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Resource Optimization for Joint LWA and LTE-U in Load-coupled and Multi-Cell Networks

Bolin Chen, Lei You, Di Yuan, Nikolaos Pappas, and Jie Zhang

Abstract—We consider performance optimization of multi-cell networks with LTE and Wi-Fi aggregation (LWA) and LTE-unlicensed (LTE-U) with sharing of the unlicensed band. Theoretical results are derived to enable an algorithm to approach the optimum. Numerical results show the algorithm's effectiveness and benefits of joint use of LWA and LTE-U.

Index Terms—LTE and Wi-Fi aggregation, unlicensed LTE, spectrum sharing, coexistence of LTE and Wi-Fi, multi-cell

I. INTRODUCTION

Offloading traffic to the unlicensed spectrum is a recent trend [1]. Two approaches for Long Term Evolution (LTE) are data offloading to Wi-Fi via LTE and Wi-Fi aggregation (LWA) [2] and LTE-unlicensed (LTE-U) with sharing of unlicensed bands occupied by Wi-Fi [3]. Existing works have addressed separately LWA or LTE-U. Motivated by this, we consider performance optimization with joint LWA and LTE-U.

With multi-cell LTE, interference is present. Reference [4] uses stochastic geometry to model the inter-cell interference. Hence the results do not apply for analyzing networks with specific given topology. Resource allocation for joint LWA and LTE-U in multi-cell networks without restrictions on network topology has not been addressed yet.

Another mathematical characterization for interference modeling is the load-coupling model [5], which enables the network-wise performance evaluation with arbitrary network topology. The load of a cell is defined to be the proportion of consumed time-frequency resources, and its value is used as the severity of generated interference. This model has been widely used [6], [7]. It has been verified in [7] through system level simulations that this model is sufficiently accurate for multi-cell network performance analysis. However, the properties of load-coupling when the amount of resource is variable have not been studied. Applying the solution approaches proposed by literature [6], [7] to the scenario with spectrum sharing guarantees neither feasibility nor optimality.

The main contributions of this work are summarized as follows. We present a new system framework for capacity optimization in Wi-Fi and load-coupled LTE networks, where LWA and LTE-U are jointly used. The novelties consist in both data aggregation by LWA as well as spectrum sharing by LTE-U. Given a base data demand of the users, the optimization task is to maximize the common scaling factor [6], via optimizing the spectrum sharing of LTE and Wi-Fi, while accounting for the resource limits as well interference. We provide theoretical analysis, resulting in an algorithm that achieves global optimality. We can effectively use numerical results to characterize the gain by joint LWA and LTE-U.

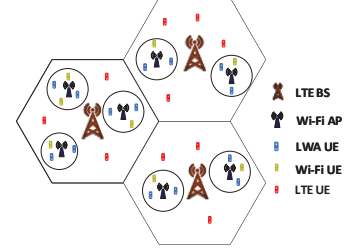


Fig. 1. System model for LTE-U and LWA.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. Network Model

As illustrated in Fig. 1, we consider a scenario with I LTE base stations (BSs), $\mathcal{I} = \{1, 2, \dots, I\}$, and H Wi-Fi APs, $\mathcal{H} = \{1, 2, \dots, H\}$. There can be one or multiple Wi-Fi APs inside an LTE cell. The coverage areas of the Wi-Fi APs are non-overlapping, and thus there is no interference among the APs. The Wi-Fi network deploys the IEEE 802.11ax protocol, and operates in the 5 GHz unlicensed band. The IEEE 802.11ax Task Group has defined the uplink and downlink orthogonal frequency division multiple access (OFDMA) [8]. In the conventional Wi-Fi setup, e.g., IEEE 802.11n, the capacity can be analyzed using a discrete-time Markov chain (DTMC) model, e.g., [9]. The DTMC model does not consider the actual signal-to-interference-and-noise ratio (SINR), which is a key parameter in case of OFDMA. There are J^{LTE} LTE user equipments (UEs), forming set $\mathcal{J}^{\text{LTE}} = \{1, 2, \dots, J^{\text{LTE}}\}$. The UE group served by BS $i \in \mathcal{I}$ is denoted by $\mathcal{J}_i^{\text{LTE}}$. All LTE UEs are able to aggregate LTE and Wi-Fi traffic. An LTE UE is served by an LTE BS and a Wi-Fi AP by LWA, if it is in the coverage area of the latter. The LTE UE group covered by the h -th Wi-Fi AP is denoted by $\mathcal{J}_h^{\text{LTE}}$. There also exist native Wi-Fi UEs, i.e., UEs served by Wi-Fi only. This UE set is denoted by $\mathcal{J}_h^{\text{Wi-Fi}}$ for AP h .

By LTE-U, LTE can share the unlicensed band with Wi-Fi via an inter-system coordinator [10]. Channel access schemes to deal with LTE and Wi-Fi coexistence are based on duty-cycle or listen-before-talk (LBT) [1]. The duty-cycle method is employed here. The unlicensed band is periodically divided into two time periods among LTE and Wi-Fi. The term $\theta \in [0, 1)$ represents the proportion of unlicensed band allocated for LTE, and links together LTE and Wi-Fi. The residual $1 - \theta$ is for Wi-Fi. The presence of Wi-Fi native UEs implies $\theta < 1$. The minimum unit for both LTE and Wi-Fi resource allocation is referred to as resource unit (RU). Denote by M^{L} and M^{U} the number of RUs in licensed and unlicensed bands, respectively.

B. LTE Load Coupling

For LTE, we use ρ_i to denote the fraction of RU consumption in cell i , used for serving UEs, also referred to as cell load. The network-wise load vector is $\boldsymbol{\rho} = (\rho_1, \rho_2, \dots, \rho_I)^T$. In the load-coupling model [5], the SINR at UE $j \in \mathcal{J}_i^{\text{LTE}}$ is

$$\gamma_j(\boldsymbol{\rho}) = \frac{p_i g_{ij}}{\sum_{k \in \mathcal{I} \setminus \{i\}} p_k g_{kj} \rho_k + \sigma^2}. \quad (1)$$

Here, p_i is the transmit power per RU of BS i , g_{ij} is the power gain between cell i and UE j , and the term σ^2 refers to the noise power. Note that g_{kj} , $k \neq i$, represents the power gain from the interfering BSs. For any RU in cell i , ρ_k is intuitively interpreted as the likelihood that the served UEs of cell i receive interference from k . The term $\sum_{k \in \mathcal{I} \setminus \{i\}} p_k g_{kj} \rho_k$ is interpreted as the interference that UE j experiences.

For UE $j \in \mathcal{J}^{\text{LTE}}$, the data rate achieved, if all the $M^{\text{L}} + \theta M^{\text{U}}$ LTE RUs are given to j , is expressed below, where B denotes one RU's bandwidth.

$$C_j^{\text{LTE}}(\boldsymbol{\rho}, \theta) = (M^{\text{L}} + \theta M^{\text{U}}) B \log_2(1 + \gamma_j(\boldsymbol{\rho})). \quad (2)$$

Denote by r_j the baseline demand of UE j . We would like to scale up r_j by a demand scaling factor $\alpha > 0$. The physical meaning of α will be discussed in Section II-D. If j is served by LTE only, then $\alpha r_j / C_j^{\text{LTE}}(\boldsymbol{\rho}, \theta)$ gives the proportion of required LTE RUs for satisfying αr_j . If j is served by both systems, we use coefficient β_j ($\beta_j \in [0, 1]$) to denote the proportion of demand to be delivered by LTE. This coefficient can be set via for example a look-up table based on the relative signal strengths of the two systems¹. The proportion of required LTE RUs for satisfying the (scaled) demand is $\alpha r_j \beta_j / C_j^{\text{LTE}}(\boldsymbol{\rho}, \theta)$. The required proportion of RUs by cell i to meet the (scaled) demand of UE j reads

$$f_{ij}(\boldsymbol{\rho}, \theta, \alpha) = \begin{cases} \frac{\alpha r_j \beta_j}{C_j^{\text{LTE}}(\boldsymbol{\rho}, \theta)}, \forall j \in \mathcal{J}_h^{\text{LTE}}, h \in \mathcal{H} \\ \frac{\alpha r_j}{C_j^{\text{LTE}}(\boldsymbol{\rho}, \theta)}, \forall j \in \mathcal{J}^{\text{LTE}} \setminus \cup_{h \in \mathcal{H}} \mathcal{J}_h^{\text{LTE}}. \end{cases} \quad (3)$$

The sum of (3) over cell i 's UEs gives the following function for cell i , which we also present in vector form for the network.

$$\mathbf{f}_i(\boldsymbol{\rho}, \theta, \alpha) = \sum_{j \in \mathcal{J}_i^{\text{LTE}}} f_{ij}(\boldsymbol{\rho}, \theta, \alpha), \quad (4)$$

$$\mathbf{f}(\boldsymbol{\rho}, \theta, \alpha) = [\mathbf{f}_1(\boldsymbol{\rho}, \theta, \alpha), \mathbf{f}_2(\boldsymbol{\rho}, \theta, \alpha), \dots, \mathbf{f}_I(\boldsymbol{\rho}, \theta, \alpha)]. \quad (5)$$

Given θ and α , $\mathbf{f}(\boldsymbol{\rho})$ is a standard interference function (SIF). Denote by \mathbf{f}^k ($k > 1$) the function composition of $\mathbf{f}(\mathbf{f}^{k-1}(\boldsymbol{\rho}))$ (with $\mathbf{f}^0(\boldsymbol{\rho}) = \boldsymbol{\rho}$). If $\lim_{k \rightarrow \infty} \mathbf{f}^k(\boldsymbol{\rho})$ exists, it is unique. Let ρ_{ij} represent the proportion of RUs allocated to UE j by j 's serving cell i . The load of any cell $i \in \mathcal{I}$ is $\rho_i = \sum_{j \in \mathcal{J}_i^{\text{LTE}}} \rho_{ij}$. The load-coupling model reads $\rho_i = \mathbf{f}_i(\boldsymbol{\rho}, \theta, \alpha)$, $\forall i$. This model leads to a non-linear equation system. In particular, the load vector $\boldsymbol{\rho}$ appears in both sides

¹Our work focuses on network level resource allocation with spectrum sharing. An extension is to consider β_j as optimization variable as well. However, this changes the problem scope – optimization is then at the level of individual UEs. Moreover, a much larger amount of control overhead will be involved to communicate the optimization results to all individual UEs.

of the equation and cannot be readily solved in closed form, since the load ρ_i for cell i affects the load ρ_k of other cells $k \neq i$, which would in turn affect the load ρ_i . Therefore, analysis using the load-coupling model is not straightforward.

C. Rate and Resource Characterization for Wi-Fi

For Wi-Fi, the counterpart of (3) for UE j of AP h reads

$$m_{hj}(\theta, \alpha) = \begin{cases} \frac{\alpha r_j (1 - \beta_j)}{C_j^{\text{Wi-Fi}}(\theta)}, \forall j \in \mathcal{J}_h^{\text{LTE}}, h \in \mathcal{H} \\ \frac{\alpha r_j}{C_j^{\text{Wi-Fi}}(\theta)}, \forall j \in \mathcal{J}_h^{\text{Wi-Fi}}, h \in \mathcal{H} \end{cases} \quad (6)$$

where $C_j^{\text{Wi-Fi}}(\theta) = (1 - \theta) M^{\text{U}} B \log(1 + \frac{p_h g_{hj}}{\sigma^2})$, with $(1 - \theta) M^{\text{U}}$ being the total number of Wi-Fi RUs. The terms p_h and g_{hj} denote the transmit power per RU of AP h and the power gain between AP h and UE j , respectively. Based on (6), we define the following entities of required resource consumption.

$$m_h(\theta, \alpha) = \sum_{j \in \mathcal{J}_h^{\text{LTE}} \cup \mathcal{J}_h^{\text{Wi-Fi}}} m_{hj}(\theta, \alpha). \quad (7)$$

$$\mathbf{m}(\theta, \alpha) = [m_1(\theta, \alpha), m_2(\theta, \alpha), \dots, m_H(\theta, \alpha)]. \quad (8)$$

Let x_{hj} denote the proportion of RUs allocated to UE j . The load of AP h is $x_h = \sum_{j \in \mathcal{J}_h^{\text{LTE}} \cup \mathcal{J}_h^{\text{Wi-Fi}}} x_{hj}$, $\forall h \in \mathcal{H}$. The values of x_h is bounded by x_h^{max} . Moreover, to meet the demand requirement, $x_h = m_h(\theta, \alpha)$. We define $\mathbf{x} = (x_1, x_2, \dots, x_H)^T$.

D. Problem Formulation

Given a base demand distribution, the maximum demand scaling factor α shows how much demand increase can still be accommodated by the network. In this sense, the largest possible α tells the network's capability of handling the increase in demand by optimizing spectrum sharing between LTE and Wi-Fi. The optimization problem is formalized as

$$\alpha' = \max_{\theta, \boldsymbol{\rho}, \mathbf{x}} \alpha \quad (9a)$$

$$\text{s.t. } \boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, \alpha), \mathbf{x} = \mathbf{m}(\theta, \alpha) \quad (9b)$$

$$\boldsymbol{\rho} \leq \boldsymbol{\rho}^{\text{max}}, \mathbf{x} \leq \mathbf{x}^{\text{max}}, \theta \in [0, 1] \quad (9c)$$

The objective is to maximize α , which is the satisfaction ratio of the UE demands. Given the baseline demand and the resource limit, the solution obtained by solving (11) is the maximum achievable ratio of r_j with the resource limit. Namely, $\alpha' \geq 1$ if r_j can be satisfied, as otherwise the network is overloaded. Constraint (9b) ensures that sufficient amount of RUs are allocated to deliver the UE's demands, taking into account α . Constraint (9c) imposes the resource limits, and the range of θ . The resource limit is assumed to be uniform.

III. SOLUTION APPROACH

Consider first maximum demand scaling for LTE and Wi-Fi separately. For each of the two systems, demand scaling is performed for its native UEs' demand and the demand proportions, $r_j \beta_j$ or $r_j (1 - \beta_j)$, for any UE j served by both systems. Denote the corresponding optimal values for θ by

$\alpha^{\text{LTE}}(\theta)$ and $\alpha^{\text{WiFi}}(\theta)$, respectively. The definition of $\alpha^{\text{LTE}}(\theta)$ is given below, and $\alpha^{\text{WiFi}}(\theta)$ is defined similarly for Wi-Fi.

$$\alpha^{\text{LTE}}(\theta) = \max_{\boldsymbol{\rho}} \alpha \text{ s.t. } \boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, \alpha), \boldsymbol{\rho} \leq \boldsymbol{\rho}^{\max} \quad (10)$$

Let $\alpha^*(\theta)$ represent the optimum of (9) for θ .

Lemma 1. $\alpha^*(\theta) = \min\{\alpha^{\text{LTE}}(\theta), \alpha^{\text{WiFi}}(\theta)\}$.

Proof: First, $\min\{\alpha^{\text{LTE}}(\theta), \alpha^{\text{WiFi}}(\theta)\}$ obviously gives a feasible α of (9) for θ , thus $\alpha^*(\theta) \geq \min\{\alpha^{\text{LTE}}(\theta), \alpha^{\text{WiFi}}(\theta)\}$. Next, by definition, for any UE j served by both LTE and Wi-Fi, the scaled demand served by LTE is $\alpha^*(\theta)r_j\beta_j$ and that by Wi-Fi is $\alpha^*(\theta)r_j(1 - \beta_j)$, at the optimum of (9) for θ . Moreover, the achieved scaling for all Wi-Fi native users is $\alpha^*(\theta)$. Hence $\alpha^*(\theta)$ is achievable when Wi-Fi is considered separately, giving $\alpha^*(\theta) \leq \alpha^{\text{WiFi}}(\theta)$. Similarly, $\alpha^*(\theta) \leq \alpha^{\text{LTE}}(\theta)$. Therefore $\alpha^*(\theta) \leq \min\{\alpha^{\text{LTE}}(\theta), \alpha^{\text{WiFi}}(\theta)\}$, and the result follows. ■

Next, we address the computation of $\alpha^{\text{LTE}}(\theta)$ and $\alpha^{\text{WiFi}}(\theta)$. For LTE, denote by $\boldsymbol{\rho}^*$ the optimal load vector, for which $\alpha^{\text{LTE}}(\theta)$ is achieved. At least one element of $\boldsymbol{\rho}^*$ equals ρ^{\max} , as otherwise all cells have spare resource and $\alpha^{\text{LTE}}(\theta)$ would not be optimal. The condition can be stated as $\|\boldsymbol{\rho}\|_{\infty} = \rho^{\max}$, where $\|\cdot\|_{\infty}$ is the maximum norm. All functions in $\mathbf{f}(\boldsymbol{\rho}, \theta, \alpha)$ are strictly concave in $\boldsymbol{\rho}$ for $\boldsymbol{\rho} \geq 0$ [5]. As \mathbf{f} is linear in α , $\frac{1}{\alpha}\boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, 1)$ is equivalent to $\boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, \alpha)$. Moreover, $\|\cdot\|_{\infty}$ is monotone. Thus, the system $\{\|\boldsymbol{\rho}\|_{\infty} = \rho^{\max}, \frac{1}{\alpha}\boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, 1), \boldsymbol{\rho} \in \mathbb{R}_+^I\}$ is a conditional eigenvalue problem for concave mapping. This can be solved using normalized fixed point iteration [6]. Given $\boldsymbol{\rho}^k$ ($k \geq 0$) and any $\boldsymbol{\rho}^0 \in \mathbb{R}_+^I$, one such iteration computes the next iterate $\boldsymbol{\rho}^{k+1}$ by $\boldsymbol{\rho}^{k+1} = \rho^{\max}\mathbf{f}(\boldsymbol{\rho}^k, \theta, 1)/\|\boldsymbol{\rho}^k\|_{\infty}$, and, if $\lim_{k \rightarrow \infty} \rho^{\max}\mathbf{f}(\boldsymbol{\rho}^k, \theta, 1)/\|\boldsymbol{\rho}^k\|_{\infty}$ exists, the sequence $\boldsymbol{\rho}^0, \boldsymbol{\rho}^1, \dots$, converges to $\boldsymbol{\rho}^*$ which is unique. Moreover, equality holds for all rows of $\frac{1}{\alpha}\boldsymbol{\rho} = \mathbf{f}(\boldsymbol{\rho}, \theta, 1)$. Thus $\alpha^{\text{LTE}}(\theta)$ is

$$\alpha^{\text{LTE}}(\theta) = \rho_i^*/f_i(\boldsymbol{\rho}^*, \theta, 1), \forall i \in \mathcal{I}. \quad (11)$$

Lemma 2. $\alpha^{\text{LTE}}(\theta)$ is continuous and monotonically increasing in θ .

Proof: Given any $\theta \in [0, 1)$, denote the optimal solution of (10) by $\dot{\boldsymbol{\rho}}$. Consider $\theta' \geq \theta$. By (3) and (4), $\mathbf{f}(\dot{\boldsymbol{\rho}}, \theta, \alpha^{\text{LTE}}(\theta)) \geq \mathbf{f}(\dot{\boldsymbol{\rho}}, \theta', \alpha^{\text{LTE}}(\theta))$. Hence $\dot{\boldsymbol{\rho}}$ along with θ' is feasible to (10), and by (3) and (4) it leads to the objective no smaller than $\alpha^{\text{LTE}}(\theta)$, thus, $\alpha^{\text{LTE}}(\theta) \leq \alpha^{\text{LTE}}(\theta')$, hence monotonicity follows. We then prove continuity. By (3) and (4), for any sufficiently small positive number ε , there exists $\boldsymbol{\delta} = (\delta_1, \delta_2, \dots, \delta_I)^T$, such that $f_i(\dot{\boldsymbol{\rho}}, \theta, \alpha^{\text{LTE}}(\theta)) = f_i(\dot{\boldsymbol{\rho}}, \theta - \delta_i, \alpha^{\text{LTE}}(\theta) - \varepsilon)$, $\forall i \in \mathcal{I}$. Let $\delta_{\min} = \min_{i \in \mathcal{I}} \delta_i$, we have $f_i(\dot{\boldsymbol{\rho}}, \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon) \leq f_i(\dot{\boldsymbol{\rho}}, \theta - \delta_i, \alpha^{\text{LTE}}(\theta) - \varepsilon) = f_i(\dot{\boldsymbol{\rho}}, \theta, \alpha^{\text{LTE}}(\theta))$, $\forall i \in \mathcal{I}$. Since $\mathbf{f}(\dot{\boldsymbol{\rho}}, \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon) \leq \mathbf{f}(\dot{\boldsymbol{\rho}}, \theta, \alpha^{\text{LTE}}(\theta)) = \dot{\boldsymbol{\rho}}$, we have $\mathbf{f}^{k+1}(\dot{\boldsymbol{\rho}}, \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon) \leq \mathbf{f}^k(\dot{\boldsymbol{\rho}}, \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon)$, $\forall k \geq 0$. Let $\boldsymbol{\rho}' = \lim_{k \rightarrow \infty} \mathbf{f}^k(\dot{\boldsymbol{\rho}}, \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon)$. At convergence, $\boldsymbol{\rho}' = \mathbf{f}(\boldsymbol{\rho}', \theta - \delta_{\min}, \alpha^{\text{LTE}}(\theta) - \varepsilon) \leq \dot{\boldsymbol{\rho}}$. Hence $\boldsymbol{\rho}'$ along with $\theta - \delta_{\min}$ is feasible to (10) and leads to $\alpha^{\text{LTE}}(\theta) - \varepsilon$, thus $\alpha^{\text{LTE}}(\theta - \delta_{\min}) \geq \alpha^{\text{LTE}}(\theta) - \varepsilon$. Similarly, $\alpha^{\text{LTE}}(\theta + \delta_{\min}) \leq \alpha^{\text{LTE}}(\theta) + \varepsilon$. By the monotonicity, for any θ' with $\theta - \delta_{\min} < \theta' < \theta + \delta_{\min}$,

$\alpha^{\text{LTE}}(\theta) - \varepsilon < \alpha^{\text{LTE}}(\theta') < \alpha^{\text{LTE}}(\theta) + \varepsilon$, proving continuity. Hence the conclusion follows. ■

For Wi-Fi, since the APs do not overlap and there is no interference among them, maximum demand scaling within each AP can be studied independently, and the bottleneck AP with the smallest achievable scaling factor gives $\alpha^{\text{WiFi}}(\theta)$. Denote by $\alpha_h^{\text{WiFi}}(\theta)$ the value for AP h , $\forall h \in \mathcal{H}$, we have

$$\alpha^{\text{WiFi}}(\theta) = \min\{\alpha_1^{\text{WiFi}}(\theta), \alpha_2^{\text{WiFi}}(\theta), \dots, \alpha_H^{\text{WiFi}}(\theta)\}. \quad (12)$$

Consider $m_h(\theta, \alpha)$. From (6) and (7), $m_h(\theta, \alpha)$ is linearly increasing in α . Thus $m_h(\theta, \alpha_h^{\text{WiFi}}) = x^{\max}$ for $h \in \mathcal{H}$, as otherwise $\alpha_h^{\text{WiFi}}(\theta)$ can be increased further. This with the linearity implies that $\alpha_h^{\text{WiFi}}(\theta)$ is the ratio between the amount of available resource and the required resource consumption by the baseline demand with $\alpha = 1$, i.e., $\alpha_h^{\text{WiFi}}(\theta) = x^{\max}/m_h(\theta, 1)$.

By (6) and (12), $\alpha^{\text{WiFi}}(\theta)$ is linearly decreasing in θ . This with Lemma 2 shows that at most one intersection point of $\alpha^{\text{WiFi}}(\theta)$ and $\alpha^{\text{LTE}}(\theta)$ exists, yielding the following result.

Theorem 3. The optimum of (9) is the intersection point of $\alpha^{\text{WiFi}}(\theta)$ and $\alpha^{\text{LTE}}(\theta)$ if $\alpha^{\text{WiFi}}(0) \geq \alpha^{\text{LTE}}(0)$. Otherwise the optimum is $\alpha^{\text{WiFi}}(0)$.

Proof: By (6), (7) and (12), $\lim_{\theta \rightarrow 1} \alpha^{\text{WiFi}}(\theta) = 0$. By Lemma 2, $\lim_{\theta \rightarrow 1} \alpha^{\text{LTE}}(\theta) > 0$, i.e., $\lim_{\theta \rightarrow 1} \alpha^{\text{LTE}}(\theta) > \lim_{\theta \rightarrow 1} \alpha^{\text{WiFi}}(\theta)$. If $\alpha^{\text{WiFi}}(0) \geq \alpha^{\text{LTE}}(0)$, there exists a point where $\alpha^{\text{WiFi}}(\theta)$ and $\alpha^{\text{LTE}}(\theta)$ intersect. This point is the optimum α of (9) by Lemma 1. Otherwise, if $\alpha^{\text{WiFi}}(0) < \alpha^{\text{LTE}}(0)$, no intersection point exists. The optimum is $\min\{\alpha^{\text{LTE}}(0), \alpha^{\text{WiFi}}(0)\}$, i.e., $\alpha^{\text{WiFi}}(0)$ due to Lemma 1. Hence the result. ■

Algorithm 1 Maximum demand scaling

Input: $\check{\theta}, \hat{\theta}, \epsilon_{\theta}$

- 1: $\theta \leftarrow 0, \check{\theta} \leftarrow 0, \hat{\theta} \leftarrow 1$
- 2: Compute $\alpha^{\text{LTE}}(\theta)$ by (11) and $\alpha^{\text{WiFi}}(\theta)$ by (12)
- 3: **if** $\alpha^{\text{WiFi}}(\theta) \geq \alpha^{\text{LTE}}(\theta)$ **then**
- 4: **repeat**
- 5: $\theta \leftarrow (\check{\theta} + \hat{\theta})/2$
- 6: Compute $\alpha^{\text{LTE}}(\theta)$ and $\alpha^{\text{WiFi}}(\theta)$
- 7: **if** $\alpha^{\text{WiFi}}(\theta) \geq \alpha^{\text{LTE}}(\theta)$ **then**
- 8: $\check{\theta} \leftarrow \theta$
- 9: **if** $\alpha^{\text{WiFi}}(\theta) < \alpha^{\text{LTE}}(\theta)$ **then**
- 10: $\hat{\theta} \leftarrow \theta$
- 11: **until** $\hat{\theta} - \check{\theta} \leq \epsilon_{\theta}$

return $\alpha^{\text{WiFi}}(\theta)$

By the theoretical results, we present Algorithm 1 for solving (9). If $\alpha^{\text{WiFi}}(0) < \alpha^{\text{LTE}}(0)$, then $\alpha^{\text{WiFi}}(0)$ is the optimum. Otherwise a bi-section search of θ is performed, where ϵ_{θ} is the accuracy tolerance. Note that in Line 6, while computing $\alpha^{\text{LTE}}(\theta)$, by (11), $\boldsymbol{\rho}^*$ needs to be calculated first.

IV. SIMULATION RESULTS

The network consists of seven LTE cells. In each cell, five APs are randomly and uniformly distributed. The ranges of a BS and AP are 500 m and 50 m, respectively. Each AP serves two native Wi-Fi UEs located randomly within the range. For

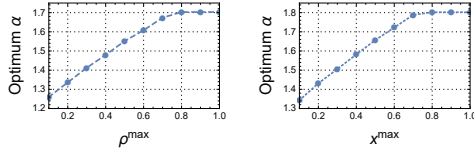


Fig. 2. Optimum α with respect to ρ^{\max} and x^{\max} .

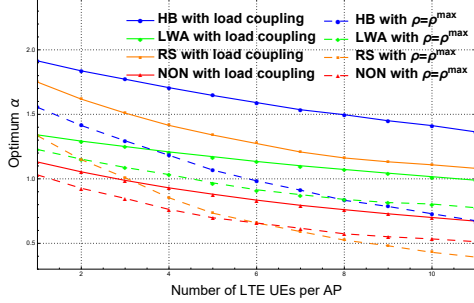


Fig. 3. Optimum α with respect to the number of LTE UEs per Wi-Fi AP.

every LTE cell, the UEs are of two groups. One consists of LWA UEs, served by both Wi-Fi and LTE simultaneously. The other group consists of 30 native LTE UEs. Both licensed and unlicensed spectrum have a bandwidth of 20 MHz. The transmit power per RU for LTE and Wi-Fi are 200 mW and 20 mW, respectively. The noise power spectral density is -174 dBm/Hz. The simulation settings follow the 3GPP and IEEE 802.11ax standardization [2], [8]. For any LWA UE, the demand split coefficient $\beta = 0.4$. The path loss follows the COST-231-HATA model. The shadowing coefficients are generated by the log-normal distribution with 6 dB and 3 dB standard deviation for LTE and Wi-Fi, respectively. The simulations have been averaged over 1000 realizations.

We refer to HB as the proposed hybrid method with both offloading via LWA and sharing of unlicensed spectrum. RS stands for using spectrum sharing only; this is equivalent to setting $\beta = 0$. LWA can be regarded as a special case of HB with demand split but no spectrum sharing ($\theta = 0$). Finally, NON is the baseline scheme with no demand split nor spectrum sharing. Fig. 2 illustrates the optimum α with respect to ρ^{\max} and x^{\max} . As expected, with ρ^{\max} or x^{\max} increasing, the maximum α increases at first, then saturates, i.e., one of Wi-Fi and LTE will be the bottleneck. Fig. 3 shows the capacity in the achievable maximum scaling α with respect to the number of LTE UEs per AP. Compared to the worst case (i.e., $\rho = \rho^{\max}$), the load coupling model gives a more realistic picture. In particular, the maximum demand scaling with load coupling is considerably higher compared to the worst case. For HB and LWA, the optimal α value is given by Algorithm 1. For RS and NON, the optimum is $\min\{\alpha^{\text{LTE}}(0), \alpha^{\text{WiFi}}(0)\}$. From the figure, HB, RS, and LWA all outperform the baseline scheme NON. Note that HB has a clear effect of leveraging synergy of LWA and spectrum sharing, showing clearly better performance than LWA and RS. One benefit of having $\beta > 0$, which is the case of HB, is the reduction of interference in the LTE network, and this is particularly beneficial if the system is interference limited. Moreover, RS performs better than LWA, indicating the lack of spectrum is a bottleneck (for

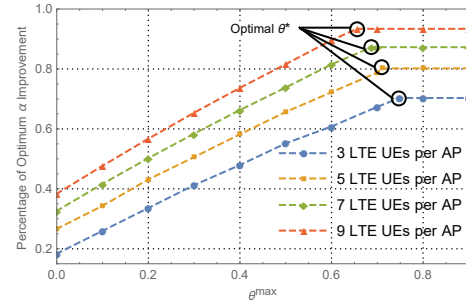


Fig. 4. Percentage improvement of HB over NON in respect of available θ .

the LTE native UEs). Furthermore, the advantage of LWA is more obvious in denser user regime, where more UEs could be served by LTE and Wi-Fi simultaneously.

Fig. 4 reveals the impact of the amount of unlicensed spectrum made available to LTE. We introduce θ^{\max} and require $\theta \leq \theta^{\max}$. The vertical axis represents the percentage improvement of HB over NON, and can be computed by $\frac{\alpha' - \min\{\alpha^{\text{LTE}}(0), \alpha^{\text{WiFi}}(0)\}}{\min\{\alpha^{\text{LTE}}(0), \alpha^{\text{WiFi}}(0)\}}$. From the figure, θ^{\max} has a clear effect on performance. The improvement curves are approximately linear, until θ^{\max} reaches θ^* , after which the curves become flat, i.e., the Wi-Fi system is now the bottleneck. Moreover, it is apparent that the optimal allocation, i.e., θ^* , varies by the number of UEs served by Wi-Fi, demonstrating the significance of the optimizing spectrum allocation when LTE-U and LWA are jointed used.

V. CONCLUSION

We have derived an optimization algorithm for the performance of adopting both LWA and LTE-U. The results demonstrate that the improvement is very significant from a capacity enhancement standpoint. A future work is to include the demand split coefficient into the optimization.

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