
MU's transmission power	$P_{mu} = 10$ dB
CSU's maximum power budget	$P_{max} = 5$ dB
CSBS/WiFi-AP's transmission power	15 dBm
Path loss between MBS and CSU	$PL = 25.3 + 37.6\log_{10}(d^{ij})$
Path loss between CSBS and CSU	$PL = 38.46 + 20\log_{10}(d^{ij}) + 0.7d^{ij}$
Path loss between CSBS and WiFi	$PL = 35.3 + 37.6\log_{10}(d^{ij})$

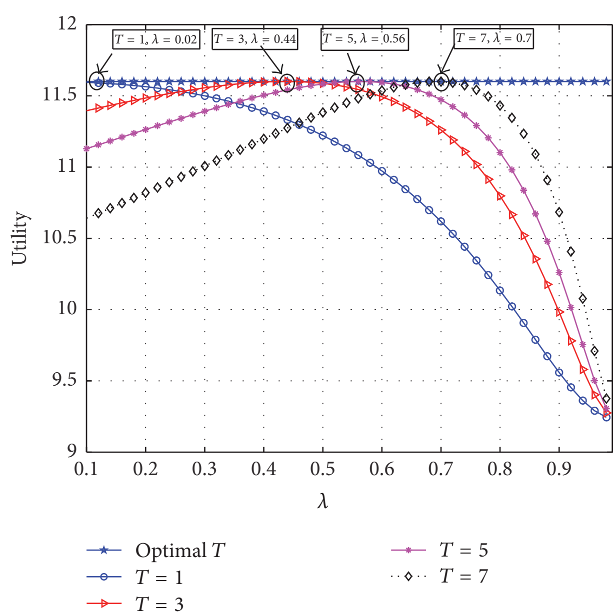

Figure 4: The utility versus the WiFi traffic load λ for different T.

Figure 5 shows the variability of utility for different data rate ratio R_L/R_u and transmission time T. Specifically, for fixed transmission time T, the bigger the data rate ratio R_L/R_u, the higher the utility of whole networks. This is because the increasing of R_L directly causes the increasing of whole networks, while the R_u does not change.

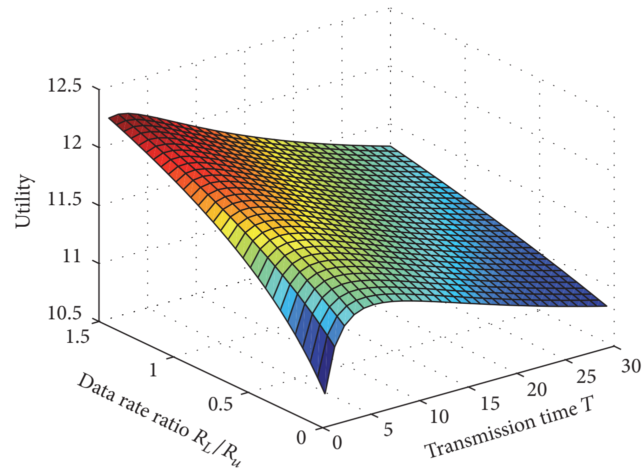

Figure 5: The utility versus data rate ratio R_L/R_u and transmission time T.

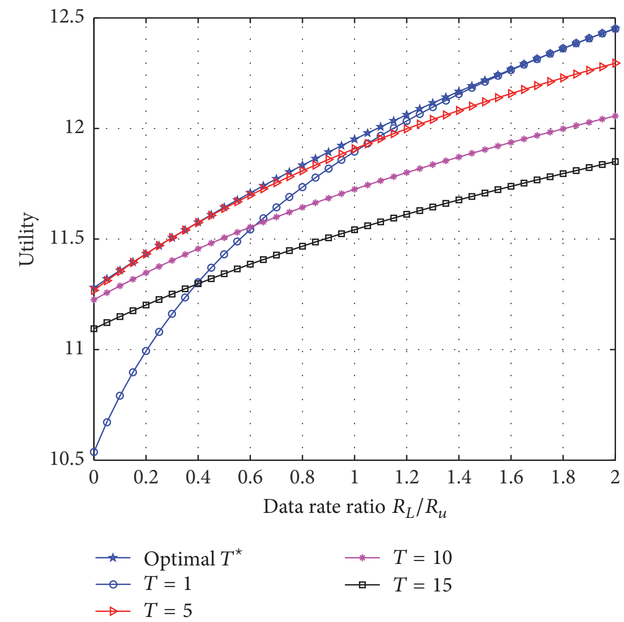

Figure 6: The utility versus the data rate ratio R_L/R_u for different T.

Figure 6 shows the utility versus the data rate ratio R_L/R_u for different T. Let $\lambda = 0.6$, $N = 1$. Based on the optimal power allocation and the optimal cell selection in the licensed band, for fixed T (e.g., $T = 10$), only the bandwidth of the licensed and unlicensed band will affect R_L and R_u, respectively. Furthermore, we fix the unlicensed bandwidth $B_u = 20$ MHz, and obtain different data rate R_L in the licensed band based on different licensed bandwidth (1.4, 3, 5, 10, 15, 20, and 30 MHz). Compare the curves of $T = 5, 10, 15$ with optimal $T^{\star}$; we can see that with the same data rate ratio R_L/R_u, the larger the T is, the lower the utility could be. This is because larger T represents the larger traffic load of DACSs, which results in the WiFi performance decreasing due to the interference from DACSs. Notice that, for $T = 1$, the smaller

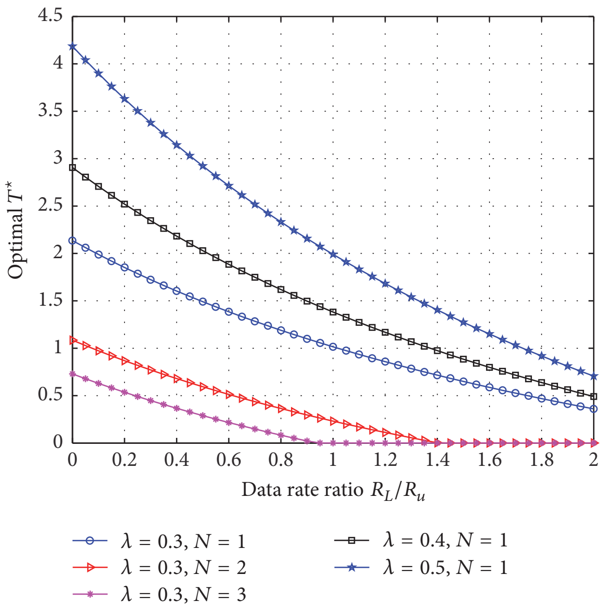

FIGURE 7: The optimal T^* versus the data rate ratio R_L/R_u for different WiFi users number N and λ.

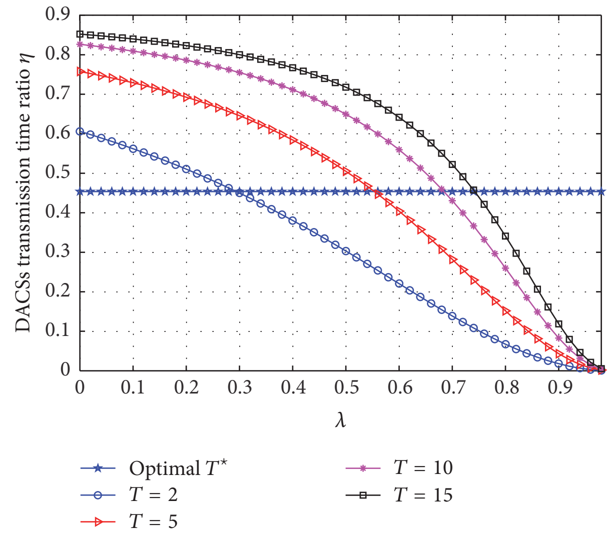

FIGURE 8: The DACSs transmission time ratio η versus the λ for different T.

the data rate ratio R_L/R_u, the lower the utility due to DACSs having a low satisfaction from the licensed band.

From Figure 7 we can observe that the optimal transmission time T depends on several parameters. For the fixed λ and N, the optimal T decreases when the data rate ratio R_L/R_u is increasing. That is because the licensed band could gradually ensure the QoS of DACSs while less resource is required from the unlicensed band. Moreover, when $\lambda = 0.3$, the optimal DACSs transmission time T is smaller with larger N. In addition, we can see that the larger the λ, the larger the optimal transmission time T of DACSs. Since larger traffic load of WiFi results in larger transmission time of DACS, guaranteeing the maximum utility of whole networks can be achieved.

From Figure 8, it is clear that the DACSs transmission time ratio $\eta = t_1 + t_2 + t_3$ is a decreasing function of λ, and an increasing function of transmission time T. Since the optimal T^* is influenced by λ, in order to keep the traffic balancing between DACSs and WiFi, and maximize the utility of whole systems, the ratio η is stable.

In Figure 9, we evaluate the optimal DACSs transmission time ratio η^* with $\lambda = 0.6$ and $k_w = 1/(1-\lambda)^2$. The optimal DACSs transmission time ratio η^* is decreasing with the increasing data rate ratio R_L/R_u for different WiFi users number N. η decreases to zero when ratio $R_L/R_u > 1.15$, $N = 2$, and $R_L/R_u > 0.75$, $N = 3$, respectively. In this case, DACSs can obtain enough resource in the licensed band and do not acquire additional resource from the unlicensed band. In addition, we also observe that the more the WiFi users, the lower the optimal DACS transmission time ratio η^*, since more WiFi users lead to fiercer competition and less available spectrum resource in unlicensed band.

In order to illustrate the dual-band access scheme based on sensing information in the licensed/unlicensed band and

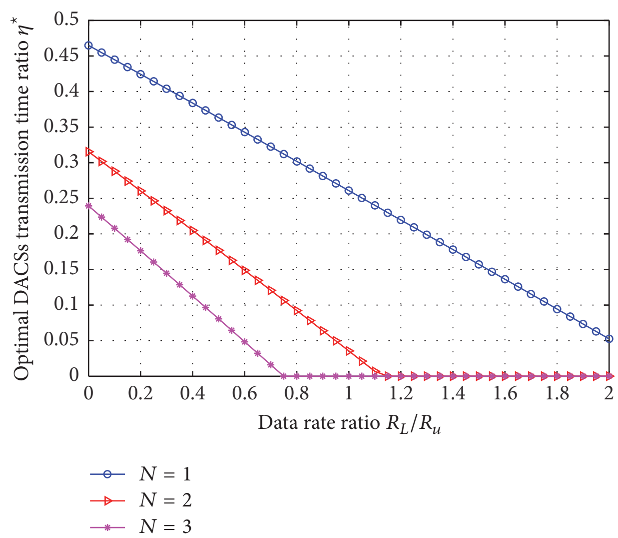

FIGURE 9: The optimal DACSs transmission time ratio η^* versus the data rate ratio R_L/R_u for different WiFi users number N.

evaluate the performance of the proposed SDTB algorithm, we use the following schemes for simulation comparison: (1) Ergodic Capacity Resource Allocation (ECRA) algorithm which only accesses the licensed band; (2) Distributed Downlink Resource Allocation (DDRA-fixed T) algorithm which only uses the unlicensed band with fixed T; (3) Optimal Distributed Downlink Resource Allocation (DDRA-optimal T) algorithm which only uses the unlicensed band with optimal T^*; (4) Dual-Band Resource Allocation (DBRA-fixed T) algorithm which uses both licensed and unlicensed bands with fixed T; (5) SDTB algorithm which could access both licensed and unlicensed bands with optimal T^*. Generally, we set $T = 15$ and $\lambda = 0.6$, $B_L = 14$ MHz, and $N = 1$.

Figures 10 and 11 show the average data rate and the utility of different algorithms, respectively. We have the following

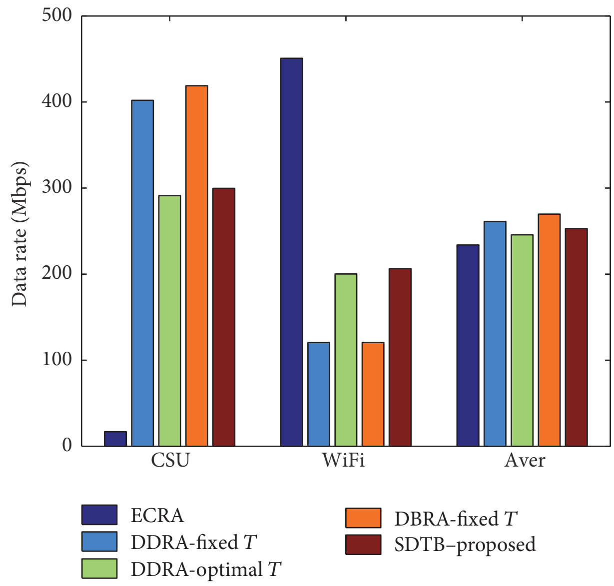

Figure 10: The average data rate for SDTB, ECRA, DDRA-fixed T, DDRA-optimal T, and DBRA-fixed T.

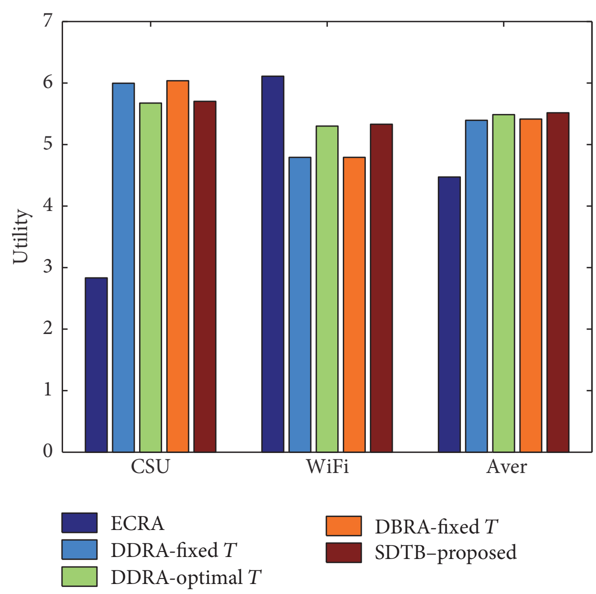

Figure 11: The average utility for SDTB, ECRA, DDRA-fixed T, DDRA-optimal T, and DBRA-fixed T.

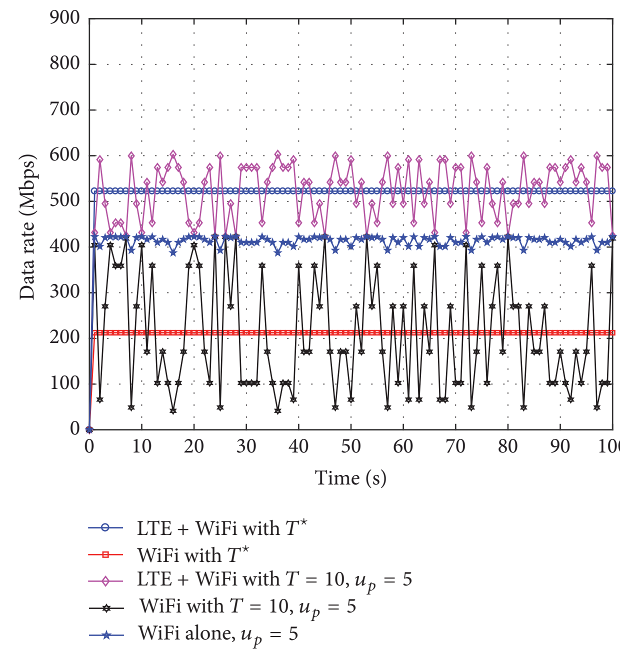

Figure 12: The data rate versus the time for different scenarios.

observations from the figures. First of all, the proposed SDTB algorithm significantly improves the performance of DACSs, while it does not significantly affect the performance of WiFi network. Secondly, based on FDD, DACSs could access both licensed and unlicensed bands simultaneously, which improves the average utility and data rate compared with the Half-Duplex model. Obviously, the proposed SDTB algorithm obtains higher average utility than other schemes. Moreover, there is very little difference between the DDRA-fixed T and the DBRA-fixed T schemes, due to the small part of contributions from the licensed band to the final results. The proposed SDTB algorithm provides a better tradeoff between maximizing the total network data rate and obtaining fairness among different networks.

In this section, we evaluate the performance of the proposed SDTB scheme and the CSMA/CA scheme in realistic channel status with multi-CSBS and multi-AP. In the realistic scenarios, the traffic load of WiFi nodes is random and formulated by the Poisson-distribution with parameter u_p. In order to obtain the optimal transmission time for both LTE users and WiFi nodes we should predict the traffic load of WiFi nodes which is random. Thus, we consider the following three scenarios: CSBSs and one WiFi node scenario with optimal-T based on the SDTB algorithm, CSBSs and one WiFi node scenario with $T = 10$ based on the DBRA-fixed T algorithm, and WiFi nodes alone. Figures 12 and 13 show the data rate and the utility versus the time for different scenarios. Considering that WiFi nodes access the channel in a random fashion, the Poisson-distribution with parameter u_p is used in the simulation to present the random arrival of WiFi users traffic load and the number of the packet obeying exponential distribution. K_p is the number of WiFi packets according to the Poisson-distribution with mean rate u_p, and the probability of a WiFi user continuing to transmit data in the next slot is $\lambda = \sum_{k=0}^{K_p}((u_p)^k \cdot e^{-u_p})/(k!)$. The mean rate $u_p = 5$ in our simulation. Based on the simulation results, the data rate of the DBRA-fixed T algorithm and the WiFi-alone is not stable during the simulation time due to the random traffic load of WiFi, while the data rate of the proposed algorithm with optimal T could provide a stable performance, as well as the traffic balancing between the DACS system and the WiFi system. Clearly, the total data rate and the data rate of WiFi with optimal-T are not always larger than those of the algorithm with $T = 10$. This is because the main purpose

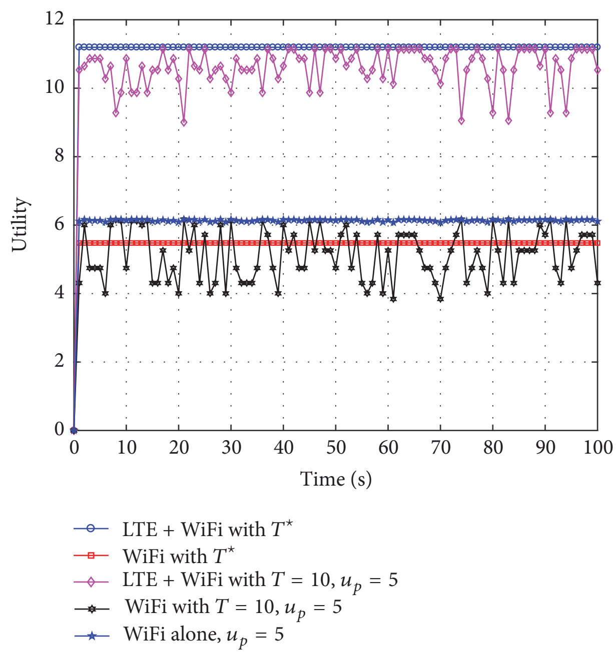

Figure 13: The utility versus the time for different scenarios.

is to maximize the total utility of the whole network. From Figure 13, we can observe that the total utility of LTE and WiFi and WiFi utility with optimal-T are stable which is in accordance with the result from the Figure 4. The proposed SDTB algorithm can obtain the optimal T under different WiFi traffic load λ and achieve the maximum utility of whole networks. Specially, the utility of WiFi-alone scenario is close to the number 6, since the WiFi access mechanism is based on the CSMA/CA protocol without the interference from LTE system. Moreover, Figure 13 shows that the proposed scheme in our paper can achieve higher and stable satisfaction.

6. Conclusion

In this paper, we have described the dual-access cognitive small cell (DACS) network that uses the LTE air interface to transmit and receive signals in the licensed and unlicensed band simultaneously. In order to maximize the total utility of the whole network, we jointly optimize the cell selection, the sensing operation, and the power allocation in the licensed band while optimizing the transmission time in the unlicensed band. A satisfaction-based dual-band traffic balancing (SDTB) algorithm over licensed and unlicensed bands for DACSs is proposed to improve the total utility of DACSs and WiFi systems. The optimization problem is divided into two suboptimization problems: sensing-based power allocation (SBPA) and dual-band traffic balancing (DBTB). The SBPA problem is formulated as a nonconvex game and it theoretically proved the existence and uniqueness of the QNE. In addition, based on the DBTB scheme, we could obtain the optimal transmission time in the unlicensed band and ensure the fairness coexistence between DACS and WiFi.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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