Decentralized Traffic Management for Heterogeneous Networks with Opportunistic Unlicensed Spectrum Sharing

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***Abstract*—This paper studies how to maximize the per-user-based throughput in an M-tier heterogeneous wireless network (HetNet) by optimally managing traffic flows among the access points (APs) in the HetNet. The APs in the first $M-1$ tiers can use the licensed spectrum at the same time whereas they share the unlicensed spectrum with the APs in the Mth tier by the proposed opportunistic CSMA/CA protocol. The APs that access the licensed and unlicensed spectra simultaneously are able to integrate their spectrum resources by the carrier aggregation technique. For an AP in each tier, the tight bounds on its mean spectrum efficiencies in the licensed and unlicensed spectra are derived in a low-complexity form for general random channel gain and AP association weight models, and they can provide some insights into how channel gains, AP association weights and void AP probabilities affect the mean spectrum efficiencies of APs. The per-user throughput based on the mean spectrum efficiencies in the licensed and unlicensed spectra is found and maximized by the proposed decentralized traffic management scheme. Numerical results show that the mean spectrum efficiencies and the per-user throughput can be significantly improved by the proposed decentralized traffic management scheme.**

I. Introduction

As more and more versatile services are offered over wireless networks and new generations of wireless smart handsets get wider and wider adoption, considerable data traffic flowing over spectrum-limited cellular networks is an inevitable phenomenon the network operators have to seriously face. To alleviate the spectrum crunch crisis of a cellular network, an effective means is to make a traditional cellular network migrate to a heterogeneous cellular network in which many different kinds of base stations (BSs), such as macro, micro and small cell BSs, are densely deployed. Although heterogeneous cellular networks have a much higher network capacity compared to their traditional counterpart, their licensed spectrum is still very limited and their per-user throughput may not be efficiently improved if the network has a huge user population. Accordingly, exploiting more available spectrum for heterogeneous cellular networks is the right track that should be followed, which fosters the idea of extending the service of the cellular BSs to the unlicensed spectrum. If cellular BSs can access the licensed and unlicensed spectra at the same time, they can integrate all available spectrum resources by using the carrier aggregation technique [1]–[3]. However, extending cellular services to the unlicensed spectrum could severely impact the throughput performance of the existing access points (APs) using the unlicensed spectrum, such as WiFi APs. Hence, how to make different kinds of BSs and APs properly share the unlicensed spectrum and improve their total throughput is an important problem that needs to be investigated thoroughly.

Earlier prior studies on the coexisting interference problem in the unlicensed spectrum focused on how to make APs in different overlaid wireless networks share the unlicensed spectrum with certain fairness. For example, reference [4] proposed a game-theoretical approach to fairly sharing the unlicensed spectrum in multiple coexisting and interfering networks. The interference modeling and mitigation problems in the unlicensed spectrum are investigated in references [5]–[7]. A more complicate coexistence problem in the unlicensed spectrum that recently attracts a lot of attentions is how to let the base stations (BSs) or APs originally using the licensed spectrum also be able to access the unlicensed spectrum and use the carrier aggregation technique to boost their overall throughput [2], [3]. A few recent works have already shown that LTE and WiFi networks coexisting in the unlicensed spectrum can significantly improve their entire network throughput [2], [3], [8], [9]. However, how to manage the traffic flows among LTE BSs and WiFi APs to maximize the total or per-user throughput in the licensed and unlicensed spectra was not addressed in these works.

In this paper, our first contribution is to propose an M-tier HetNet architecture that generally characterizes the licensed and unlicensed spectrum sharing problem of different kinds of APs using the opportunistic CSMA/CA protocol. A general AP association scheme that can cover several pathloss-based AP association schemes is proposed in the HetNet. Our second contribution is to derive the tight lower bound (of a very general form) on the mean spectrum efficiencies in the unlicensed and licensed spectra. The per-user throughput is defined based on the spectrum efficiencies in the licensed and unlicensed spectra and it is shown to be maximized by the proposed decentralized traffic management scheme, which is our third contribution. Finally, some numerical results are presented to validate our analytical findings.

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II. Network Model and Preliminaries

Consider a large-scale interference-limited heterogeneous wireless network consisting of M tiers of access points (APs). All the APs in the same tier are of the same type and performance. Specifically, the APs in the mth tier, denoted by set $\mathcal{X}_m$, follow an independent marked Poisson point process (PPP) of intensity λ_m defined as follows

$$\mathcal{X}_m \triangleq \{(X_{m,i}, P_m, V_{m,i}) : X_{m,i} \in \mathbb{R}^2, P_m \in \mathbb{R}_{++}, V_{m,i} \in \{0,1\}, i \in \mathbb{N}_+\},\ m \in \mathcal{M} \triangleq \{1, \ldots, M\}, \quad (1)$$

where $X_{m,i}$ denotes AP i in the mth tier and its location, P_m is the transmit power used by the APs in the mth tier, and $V_{m,i}$ is a Bernoulli random variable indicating whether AP $X_{m,i}$ is void or not: if AP $X_{m,i}$ is associated with at least one user (i.e., it is not void), then $V_{m,i} = 1$ and zero otherwise. Without loss of generality, we assume the APs in the Mth tier only use the unlicensed spectrum to deliver data, and all other APs in the first $M-1$ tiers primarily use the licensed spectrum and opportunistically use the unlicensed spectrum by carrier aggregation to transmit data if they have a chance to access the unlicensed spectrum. This network model with unlicensed spectrum sharing has a practical application context. In a heterogeneous cellular network, for example, LTE-U macro and small cell base stations (BSs) consisting of the APs in the first $M-1$ tiers can coexist and share the unlicensed spectrum with WiFi APs in the Mth tier if the LTE-U BSs can use the carrier aggregation technique to integrate the licensed and unlicensed spectrum resources [2], [3].

All users also form an independent PPP $\mathcal{U}$ of intensity μ given by

$$\mathcal{U} \triangleq \{U_j : U_j \in \mathbb{R}^2, \forall j \in \mathbb{N}_+\} \quad (2)$$

and we assume there is typical user U_0 located at the origin without loss of generality. Our following location-dependent analyses will be based on typical user U_0 for simplicity since the analytical results do not depend where the typical user is located due to Slivnyak's theorem [10]. We consider a *downlink* transmission scenario in this paper and each user selects its serving AP X_o by adopting the following AP association scheme

$$X_o \triangleq \arg \sup_{m,i:X_{m,i}\in\bigcup_{m=1}^M \mathcal{X}_m} W_{m,i}\|X_{m,i}\|^{-\alpha}, \quad (3)$$

where $W_{m,i}$ is the (random) AP association weight with mean $\bar{w}_m$ for AP $X_{m,i}$, $\|X_i - X_j\|$ denotes the distance between nodes X_i and X_j for $i \neq j$, and $\alpha > 2$ is called pathloss exponent. Furthermore, we assume that all $W_{m,i}$'s are independent, all $\frac{W_{m,i}}{\bar{w}_m}$'s are i.i.d. random variables with unit mean, and the a-fractional moment of $W_{m,i}$ always exists[1] for all $i \in \mathbb{N}_+$ and $m \in \mathcal{M}$, i.e., $\mathbb{E}[W_m^a] < \infty$ for all $a \in (0,1)$. Note that the scheme in (3) makes users associate with an AP in any tier no matter which spectrum the AP primarily/only uses, and it can cover several different pathloss-based AP association schemes by changing the design of the AP association weights, such as the *biased nearest AP association* (BNA) scheme if W_m is a constant, the *biased mean strongest AP association* (BMSA) scheme if $W_{m,i} \equiv b_m P_m H^{(s)}_{m,i}$ for all $m \in \mathcal{M}$ where $b_m > 0$ is a constant bias and $H^{(s)}_{m,i}$ characterizes the large-scale channel gain of the tier-m APs such as shadowing, and other schemes etc. [11].

In this paper, all APs are assumed to always have data to transmit to their tagged users. The channel access protocols for the licensed spectrum and unlicensed spectrum are quite different. All APs in the first $M-1$ tiers share the entire licensed spectrum at the same time and they are synchronized while accessing the licensed channel[2]. Note that the tier-M APs cannot access the licensed channel and they are only allowed to access the channel in the unlicensed spectrum. All APs have to use the (slotted non-persistent) *opportunistic* CSMA/CA (carrier sense multiple access with collision avoidance) protocol to access the unlicensed channel[3]. By adopting such an opportunistic CSMA/CA protocol, the APs having their channel gains greater than some threshold are qualified and synchronized to contend the unlicensed channel in the predesignated time slots.

The feature of this opportunistic CSMA/CA protocol is able to make the unlicensed spectrum resource effectively utilized by the APs with good channel conditions so as to improve the spectrum sharing efficiency and throughput. Each AP in the mth tier that performs the opportunistic CSMA/CA protocol has a sensing region $\mathcal{S}_m$ in which all unlicensed channel accessing activities can be detected by the AP. The channel access probability of the tier-m APs using the opportunistic CSMA/CA protocol is already derived in our previous works [8], and it can be modified for the AP association scheme in (3) and expressed as shown in the following:

$$\rho_m = \frac{1 - \exp\left(-\tau \sum_{k=1}^M A_{m,k}\xi_k q_{k,0}\lambda_k(\bar{w}_k/\bar{w}_m)^{\frac{2}{\alpha}}\right)}{\tau \sum_{k=1}^M A_{m,k}\xi_k q_{k,0}\lambda_k(\bar{w}_k/\bar{w}_m)^{\frac{2}{\alpha}}}, \quad (4)$$

where τ is the maximum backoff time of each AP, $A_{m,k}$ is the mean area of region $\mathcal{S}_m$ where the tier-k APs are distributed (see [8] for the details of how to calculate $A_{m,k}$.), $q_{k,0} \triangleq \mathbb{P}[V_{k,i} = 1]$ is the non-void probability of a tier-k AP and $\xi_k \in [0,1]$ is the probability that the unlicensed channel (power) gain from a tier-k AP to its servicing user is greater than threshold $\delta > 0$, i.e., $\xi_k \triangleq \mathbb{P}[H_k \geq \delta]$ in which H_k denotes the channel gain of a tier-k AP in the unlicensed spectrum.

The channel access probability in (4) indicates not only how much chance a tier-m AP can successfully access the unlicensed channel in a particular timeslot but also the fraction of time it can access the unlicensed channel in the long-term sense. Adjusting the random backoff time limit τ can

[1]Throughout this paper, we define the a-fractional moment of random variable Z as $\mathbb{E}[Z^a]$ for all $a \in (0,1)$ and all $m \in \mathcal{M}$.

[2]Such a licensed channel access protocol is widely used in the cellular networks. In addition, we assume there is only one channel in the licensed spectrum for the ease of analysis.

[3]Like the case in the licensed spectrum, we assume there is only one available channel in the unlicensed spectrum in order to simplify our following analysis.

make tier-m APs have more/less priority or time fraction to access the unlicensed spectrum. For example, if the tier-M APs represent the WiFi APs, we can make their backoff time limit τ_M much shorter than those of the APs in the first $M-1$ tiers so that the throughput of the WiFi APs is guaranteed to remain at some level and not significantly reduced when the unlicensed spectrum is shared by many APs in other tiers at the same time. This is similarly implementing the ideas of the Listen-Before-Talk (LBT) with Carrier Sensing Adaptive Transmission (CSAT) and Licensed-Assisted Access (LAA) protocols proposed in the LTE-U [2], [3]. We will see how the channel access probability plays a pivotal role in analyzing the throughput in the unlicensed spectrum.

III. Analyses of Mean Spectrum Efficiency and Per-User Throughput

In this section, we would like to study the mean spectrum efficiencies of a user in the unlicensed and licensed spectra. Finding the explicit expressions of these mean spectrum efficiencies is an important task since they provide the insights into how to manage traffic flow in order to achieve the throughput optimality. The prior approaches to deriving the mean spectrum efficiency in the literatures are based on integrating the function of the coverage (success) probability under the Rayleigh fading channel model (typically see [8]). Hence, these approaches cannot characterize the mean spectrum efficiencies in a non-Rayleigh fading environment. In the following analysis, we will show how to derive the mean spectrum efficiency for any general channel gain and AP association weight models in a low-complexity expression.

A. Mean Spectrum Efficiency in the Unlicensed Spectrum

Consider the scenario that typical user U_0 associates with a tier-m AP by scheme (3) and is receiving data over the unlicensed channel. The mean spectrum efficiency (achievable rate per bandwidth, bps/Hz) the tier-m AP offers to the user in the unlicensed spectrum is defined as

$$R_{\mathsf{U}_m} = \mathbb{E}\left[\log_2\left(1+\frac{P_m H_m}{I_{\mathsf{U}_m}\|X_o\|^{\alpha}}T_m\Xi_m\right)\right],\ m\in\mathcal{M}, \quad (5)$$

where H_m is the random channel (power) gain with mean $\bar{h}_m$ from AP X_o to typical user U_0, and I_{U_m} is the interference as shown in the following

$$I_{\mathsf{U}_m} \triangleq \sum_{m,i:X_{m,i}\in\bigcup_{m=1}^{M}\mathcal{X}_m\setminus X_o} P_m H_{m,i}V_{m,i}T_{m,i}\Xi_{m,i}\|X_{m,i}\|^{-\alpha}$$

in which $H_{m,i}$ denotes the random channel gain with mean $\bar{h}_m$ from AP $X_{m,i}$ to typical user U_0, $\Xi_{m,i}\in\{0,1\}$ is a Bernoulli random variable that equals to one if AP $X_{m,i}$'s channel gain is greater than threshold δ and zero otherwise, $T_{m,i}\in\{0,1\}$ is also a Bernoulli random variable that equals to one if AP X_{k_i} can access the unlicensed channel and zero otherwise[4], $T_m\in\{T_{m,i}\}$ indicates whether AP X_o can access the unlicensed channel, and $\Xi_m\in\{\Xi_{m,i}\}$ indicates whether the channel gain of AP X_o in the unlicensed spectrum is greater than threshold δ. For the ease of analysis, we assume that all $\frac{H_{m,i}}{\bar{h}_m}$'s are i.i.d. for all $i\in\mathbb{N}_+$ and $m\in\mathcal{M}$ throughout this paper.

The explicit expression of R_{U_m} derived is shown in the following theorem.

Theorem 1. *If all non-void APs that use the opportunistic CSMA/CA protocol to access the unlicensed channel, the mean spectrum efficiency of the user in the unlicensed spectrum in* (5) *can be explicitly lower bounded by*

$$R_{\mathsf{U}_m} \geq \int_{0^+}^{\infty} \frac{\rho_m\xi_m\left[1-\mathcal{L}_{\widehat{H}}(u)\right]du/\ln(2)}{u\left(\sum_{k=1}^{M} q_{k,0}\xi_k\rho_k\vartheta_k\ell_{\widehat{H}}(\frac{\bar{w}_m\bar{h}_k P_k}{\bar{w}_k\bar{h}_m P_m}u,\frac{2}{\alpha})+1\right)}, \quad (6)$$

where $\widehat{H}\triangleq\frac{H_m\bar{w}_m}{W_m\bar{h}_m}$ *is a random variable with unit mean,* $\mathcal{L}_Z(u)=\mathbb{E}[e^{-uZ}]$ *denotes the Laplace transform of random variable* Z *and* $\ell_Z(x,y)$ *for* $y\in(0,1)$ *is defined as*

$$\ell_Z(x,y)\triangleq x^y\Gamma(1-y)\,\mathbb{E}[Z^y]+\int_0^1\mathcal{L}_Z\left(xt^{-\frac{1}{y}}\right)dt-1. \quad (7)$$

Proof: Please see the proof of Theorem 2 in [12]. ∎

It is worth mentioning a couple of the features of the lower bound in (6). First of all, the lower bound is in general fairly tight since the location correlations among the non-void APs due to AP association and opportunistic CSMA/CA are usually very weak. These location correlations will be weakened and thus R_{U_m} will be very close to its lower bound when either the user intensity or the channel gain threshold for opportunistic CSMA/CA increases. The tightness of the lower bound in (6) will be verified by the numerical results presented in Section V. Second, the lower bound in (6) is valid for all random models of channel gains and AP association weights as long as the Laplace transforms of the channel gains and the AP association weights exist, which is never derived in the literatures. This is a very important feature since we are able to realize how different channel and AP association models affect R_{U_m} and gain some insights into how to improve R_{U_m} by appropriately designing the AP association weights in order to manage the traffic flows among different tiers of the APs.

B. Mean Spectrum Efficiency in the Licensed Spectrum

For the mean spectrum efficiency of a user associating with a tier-m AP in the licensed spectrum, its formal definition can be written as

$$R_{\mathsf{L}_m} = \mathbb{E}\left[\log_2\left(1+\frac{P_m H_m}{I_{\mathsf{L}_m}\|X_o\|^{\alpha}}\right)\right], \quad (8)$$

where $X_o\in\mathcal{X}_m$ and I_{L_m} is given by

$$I_{\mathsf{L}_m} \triangleq \sum_{m,i:X_{m,i}\in\bigcup_{m=1}^{M-1}\mathcal{X}_m\setminus X_o} P_m H_{m,i}V_{m,i}\|X_{m,i}\|^{-\alpha}. \quad (9)$$

Note that all channel gains in (8) are evaluated in the licensed spectrum. The explicit result of R_{L} is given in the following theorem.

[4] Namely, the probability that $\Xi_{m,i}$ is equal to one is $\mathbb{P}[\Xi_m=1]=\xi_m$, and the probability that $T_{m,i}$ is equal to one is $\mathbb{P}[T_m=1]=\rho_m$ for all $m\in\mathcal{M}$.

Theorem 2. *If users adopt the AP association scheme in* (3)*, then the mean spectrum efficiency of a user in the licensed spectrum defined in* (8) *in can be shown as*

$$R_{\mathsf{L}_m}\geq\frac{1}{(\ln 2)}\int_{0^+}^{\infty}\frac{\left[1-\mathcal{L}_{\widehat{H}}(u)\right]du}{u\left(\sum_{k=1}^{M-1}q_{k,0}\vartheta_k\ell_{\widehat{H}}(\frac{\bar{w}_m\bar{h}_kP_k}{\bar{w}_k\bar{h}_mP_m}u,\frac{2}{\alpha})+1\right)},\tag{10}$$

where $m\in\{1,2,\dots,M-1\}$.

Proof: Please see the proof of Theorem 3 in [12]. ■

The result in Theorem 2 is also valid for any channel gain and AP association weight models as well. The lower bound on R_{L_m} in (10) is obtained by assuming the non-void correlated APs form M independent thinning homogeneous PPPs and in general it is also very tight, like the lower bounds on R_{U_m} in Theorem 1, since the location correlations of the non-void APs are fairly weak.

C. Per-User Throughput Characterization

In the previous subsections, we have characterized the mean spectrum efficiencies of a tier-m AP in the licensed and unlicensed spectra. Assume the bandwidths of the licensed spectrum and unlicensed spectrum are denoted by B_{L} and B_{U}, respectively. Accordingly, the total link throughput of a tier-m AP in the licensed and unlicensed spectra can be written as

$$C_m=B_{\mathsf{L}}R_{\mathsf{L}_m}\mathbb{1}(m\neq M)+B_{\mathsf{U}}R_{\mathsf{U}_m},\,(\text{bps})\,m\in\mathcal{M},\tag{11}$$

where $\mathbb{1}(\mathcal{E})$ is an indicator function which is one if event $\mathcal{E}$ is true and zero otherwise. Note that the link throughput of a tier-M AP, only in the unlicensed spectrum, is $C_M=B_{\mathsf{U}}R_{\mathsf{U}_M}$. The total link throughput of each AP highly depends on how the AP association weights in (3) are designated. For instance, when $\mathbb{E}\left[W_m^{2/\alpha}\right]$ becomes larger, more users associate with the tier-m APs (i.e., more traffic is offloaded to the tier-m APs) so that the mean spectrum efficiencies would change very likely due to interference variations since the void probability of the tier-m APs reduces and correspondingly the void probabilities of the APs in other tiers increase. In this case, whether the total link throughput of the tier-m APs increases/decreases is dependent upon whether the interferences in the licensed and unlicensed spectra decrease/increase and the channel access probability of the APs in the unlicensed spectrum decreases/increases due to offloading traffic to the tier-m APs.

According to our previous work in [13], the mean number of the users associating with a tier-m AP is $\mu\lambda_m\mathbb{E}\left[W_m^{\frac{2}{\alpha}}\right]/\sum_{k=1}^{M}\lambda_k\mathbb{E}\left[W_k^{\frac{2}{\alpha}}\right]$. By assuming all users equally share the spectrum resources, the per-user throughput of the tier-m APs can be shown as

$$c_m=\frac{q_{m,0}\lambda_m}{\mu\vartheta_m}[B_{\mathsf{L}}R_{\mathsf{L}_m}\mathbb{1}(m\neq M)+B_{\mathsf{U}}R_{\mathsf{U}_m}],\tag{12}$$

where $\vartheta_m\triangleq\lambda_m\mathbb{E}\left[W_m^{\frac{2}{\alpha}}\right]/\sum_{k=1}^{M}\lambda_k\mathbb{E}\left[W_k^{\frac{2}{\alpha}}\right]$ is the probability that a user associates with a tier-m AP. In general, this per-user link throughput decreases as the traffic offloaded to the tier-m APs increases in that $\mu\vartheta_m$ increases but C_m may not increase.

IV. Decentralized Traffic Management for Coexisting Licensed and Unlicensed APs

The traffic management problem that interests us here is how to offload or load traffic between two orthogonal spectrum domains such that the per-user-based throughput increases. Since the APs in the first $M-1$ tiers could simultaneously assess the unlicensed channel, their transmitting behaviors in the unlicensed spectrum definitely affect the throughput of the APs in the Mth tier. Accordingly, the primary premise of managing the traffic in different tiers is to make the per-user throughput of the APs in the Mth tier higher than some minimum required value. Namely, assuming the per-user throughput of the tier-M APs must be at least greater than some minimum value $c_{\min}$, i.e., $c_M\geq c_{\min}$ and it is

$$\frac{q_{M,0}B_{\mathsf{U}}}{c_{\min}\mu}\left(\sum_{m=1}^{M}\lambda_m\bar{w}_m^{\frac{2}{\alpha}}\right)\geq\frac{\bar{w}_M^{\frac{2}{\alpha}}}{R_{\mathsf{U}_M}}.\tag{13}$$

With this constraint on $\bar{w}_M^{\frac{2}{\alpha}}$, we are able to study how to maximize the per-user throughput of the APs in any particular tier and the per-user network throughput by optimizing the designs of the AP association weights.

According to Theorems 1, 2 and the per-user throughput of the tier-m APs given in (12), c_m is significantly affected by all $\{\bar{w}_m^{2/\alpha}\}$. Now our interest here is to gain some insights into when an AP in a particular tier should independently determine to offload its traffic to APs in other tiers (i.e., reduce its AP association weight) or load traffic from APs in other tiers (i.e., increase its AP association weight) so that its per-user throughput increases. This is essentially a "decentralized" traffic management problem since the traffic loading or offloading decision is independently made by each AP from the perspective of the per-user throughput. In other words, this decentralized traffic management problem is to study how to increase or even maximize c_m by unilaterally changing or even optimizing the value $\bar{w}_m^{2/\alpha}$ of a tier-m AP under the constraint (13). That is, if possible, we would like to solve the following optimization problem of $\bar{w}_m^{2/\alpha}$:

$$\begin{cases}\max\limits_{\omega_m>0} & c_m(\omega_m)\\ \text{s.t.} & \left(\sum_{k=1}^{M}\lambda_k\omega_k\right)\frac{R_{\mathsf{U}_M}}{\omega_M}\geq\frac{c_{\min}\mu}{q_{M,0}B_{\mathsf{U}}}\end{cases}\tag{14}$$

in which we define $\omega_k\triangleq\bar{w}_k^{2/\alpha}$ to simplify the notation in the problem. The feasible solution of this optimization problem exists as shown in the following theorem.

Theorem 3. *Let* Ω_m *be the feasible set of* ω_m *with the constraint* (13)*, i.e., it is*

$$\Omega_m\triangleq\Bigg\{\omega_m\in\mathbb{R}_{++}:\left(\sum_{k=1}^{M}\lambda_k\omega_k\right)\frac{R_{\mathsf{U}_M}}{\omega_M}\geq\frac{c_{\min}\mu}{q_{M,0}B_{\mathsf{U}}},\\ \omega_k>0,k\in\mathcal{M}\setminus m\Bigg\}.\tag{15}$$

If Ω_m is nonempty, there exists a maximizer ω^*_m of c_m over Ω_m for all $m \in \{1, 2, \dots, M-1\}$.

Proof: Please see the proof of Lemma 4 in [12]. ■

Theorem 3 reveals that $\omega^*_m \in \{\arg\sup_{\omega_m \in \Omega_m} c_m(\omega_m)\}$ and $\frac{\partial c_m}{\partial \omega_m}|_{\omega_m=\omega^*_m} = 0$. However, finding ω^*_m needs the information of other ω_k's which is in general unknown for the APs in the mth tier in the decentralized context.

The two fundamental traffic management rules for a tier-m AP can be easily realized as

$$\frac{\partial c_m}{\partial \omega_m} < 0 \Leftrightarrow \begin{cases} \text{loading traffic reduces } c_m \\ \text{offloading traffic increases } c_m \end{cases} \tag{16}$$

and

$$\frac{\partial c_m}{\partial \omega_m} > 0 \Leftrightarrow \begin{cases} \text{loading traffic increases } c_m \\ \text{offloading traffic reduces } c_m \end{cases}. \tag{17}$$

These two rules indicate that *the APs in the first $M-1$ tiers need to offload traffic if $\frac{\partial c_m}{\partial \omega_m} < 0$ and load traffic if $\frac{\partial c_m}{\partial \omega_m} > 0$ under the constraint that the APs in the Mth tier need to maintain their per-user throughput above the threshold value $c_{\min}$*. According to the facts in (16) and (17), we develop a decentralized traffic management scheme for the APs in each tier as shown in the following theorem.

Theorem 4. *For the tier-m APs and $m \in \{1, 2, \dots, M-1\}$, the following decentralized traffic management scheme maximizes their per-user throughput under the constraint in* (13)

$$\omega_m(n+1) = \frac{c^*(n) N_m(n) \omega_m(n)}{C_m(n)},\ \omega_m(0) > 0, \tag{18}$$

where $n \in \mathbb{N}$, $N_m(n) = \frac{1}{n}\sum_{i=0}^{n-1} N_m(i)$ denotes the average number of the users tagged a tier-m AP at time n and $c^*(n) \triangleq \max\{c_{\min}, c^*(n-1), C_m(n)/N_m(n)\}$. In addition, as n goes to infinity this scheme makes ω_m converge to ω^*_m that is the fixed point of the function $\Upsilon_m(x)$ given by

$$\Upsilon_m(x) = \frac{q_{m,0}(x) C_m(x)}{\mu c_{\min}} \left(\sum_{k \in \mathcal{M}\setminus m} \lambda_k \omega_k + \lambda_m x \right). \tag{19}$$

Proof: Please see the proof of Theorem 4 in [12]. ■

Since a tier-m AP can estimate $R_{\mathsf{L}_m}(n)$ and $R_{\mathsf{U}_m}(n)$ and other parameters in (18) are locally available to the AP, the scheme in (18) can be easily implemented by the AP. Function $\Upsilon_m(x)$ in (19) can help us roughly determine the initial value $\omega_m(0)$ of $\omega_m(n)$ provided that each tier-m AP initially knows all other ω_k's and this would shorten the process of $\omega_m(n)$ converging to ω^*_m. Note that in general the per-user throughput achieved by the scheme in (18) in the steady state is just a suboptimal result because other $M-1$ parameters $\{\omega_k, k \in \mathcal{M}\setminus m\}$ are not optimized. We will implement this decentralized traffic management scheme and present its throughput performance in the following section of numerical results.

TABLE I
NETWORK PARAMETERS FOR SIMULATION

AP Type (Tier #)	Macro (1)	Pico (2)	Femto (3)	WiFi (4)
Power P_m (W)	20	1	0.2	0.1
Intensity λ_m	5×10^{-6}	$10\lambda_1$	$50\lambda_1$	$100\lambda_1$
Backoff Time τ_m	∞	2		1
$\mathcal{S}_m$ (m^2)	N/A	900π		
CSMA Threshold δ	N/A	4.481		
Chanel Gain $H_{m,i}$	$\sim \exp(1,1)\times \ln\mathcal{N}(0,3(\text{dB}))$			
Bandwidth B_{U}	160 MHz			
Bandwidth B_{L}	100 MHz			
Pathloss Exponent α	4			
User Intensity μ	500 (users/Km^2)			

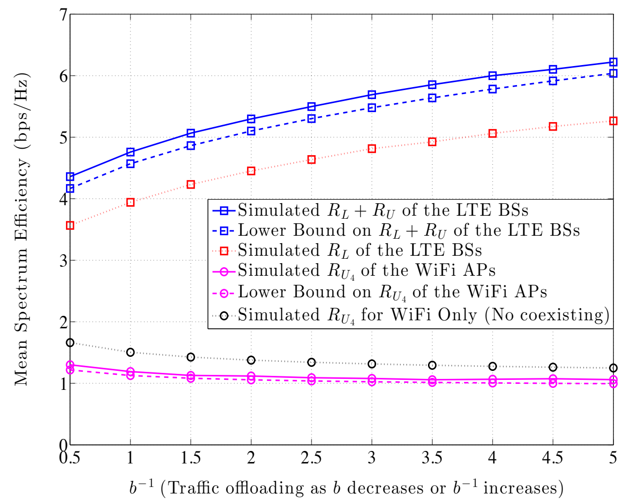

Fig. 1. Simulation results of the mean spectrum efficiencies in licensed and unlicensed spectra.

V. Numerical Example for Coexisting LTE and WiFi Networks

In this section, we provide some numerical results by simulating a scenario that there are four tiers in the HetNet consisting of LTE BSs and WiFi APs. All the network parameters for simulation are listed in Table I. The BSs and APs in the last three tiers use the opportunistic CSMA/CA protocol to access the unlicensed spectrum. All users adopt the BMSA scheme defined in Section II to associate their serving BSs or APs. Specifically, the AP association weight in Scheme (3) for the BSs in the first three tiers is designated as $W_{m,i} = bP_m H^{(s)}_{m,i}$ for $m \in \{1, 2, 3\}$ in which $b > 0$ is a constant bias and $H^{(s)}_{m,i}$ characterizes the channel gain due to log-normal shadowing, whereas the AP association weight for the WiFi APs in the fourth tier is $W_{4_i} = H^{(s)}_{4_i}$, i.e., adopting the unbiased MSA scheme. Note that we have $\omega_m = (bP_m \mathbb{E}[H^{(s)}_m])^{\frac{2}{\alpha}}$ for $m \in \{1, 2, 3\}$ and $\omega_4 = (P_4 \mathbb{E}[H^{(s)}_4])^{\frac{2}{\alpha}}$.

The simulation results of the mean spectrum efficiencies in the licensed and unlicensed spectra are shown in Fig. 1. Since all BSs in the first three tiers use the BMSA scheme with the same bias, their mean spectrum efficiencies in the licensed spectrum are the same, i.e., $R_{\mathsf{L}_1} = R_{\mathsf{L}_2} = R_{\mathsf{L}_3} = R_{\mathsf{L}}$.

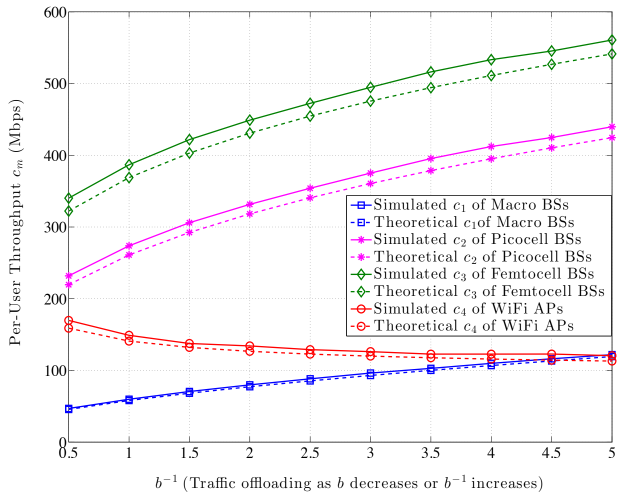

Fig. 2. Simulation results of the per-user throughputs of the BSs and APs in the four different tiers.

Also, note that $R_{\mathsf{U}_1} = 0$ since macro BSs do not access the unlicensed spectrum, and the BSs in the second and third tiers have the same spectrum efficiency in the unlicensed spectrum, i.e., $R_{\mathsf{U}_2} = R_{\mathsf{U}_3} = R_{\mathsf{U}}$, because they have the same channel access probability in the unlicensed spectrum. As a result, the BSs in the second and third tiers have the same sum of the mean spectrum efficiencies in the licensed and unlicensed spectra, i.e., $R_{\mathsf{L}} + R_{\mathsf{U}}$. From Fig. 1, we can gain a few important observations. First, the theoretical lower bound on $R_{\mathsf{L}} + R_{\mathsf{U}}$ is very tight to the simulated result of $R_{\mathsf{L}} + R_{\mathsf{U}}$, and the lower bound on R_{U_4} is also very close to the simulated result of R_{U_4}. Thus, the derived lower bounds in (6) and (10) are fairly tight. Second, when LTE BSs offload their traffic, R_{L} significantly increases and R_{U} slightly increases so that $R_{\mathsf{L}} + R_{\mathsf{U}}$ significantly increases, as expected, whereas the mean spectrum efficiency R_{U_4} of the WiFi APs just slightly reduces. Hence, letting LTE small cell BSs and WiFi APs coexist and them share the unlicensed spectrum indeed improves their total mean spectrum efficiency in the unlicensed spectrum. Third, since the mean spectrum efficiency of the WiFi APs just slightly reduces as more traffic is offloaded from the LTE network to the WiFi network, offloading the traffic from the LTE network to the WiFi network is the best traffic management strategy for the BSs in this network setting.

The simulation results of the per-user throughputs of the APs in the four different tiers are shown in Fig. 2 when the decentralized traffic management scheme in (18) is performed. The minimum required per-user throughput of an WiFi AP is $c_{\min} = 100$ Mbps. Initially, the unlicensed per-user throughput of the WiFi APs is much higher than $c_{\min}$ so that all BSs start to offload their traffic as shown in Fig. 2. As can be seen, offloading traffic from the LTE network to the WiFi network largely improves the per-user throughput of the LTE BSs since $\frac{\partial c_m}{\partial \omega_m} < 0$ holds in this context. Although the per-user throughput of the WiFi APs also reduces, the throughput loss of the WiFi APs is actually not much. Accordingly, *offloading the traffic from LTE to WiFi as much as possible can significantly benefit the per-user throughput of the LTE BSs as long as* $\frac{\partial c_m}{\partial \omega_m} < 0$ *holds and the required per-user throughput of the WiFi APs is maintained*. However, we should notice that offloading too much traffic from the LTE network to the WiFi network could eventually give rise to the reduction in c_m since R_{L_m} and R_{U_m} both could reduce in this case.

VI. Conclusion

In this paper, we consider an M-tier HetHet in which all APs in any particular tier form an independent PPP and the APs in the first $M-1$ tiers can simultaneously access the licensed spectrum and use the opportunistic CSMA/CA protocol to share the unlicensed spectrum with the APs in the Mth tier. A novel approach is devised to find the tight lower bounds on the mean spectrum efficiencies of an AP in the licensed and unlicensed spectra for any general channel gain and AP association weight models. The per-user throughput of an AP proposed is used to develop the decentralized traffic management scheme that is shown to have the capability of maximizing the per-user throughput of an AP under the constraint posed on the per-user throughput of the tier-M APs.

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