Cellular Meets WiFi: Traffic Offloading or Resource Sharing?

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***Abstract*—Traffic offloading and resource sharing are two common methods for delivering cellular data traffic over unlicensed bands. In this paper, we first develop a hybrid method to take full advantages of both traffic offloading and resource sharing methods, where cellular *base stations* (BSs) offload traffic to WiFi networks and simultaneously occupy certain number of time slots on unlicensed bands. Then, we analytically compare the cellular throughput of the three methods with the guarantee of WiFi per-user throughput in the single-BS scenario. We find that traffic offloading can achieve better performance than resource sharing when existing WiFi user number is below a threshold and the hybrid method achieves the same performance as the resource sharing method when existing WiFi user number is large enough. In the multi-BS scenario where the coverage of small cells and WiFi access points are mutually overlapped, we consider to maximize the minimum average per-user throughput of each small cell and derive a closed-form expression for the throughput upper bound in each method. Meanwhile, practical traffic offloading and resource sharing algorithms are also developed for the three methods, respectively. Numerical results validate our theoretical analysis and demonstrate the effectiveness of the proposed algorithms as well.**

***Index Terms*—Traffic offloading, resource sharing, coexistence of WiFi and cellular, unlicensed LTE.**

I. Introduction

THE CELLULAR data traffic has been dramatically increased in the past few years due to the explosive growth in mobile applications, putting a lot of pressure on capacity improvement of cellular networks. To deal with it, many new techniques have been introduced for *long-term evolution* (LTE) and LTE-Advanced networks, such as massive *multiple-input multiple-output* (MIMO), heterogeneous networks with small cells, direct device-to-device communications, etc. Despite these cutting-edge techniques, the limited licensed spectrum is still the principal bottleneck for capacity improvement.

To tackle this problem, several methods have been recently developed to use the unlicensed bands for delivering cellular data traffic. Among them, traffic offloading is the most common one, which offloads the data initially targeted for cellular systems to WiFi networks. However, how to guarantee the *quality-of-service* (QoS) of cellular traffic is a challenging issue since WiFi is operated in unlicensed bands and difficult to provide QoS due to the *distributed coordination function* (DCF) protocol. Moreover, the amount of the offloaded traffic should be carefully designed to avoid over saturation and excessive packet collisions in the WiFi network.

An alternative way is to directly transmit cellular signals on the unlicensed spectrum, which is known as *unlicensed LTE* (U-LTE) and will be standardized by the *3rd Generation Partnership Project* (3GPP) into its Release 13 by 2016. Since LTE is a centralized scheduling system with many advanced techniques, such as adaptive coding and modulation, dynamic resource allocation, and interference management mechanism, it can achieve a higher spectral efficiency and provide better QoS for users than the WiFi system. However, the coexistence of LTE and WiFi in the same unlicensed band becomes a major challenge and effective resource sharing strategies should be designed to provide good performance for both networks.

A. Literature Review

Mobile data offloading has been widely investigated in recent years [2]. A quantitative study on offloading cellular traffic to WiFi networks has been presented in [3]. The authors in [4] have developed a distributed cross-system learning framework to improve the cellular throughput by offloading delay-tolerant traffic to WiFi networks. Various WiFi offloading algorithms have been developed to improve the system performance [5]–[7].

Besides inter-network data offloading, intra-network data offloading has also been investigated where the macro *base station* (BS) offloads traffic to femtocells. A tractable model to analyze the effects of traffic offloading has been developed for heterogeneous networks in [8]. The load balancing through user association has been investigated [9]. Economic issues of data offloading in femtocells networks have been investigated in [10] and [11], respectively.

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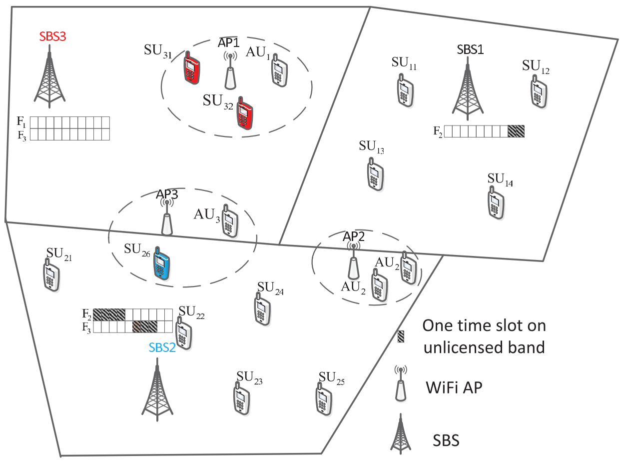


Fig. 1. System model for LTE and WiFi coexistence.

U-LTE also aroused much research interests from both industry and academia recently. The potentials and challenges associated with coexisting WiFi and heterogeneous cellular networks sharing the unlicensed spectrum have been investigated in [12]. As pointed out in [14], the WiFi performance will be significantly degraded by the presence of LTE in unlicensed bands if no adaptation is made for LTE protocols. Therefore, to fairly coexist with WiFi, the *listen-before-talk* (LBT) [15] and the duty-cycle methods [13], [14] have been developed for the U-LTE system, respectively. By a coexistence mechanism in [16], a satisfactory performance can be achieved by LTE with little impact to WiFi users. A cognitive coexistence scheme to achieve both spectral efficiency and fairness between LTE and WiFi has been developed in [17].

In U-LTE, joint radio resource management on licensed and unlicensed bands can further improve the cellular system performance [18]. In [19], a traffic balancing algorithm has been developed for the *dual band femtocell* (DBF) networks. Optimal resource allocation algorithms for both DBF and *integrated Femto-WiFi* (IFW) networks have been investigated in [20]. The energy efficiency optimization in U-LTE systems has been investigated in [21].

B. Main Results and Paper Organization

As shown in Fig. 1, in this paper, we consider a cellular system with *small cell base stations* (SBSs) coexisting with WiFi networks. Each SBS is overlapped with several WiFi *access points* (APs) and each AP is also overlapped with several SBSs. The SBSs transmit on certain licensed bands. However, they can also offload traffic to the APs overlapped with them and/or share their unlicensed bands. Existing works mentioned above have addressed only traffic offloading or resource sharing (such as unlicensed LTE), while not both of them simultaneously. Motivated by this, in this work, we jointly consider traffic offloading and resource sharing to further improve the system performance.

To avoid inter-system interference, orthogonal resource sharing is considered, which can be guaranteed by the LBT protocol or the duty-cycle method. Here, we employ the duty-cycle method, where some time slots on the unlicensed bands are occupied by the cellular system while the others are used by WiFi [13], [14]. In such a coexisting network, we will address the following three problems: 1) Traffic offloading or resource sharing, which one is better? 2) How can we jointly consider both to further improve the performance? 3) How to design traffic offloading and resource sharing algorithms to maximize the LTE performance while guaranteeing the per-user throughput of WiFi networks?

The main contributions of this work are summarized as follows.

- To further improve the performance by taking full advantages of both traffic offloading and resource sharing methods, a hybrid method is developed where SBS can offload traffic to WiFi and simultaneously occupy certain number of time slots on unlicensed bands.
- We analytically compare the LTE throughput in the three methods, namely traffic offloading, resource sharing, and the hybrid method, in the single-BS scenario with the minimum WiFi per-user throughput guaranteed. It is proved that traffic offloading outperforms resource sharing when the existing WiFi user number is below a threshold and the hybrid method achieves the same performance as the resource sharing method when the existing WiFi user number is greater than a threshold.
- In the multi-BS scenario where the coverages of SBS and APs are mutually overlapped, we consider to maximize the minimum average per-user throughput of each SBS and derive closed-form expressions for the performance upper bound of the three methods, respectively. Heuristic traffic offloading and resource sharing algorithms are also developed, and their performances are evaluated via numerical simulation. Simulation results match well with our theoretical analysis.

The rest of this paper is organized as follows. The system model and problem formulation will be presented in Section II. We will investigate the single-BS scenario and the multi-BS scenario in Section III and Section IV, respectively. Section V presents the simulation results and the whole paper is finally concluded in Section VI.

II. System Model and Problem Description

In this section, we first describe the LTE and WiFi coexistence system model and introduce the three different unlicensed spectrum utilization methods. After that, we will formulate the analytical problem for each method.

A. System Model

As illustrated in Fig. 1, we consider a scenario with M SBSs, $\mathcal{M} = \{1, 2, \cdots, M\}$, and K APs, $\mathcal{K} = \{1, 2, \cdots, K\}$. Both SBSs and APs are randomly located according to the *Poisson point process* (PPP) model. The coverage region of SBS can be modeled via an Voronoi tessellation. Denote a_{mk} as the overlapping indicator where $a_{mk} = 1$ indicates that SBS m is overlapped with AP k and $a_{mk} = 0$ otherwise. Let Φ_m denote the set of APs that have overlapping coverage with SBS m. We further assume that each SBS is allocated with B_m^{S} licensed bandwidth to serve N_m^{S} users and there are N_k^{A} users in AP k.

The WiFi network is assumed to support the IEEE 802.11n protocol, working in the 5GHz band. There are several channels with a bandwidth of B and each AP can dynamically select an available channel with less interference to transmit. We further assume that the APs overlapping with the same SBS will choose different channels to avoid severe interference due to geographical proximity. This is feasible since the WiFi channels are generally sufficient to support different APs in one SBS, e.g., there are 23 channels for IEEE 802.11n in the 5GHz band. As illustrated in Fig. 1, AP1, AP2, and AP3 will use unlicensed channel F1, F2, and F3, respectively.

The following three methods are investigated.

- Traffic offloading: In this method, SBS m will offload N_{mk} users to AP k if $k \in \Phi_m$. We assume that the maximum number of users that can be offloaded from SBS m to AP k is $N_{mk}^{\max}$, which can be determined by the number of those cellular users in SBS m that are also located within the coverage of AP k and is known a priori.
- Resource sharing: In this method, the unlicensed band is divided into a total of L^{A} time slots whose length is long enough to transmit one LTE frame. SBS m will occupy $\tilde{L}_{mk}$ of L^{A} time slots from AP k [18]. For convenience, we normalize $L_{mk} = \frac{\tilde{L}_{mk}}{L^{\mathrm{A}}}$ ($L_{mk} \in [0, 1]$) and assume that each SBS can coordinate such that the time slots occupied from different APs will not overlap.
- The hybrid method: In this method, SBS can both offload users to WiFi and at the same time occupy time slots on unlicensed bands. Specifically, SBS m will offload N_{mk} users to AP k and occupy its L_{mk} time slots.

As in Fig. 1, SBS3 employs the traffic offloading method, which offloads two cellular users, SU_{31} and SU_{32}, to AP1, SBS1 utilizes the resource sharing method, occupying two time slots of AP2, and SBS2 uses the hybrid method, which offloads SU_{26} to AP3 and at the same time occupies three time slots of AP3 and four time slots of AP2.

In this paper, we assume that traffic offloading and resource sharing are coordinated by a central controller, which has all information, such as the locations, the number of users in each SBS. Moreover, the number of users in each AP can be estimated by the method proposed in [23]. It should be noted that the SBS can also share the unlicensed spectrum with those APs beyond its coverage. However, complicated resource scheduling among different SBSs is required. Therefore, we do not consider this situation in the paper.

B. WiFi Throughput Analysis

The *carrier sense multiple access with collision avoidance* (CSMA/CA) scheme with binary slotted exponential backoff is adopted in WiFi networks. The saturation throughput of a WiFi network with n users represents the maximum load that the system can carry in stable conditions, which can be analyzed with a *discrete-time Markov chain* (DTMC) model developed in [22]. Note that although we focus on the saturation system, our analysis can be also extended into the non-saturation system after some minor modifications since both systems have very similar WiFi throughput models [24].

Let P_{tr} and P_{s} be the probability that there is at least one transmission in a slot time and a transmission occurring on the channel is successful, respectively, which can be expressed as

$$P_{\mathrm{tr}} = 1 - (1-\tau)^n, \tag{1}$$

$$P_{\mathrm{s}} = n\tau\,(1-\tau)^{n-1} / P_{\mathrm{tr}}, \tag{2}$$

where τ is the transmission probability of each user. Then, from [22], the saturation throughput of the WiFi network can be expressed as

$$R(n) = \frac{P_{\mathrm{tr}} P_{\mathrm{s}} E[P]}{(1-P_{\mathrm{tr}})\,T_\sigma + P_{\mathrm{tr}} P_{\mathrm{s}} T_{\mathrm{s}} + P_{\mathrm{tr}}\,(1-P_{\mathrm{s}})\,T_{\mathrm{c}}}, \tag{3}$$

where T_{s} is the average time the channel is sensed busy because of a successful transmission, T_{c} is the average time the channel is sensed busy by each station during a collision, T_σ is the duration of an empty slot time, and $E[P]$ is the average packet size.

To compute (3) for a given DCF access mechanism, it is necessary to specify the corresponding values T_{c} and T_{s}. There are two packet transmission schemes employed by DCF, namely, the basic mechanism and the RTS/CTS access mechanism. T_{c} and T_{s} in these two mechanisms can be respectively expressed as [22]

$$\begin{cases} T_{\mathrm{s}}^{\mathrm{bas}} = & (\mathrm{H}+E[P])/C+\mathrm{SIFS}+\delta+\mathrm{ACK}/C+\mathrm{DIFS}+\delta, \\ T_{\mathrm{c}}^{\mathrm{bas}} = & \left(\mathrm{H}+E\left[P^*\right]\right)/C+\mathrm{DIFS}+\delta, \end{cases}$$

$$\begin{cases} T_{\mathrm{s}}^{\mathrm{rts}} = & \mathrm{RTS}/C+\mathrm{SIFS}+\delta+\mathrm{CTS}/C+\mathrm{SIFS}+\delta+(\mathrm{H} \\ & +E[P])/C+\mathrm{SIFS}+\delta+\mathrm{ACK}/C+\mathrm{DIFS}+\delta, \\ T_{\mathrm{c}}^{\mathrm{rts}} = & \mathrm{RTS}/C+\mathrm{DIFS}+\delta, \end{cases}$$

where $\mathrm{H} = \mathrm{PHY}_{\mathrm{hdr}} + \mathrm{MAC}_{\mathrm{hdr}}$, $E\left[P^*\right]$ is the average length of the longest packet traffic involved in a collision, C is the WiFi channel bit rate, and ACK, DIFS, δ, RTS, and CTS are WiFi parameters. Although IEEE 802.11n supports various channel data rates, we could assume that C is constant in the above equations since the channel data rate is a system-level parameter and does not frequently change with user distribution, traffic pattern, and channel status. In other words, the time-scale of changing the data rate is much longer than that of executing the traffic offloading or resource sharing algorithm.

Note that the expression in (3) ignores the hidden terminal. However, our results can be easily extended into that scenario with hidden terminals since WiFi with hidden terminals has a similar throughput expression as (3) according to [25]. Furthermore, even if the expression in (3) is for the uplink, the developed algorithms can be also used in the downlink, as will be discussed in Section III-E.

C. LTE Throughput Analysis

Both traffic offloading and resource sharing will definitely degrade the performance of the WiFi network. In this paper, we aim to maximize the LTE throughput while guaranteeing the performance of the WiFi network. Since both methods are generally performed in a large time scale, we ignore the diversity of different users, such as different QoS requirements, random channel fading, and user mobility, etc. Instead, we take the average throughput of each user as the performance metric, by averaging among all users and over all channel randomness. This metric has also been used in other related works, such as [7]. In addition, the short-term user scheduling and resource allocation strategies for the LTE network are not considered in this work since we focus on long-term system-level performance. Moreover, since different SBSs have different throughputs, we consider to maximize the minimum average per-user throughput of LTE SBSs to ensure fairness.

On the other hand, for the WiFi network, the minimum per-user throughput should be guaranteed, i.e., R_k^{T} for AP k. This value is very important to ensure the inter-system fairness in such an LTE and WiFi coexisting network, which can be determined by LTE after negotiating with WiFi or monitoring the WiFi network performance.

Let γ_{mi}^{S} be the *signal-to-interference-plus-noise ratio* (SINR) on the $i-th$ *resource block* (RB) of SBS m on the licensed spectrum, which can be expressed as

$$\gamma_{mi}^{\mathrm{S}} = \frac{g_{mi} P}{\sum\limits_{m' \neq m} g_{m'mi} P + \sigma_{\mathrm{S}}^2}, \tag{4}$$

where g_{mi} is the channel power gain, P is the transmit power, σ_{S}^2 is the noise power, and $g_{m'mi}$ is the interference power gain from SBS m' to SBS m on the i-th RB. Since this paper emphasizes on the analysis of coexistence scenario between LTE and WiFi, we focus on the average throughput of SBS m on the licensed spectrum, which can be expressed as

$$C_m^{\mathrm{S}} = B_m^{\mathrm{S}} E_m \left\{ \log_2 \left(1 + \gamma_{mi}^{\mathrm{S}} \right) \right\}, \tag{5}$$

where E_m denotes the expectation over different RBs, channel fading, and interference. It is a bit difficult to average the SINR in (4) due to complicated inter-cell interference. Fortunately, owing to the tractability of the PPP model used in our work, a closed-form expression of the expected overall throughput of a SBS can be derived by utilizing stochastic geometry (please refer to [26], [27] for the detailed derivations, which are omitted here due to page limits).

We shall also note that since we focus on the average channel capacity in (5), the channel dynamics would not affect our analysis too much. On the other hand, the short-term channel varying can be dealt with by other radio resource management strategies, such as power control, adaptive modulation and coding, and have been addressed to a great extent in other literature. Nevertheless, our algorithms do not rely on the detailed interference cancellation and resource management strategies since C_m^{S} is regarded as a constant in the sequel.

Similarly, if the whole unlicensed spectrum is used by SBS m, the expected overall throughput on it can be expressed as

$$C_m^{\mathrm{A}} = B E_m \left\{ \log_2 \left(1 + \gamma_{mi}^{\mathrm{A}} \right) \right\}, \tag{6}$$

where γ_{mi}^{A} is the SINR of the i-th RB on the unlicensed band, which can be expressed in a similar way as (4). Here we assume that the same LTE transmission protocol in the licensed band is employed in the unlicensed band. We also assume that the average throughputs on different unlicensed bands are the same to each SBS.

D. Problem Formulation

In the following, we will formulate the optimization problem in each method.

1) Traffic Offloading: Although the choice of which users to offload will affect the system performance, the overall system throughput significantly depends on the total amount of offloaded users in a large time scale. Assuming that SBS m will offload N_{mk} users to AP k, the optimization problem to maximize the minimum average per-user throughput among all SBSs can be formulated as

$$\max_{\{N_{mk}\}} \min_{m} \left\{ \frac{C_m^{\mathrm{S}}}{N_m^{\mathrm{S}} - \sum\limits_{k=1}^{K} N_{mk}} \right\}, \tag{7}$$

subject to

$$\frac{R\left(N_k^{\mathrm{A}} + \sum\limits_{m=1}^{M} N_{mk}\right)}{N_k^{\mathrm{A}} + \sum\limits_{m=1}^{M} N_{mk}} \geq R_k^{\mathrm{T}}, \ \forall k, \tag{7a}$$

$$N_{mk} \leq N_{mk}^{\max}, \ \forall m, k, \tag{7b}$$

where (7a) ensures the minimum per-user throughput of WiFi and (7b) limits the maximum number of users that can be offloaded from SBS m to AP k. Here, $R(\cdot)$ in (7a) is expressed in (3). Note that we do not count those cellular users offloaded to the WiFi network when calculating the average per-user LTE throughput since they are now connected with WiFi APs and their performance could be guaranteed by the WiFi network.

2) Resource Sharing: In the resource sharing method, SBS m can occupy L_{mk} time slots from AP k. We aim to obtain the optimal L_{mk} that maximizes the minimum average per-user LTE throughput while guaranteeing the WiFi performance, which can be formulated as

$$\max_{\{L_{mk}\}} \min_{m} \left\{ \frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum\limits_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}}} \right\}, \tag{8}$$

subject to

$$\frac{R\left(N_k^{\mathrm{A}}\right)\left(1 - \sum\limits_{m=1}^{M} L_{mk}\right)}{N_k^{\mathrm{A}}} \geq R_k^{\mathrm{T}}, \ \forall k. \tag{8a}$$

3) The Hybrid Method: To further improve the LTE throughput, the hybrid method can be utilized, where SBS m offloads N_{mk} users to AP k and occupies its L_{mk} time slots as well. The optimization problem can be modeled as

$$\max_{\{N_{mk},L_{mk}\}} \min_{m} \left\{ \frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}} \right\}, \tag{9}$$

subject to

$$\frac{R\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)\left(1 - \sum_{m=1}^{M} L_{mk}\right)}{\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)} \geq R_k^{\mathrm{T}},\ \forall k, \tag{9a}$$

$$N_{mk} \leq N_{mk}^{\max},\ \forall m, k. \tag{9b}$$

Note that the hybrid method is more general than both traffic offloading and resource sharing. It will become the traffic offloading method if setting $L_{mk} = 0, \forall m, k$, and the resource sharing method if setting $N_{mk} = 0, \forall m, k$. On the other hand, since L_{mk} and N_{mk} can be jointly optimized, the hybrid method outperforms the other two methods.

III. The Single-BS Scenario

In this section, we will first investigate a simple scenario with only one SBS and one AP to get some insights into the performance comparison of the three methods mentioned above. In the single-BS scenario, we can omit the subscripts "k" and "m" for brevity.

A. Traffic Offloading

In the single-BS scenario, we can rewrite (7a) as

$$\frac{R\left(N^{\mathrm{A}} + N\right)}{N^{\mathrm{A}} + N} \geq R^{\mathrm{T}}, \tag{10}$$

where N is the number of offloaded users from LTE to WiFi. Since $R(n)$ in (3) monotonously decreases with n while the objective function in (7) increases with n, we can easily obtain the maximum average per-user throughput of LTE system as

$$\frac{C^{\mathrm{S}}}{N^{\mathrm{S}} - \min\{N^*, N^{\max}\}}, \tag{11}$$

where N^* is the largest integer to satisfy (10). Note that the above result presents the throughput limit of the LTE system with the minimum per-user throughput of the WiFi network guaranteed in the traffic offloading method.

B. Resource Sharing

In the resource sharing method, we assume LTE occupies L ($L \in [0, 1]$) time slots on the unlicensed band. The per-user throughput of WiFi should be guaranteed

$$\frac{R\left(N^{\mathrm{A}}\right)(1 - L)}{N^{\mathrm{A}}} \geq R^{\mathrm{T}}. \tag{12}$$

Since the left side of (12) decreases but the objective function in (8) increases with L, the optimal L^* can be expressed as $L^* = 1 - \frac{R^{\mathrm{T}} N^{\mathrm{A}}}{R(N^{\mathrm{A}})}$. Thus, the maximum average per-user LTE throughput can be expressed as

$$\frac{C^{\mathrm{S}} + C^{\mathrm{A}} L^*}{N^{\mathrm{S}}}. \tag{13}$$

This is the throughput limit of the LTE system under the minimum performance requirement of the WiFi network in the resource sharing method.

C. The Hybrid Method

In the hybrid method, the optimization problem can be rewritten as

$$\max_{\{L, N\}} \frac{C^{\mathrm{S}} + L C^{\mathrm{A}}}{N^{\mathrm{S}} - N}, \tag{14}$$

subject to

$$(1 - L) \cdot \frac{R\left(N^{\mathrm{A}} + N\right)}{N^{\mathrm{A}} + N} \geq R^{\mathrm{T}}. \tag{14a}$$

Since the objective function increases with both L and N, but the left side of (14a) decreases with them, the equality in (14a) should be achieved. Therefore, we have

$$L = 1 - \frac{R^{\mathrm{T}} \cdot \left(N^{\mathrm{A}} + N\right)}{R\left(N^{\mathrm{A}} + N\right)}. \tag{15}$$

Then, (14) is equivalent to

$$\max_{0 \leq N \leq N^{\max}} f(N) = \frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{C^{\mathrm{A}} R^{\mathrm{T}} \cdot (N^{\mathrm{A}} + N)}{R(N^{\mathrm{A}} + N)}}{N^{\mathrm{S}} - N}, \tag{16}$$

which presents the maximum average per-user throughput of the LTE system in the hybrid method.

D. Performance Comparison

Now we begin to address the following two questions as raised in the Introduction part:

1. Traffic offloading and resource sharing: which one is better?

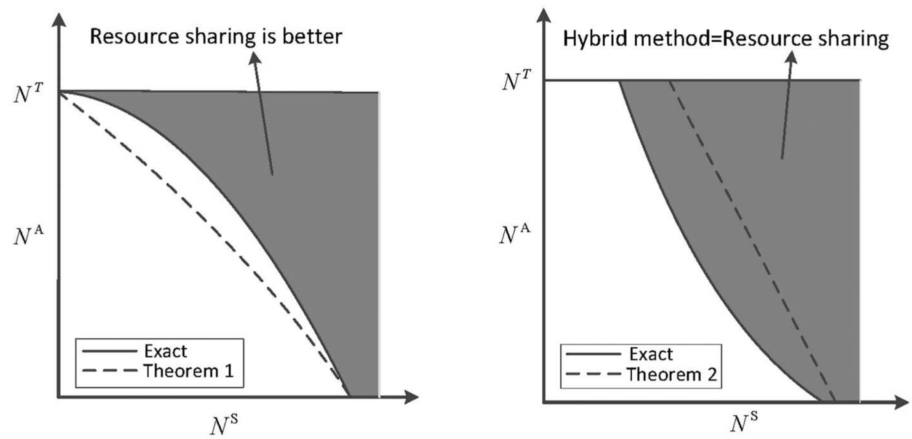
2. How much performance gain can be achieved by the hybrid method?

To answer these questions, we need to assume that $N^{\max}$ is large enough. Then, we introduce the following theorem to address the first problem, which is proved in Appendix A.

Theorem 1: When the number of WiFi users, N^A, and the number of cellular users, N^S, satisfy (17), traffic offloading performs better than resource sharing

$$N^{\mathrm{A}} < N^{\mathrm{T}} - \frac{C^{\mathrm{A}}}{C^{\mathrm{S}} + C^{\mathrm{A}}} N^{\mathrm{S}}, \tag{17}$$

where N^T is the maximal number of WiFi users satisfying $R(N^T)/N^T \geq R^T$.



(a) Comparison between traffic offloading and resource sharing. (b) Comparison between resource sharing and the hybrid method.

Fig. 2. Performance comparison of the three methods in the single-BS scenario.

Remark 1: Theorem 1 shows that traffic offloading is better only if the number of existing users in WiFi is small, which can be intuitively explained in the following. When the traffic load of the WiFi network is light, the per-user throughput of WiFi will be greater than that of LTE. In this situation, more LTE users can be offloaded to WiFi networks, leading to better average per-user LTE throughput than in the resource sharing method. However, when N^{A} is large, offloading new users will significantly increase the collision, leading to the degradation of WiFi throughput. Therefore, in this case, it is better to use the unlicensed bands by directly occupying several time slots. Moreover, from the theorem, for larger N^{S} and C^{A}, resource sharing is more likely to be superior. Once N^{S} is large enough, i.e., $N^{\mathrm{S}} > \frac{N^{\mathrm{T}}(C^{\mathrm{S}}+C^{\mathrm{A}})}{C^{\mathrm{A}}}$, resource sharing will be definitely better than traffic offloading regardless of N^{A}. The reason is that more spectrum resource are required to support a large number of LTE users in this case. Fig. 2(a) compares the curve in (17) (the dashed line) with the exact boundary curve (the solid line), where resource sharing is superior in the shadowing area. This figure demonstrates that (17) is a necessary condition for traffic offloading surpassing resource sharing.

To answer the second question, we present the following theorem, as proved in Appendix B.

Theorem 2: When the number of users in WiFi AP, N^{A}, is sufficiently large, i.e., both the following inequations are satisfied, the hybrid method has the same performance as the resource sharing method.

$$N^{\mathrm{A}} N^{\mathrm{S}} \beta + \frac{N^{\mathrm{S}} + N^{\mathrm{A}}}{R\left(N^{\mathrm{A}}\right)} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{C^{\mathrm{A}} R^{\mathrm{T}}}, \quad (18)$$

$$\left(N^{\mathrm{S}} + N^{\mathrm{A}} - N^{\mathrm{T}}\right) N^{\mathrm{T}} \beta + \frac{N^{\mathrm{S}} + N^{\mathrm{A}}}{R\left(N^{\mathrm{T}}\right)} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{C^{\mathrm{A}} R^{\mathrm{T}}}, \quad (19)$$

where $\beta = \min\limits_{N} \left\{ \frac{1}{R(N^{\mathrm{A}}+N+1)} - \frac{1}{R(N^{\mathrm{A}}+N)} \right\}$.

Remark 2: Theorem 2 indicates that when N^{A} is large enough, offloading users to WiFi is no longer necessary and the hybrid method is identical to the resource sharing method. The reason can be explained in a similar way as in Theorem 1. Note that to guarantee the minimum per-user throughput of WiFi system, $N^{\mathrm{A}} < N^{\mathrm{T}}$ should be satisfied. However, for a sufficiently large N^{S}, there will always exist N^{A} satisfying (18) and (19) since the left sides of both inequations increase with N^{S} and N^{A}. Moreover, as indicated by the above inequations, the dynamic region of N^{A} increases with N^{S}, which shows that traffic offloading is more likely to be unnecessary for large N^{S} and the hybrid method can be degraded into the resource sharing method in this case. Fig. 2(b) demonstrates the theorem, where the solid line corresponds to the exact boundary line, the dashed line is given by (18) and (19), and the shadowing area means that the hybrid method has the same performance as the resource sharing method. From the figure, (18) and (19) serve as necessary conditions.

E. Extension to Downlink

In the downlink case, the saturation throughput in (3) would be a constant since there is no competing users, that is

$$R\left(n\right) = R, \forall n, \quad (20)$$

where R is the overall WiFi throughput. In this case, the maximum supported WiFi user $N^{\mathrm{T}} = \frac{R}{R^{\mathrm{T}}}$. Therefore, if (17) exists, we can also demonstrate that

$$\frac{C^{\mathrm{S}}}{N^{\mathrm{S}} + N^{\mathrm{A}} - N^{\mathrm{T}}} > \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{N^{\mathrm{S}}} > \frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{N^{\mathrm{A}}}{N^{\mathrm{T}}} C^{\mathrm{A}}}{N^{\mathrm{S}}}, \quad (21)$$

which means that traffic offloading is better than resource sharing.

On the other hand, $\beta = 0$ in this case as shown in Appendix B. Therefore, (18) and (19) reduce to

$$\frac{N^{\mathrm{S}} + N^{\mathrm{A}}}{R} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{C^{\mathrm{A}} R^{\mathrm{T}}}. \quad (22)$$

From (22), we can easily derive that

$$\max_{N} f\left(N\right) = f\left(0\right) = \frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{N^{\mathrm{A}}}{N^{\mathrm{T}}} C^{\mathrm{A}}}{N^{\mathrm{S}}}, \quad (23)$$

which implies that the hybrid method has the same performance as resource sharing in this case.

From the above discussion, our derivation can also be extended into the downlink case.

IV. The Multi-BS Scenario

In this section, we will discuss the three methods in the multi-BS scenario, i.e., with multiple SBSs and multiple APs. We first derive the performance upper bound and then develop practical algorithm for each method.

A. *Traffic Offloading*

First, we will investigate the optimal traffic offloading problem in (7). We denote R^{TO} as the minimum average per-user throughput among SBSs, i.e., $R^{\mathrm{TO}} = \min\limits_{m} \left\{ \frac{C_m^{\mathrm{S}}}{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}} \right\}$. Then, by parametric algorithm [28], (7) can be transformed into

$$\max\ R^{\mathrm{TO}}, \tag{24}$$

subject to

$$\frac{C_m^{\mathrm{S}}}{N_m^{\mathrm{S}} - \sum\limits_{k=1}^{K} N_{mk}} \geq R^{\mathrm{TO}},\ \forall m, \tag{24a}$$

$$\frac{R\left(N_k^{\mathrm{A}} + \sum\limits_{m=1}^{M} N_{mk}\right)}{N_k^{\mathrm{A}} + \sum\limits_{m=1}^{M} N_{mk}} \geq R_k^{\mathrm{T}},\ \forall k, \tag{24b}$$

$$N_{mk} \leq N_{mk}^{\max},\ \forall m, k. \tag{24c}$$

The above problem is an integer optimization problem and not easy to solve. To make it better tractable, we first relax N_{mk} into a continuous variable and further ignore the constraint in (24c) to achieve its upper bound. With these assumptions, we can obtain a closed-form solution.

Moreover, it is rather intuitive that to achieve the largest R^{TO}, more users should be offloaded to WiFi since $R(n)$ is a decreasing function and R^{TO} increases with N_{mk}. In this situation, (24b) can be rewritten as $\sum\limits_{m=1}^{M} N_{mk} = N_k^{\mathrm{T}} - N_k^{\mathrm{A}}$, where N_k^{T} denotes the maximum number of users that could be supported in AP k to satisfy the minimum per-user throughput, as $R(N_k^{\mathrm{T}})/N_k^{\mathrm{T}} = R_k^{\mathrm{T}}, \forall k$.

With the continuous relaxation of N_{mk} and the above analysis, an upper bound for R^{TO} could be expressed in a closed-form expression as shown in the following corollary, which is proved in Appendix C.

Corollary 1: An upper bound for R^{TO} can be expressed as

$$R^{\mathrm{TO}} = \frac{\sum\limits_{m=1}^{M} C_m^{\mathrm{S}}}{\sum\limits_{m=1}^{M} N_m^{\mathrm{S}} + \sum\limits_{k=1}^{K} N_k^{\mathrm{A}} - \sum\limits_{k=1}^{K} N_k^{\mathrm{T}}}. \tag{25}$$

TABLE I
The Algorithm for Traffic Offloading

Algorithm 1 The algorithm for traffic offloading.

Initialize $N_{mk} = 0, \forall m, k,\ S = \{1, 2, \cdots, M\},\ \Omega_m = \{k | N_{mk} < N_{mk}^{\max} \text{ and } \sum\limits_{m=1}^{M} N_{mk} < N_k^{\mathrm{T}} - N_k^{\mathrm{A}}\}$.
Do
Select $m^* = \arg\min\limits_{m\in S} \frac{C_m^{\mathrm{S}}}{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}}$.
  If $\Omega_{m^*} = \emptyset$
    $S = S - \{m^*\}$.
  else
    Select $k^* = \arg\max\limits_{k\in\Omega_{m^*}} \left(N_k^{\mathrm{T}} - N_k^{\mathrm{A}} - \sum\limits_{m=1}^{M} N_{mk}\right)$.
    $N_{m^*k^*} = N_{m^*k^*} + 1$.
    Update Ω_{m^*}.
  End if
Until $S = \emptyset$

TABLE II
The Algorithm for Resource Sharing

Algorithm 2 The algorithm for resource sharing.

Initialize $L_{mk} = 0,\ S = \{1, 2, \cdots, M\},\ R_k = R\left(N_k^{\mathrm{A}}\right)/N_k^{\mathrm{A}}$,
$\Omega_m = \left\{k | \left(1 - \sum\limits_{m=1}^{M} L_{mk}\right) R_k \geq R_k^{\mathrm{T}} \text{ and } a_{mk} = 1\right\}$.
Do
  Select $m^* = \arg\min\limits_{m\in S} \frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}}}$.
  If $\Omega_{m^*} = \emptyset$
    $S = S - \{m^*\}$.
  Else
    Select $k^* = \arg\max\limits_{k\in\Omega_{m^*}} \left\{\left(1 - \sum\limits_{m=1}^{M} L_{mk}\right) R_k - R_k^{\mathrm{T}}\right\}$.
    $L_{m^*k^*} = L_{m^*k^*} + 1/L^{\mathrm{A}}$.
    Update Ω_{m^*}.
  End if
Until $S = \emptyset$

It should be noted that the above equation is achieved with the assumption of continuous N_{mk} and the relaxation of constraint (24c). In the following, we present a practical traffic offloading algorithm in the multi-BS scenario, as described in Table I. The main idea of the algorithm is to offload one user from the SBS with the minimum average per-user throughput to an overlapped AP which has the largest capacity in each iteration until all APs reach the minimum per-user throughput threshold.

B. *Resource Sharing*

Similar to the traffic offloading case, the problem in (8) can be reformulated as

$$\max\ R^{\mathrm{RS}}, \tag{26}$$

TABLE III
THE ALGORITHM FOR THE HYBRID METHOD

Algorithm 3 The algorithm for the hybrid method.

Initialize $N_{mk}=0, L_{mk}=0, \forall m,k,\ S=\{1,2,\cdots,M\}$,
$R_k = R\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right) / \left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)$,
$\Omega_m = \left\{k \middle| \left(1-\sum_{m=1}^{M} L_{mk}\right) R_k \geq R_k^{\mathrm{T}} \text{ and } a_{mk}=1\right\}$.
Do
Select $m^* = \arg\min_{m\in S} \frac{C_m^{\mathrm{S}}+C_m^{\mathrm{A}}\sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}}-\sum_{k=1}^{K} N_{mk}}$.
  If $\Omega_{m^*}=\emptyset$
    $S=S-\{m^*\}$.
  Else
    Select $k^* = \arg\max_{k\in\Omega_{m^*}} \left\{\left(1-\sum_{m=1}^{M} L_{mk}\right) R_k - R_k^{\mathrm{T}}\right\}$.
    Calculate R^{TO} and R^{RS} according to (25), (30).
    If $R^{\mathrm{TO}} > R^{\mathrm{RS}}$ and $N_{m^*k^*} < N_{m^*k^*}^{\max}$
      $N_{m^*k^*} = N_{m^*k^*}+1$.
      Update R_{k^*}.
    Else
      $L_{m^*k^*} = L_{m^*k^*} + 1/L^{\mathrm{A}}$.
    End if
    Update Ω_{m^*}.
  End if
Until $S=\emptyset$

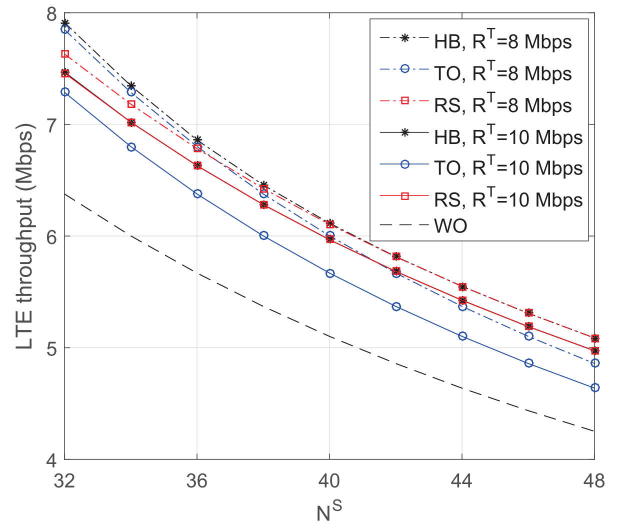
TABLE IV
SYSTEM PARAMETERS

Parameters	Settings
Noise power	-95 dBm
Path loss model (Licensed, unlicensed)	$15.3+\alpha\times 10\log_{10}(d)$ $\alpha=3.75, 5$
Transmit power	20 dBm
$E[P]$	1500 byte
B^{S}, B	20 MHz, 20 MHz
$CW_{\min}$	16
$CW_{\max}$	1024
R_{limit}	6
WiFi channel bit rate	130 Mbps
PHY header	192 bits
MAC header	224 bits
T_δ	20 μs
SIFS	16 μs
DIFS	50 μs
Slot time	9 μs
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
L^{A}	100

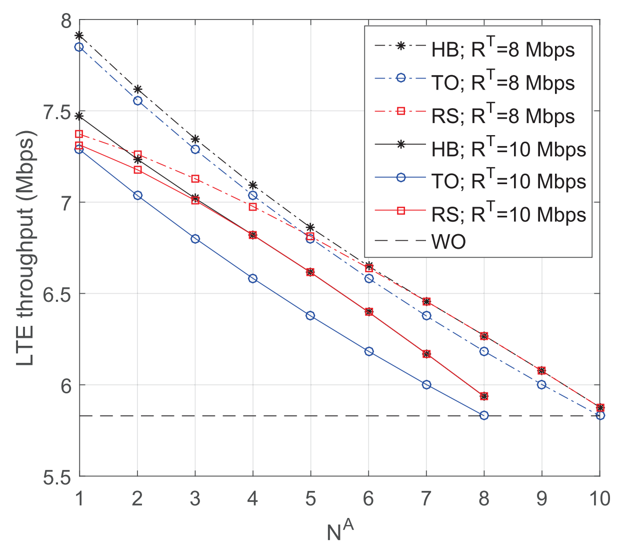
subject to

$$\frac{C_m^{\mathrm{S}}+C_m^{\mathrm{A}}\sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}}} \geq R^{\mathrm{RS}},\ \forall m, \tag{26a}$$

$$\frac{R\left(N_k^{\mathrm{A}}\right)\left(1-\sum_{m=1}^{M} L_{mk}\right)}{N_k^{\mathrm{A}}} \geq R_k^{\mathrm{T}},\ \forall k. \tag{26b}$$



(a) LTE throughput with different numbers of cellular users. $N^{\mathrm{A}}=4$.



(b) LTE throughput with different numbers of WiFi users. $N^{\mathrm{S}}=35$.

Fig. 3. Performance comparison in the single-BS scenario.

Again, we can relax L_{mk} into a continuous variable to obtain an upper bound of R^{RS}, as shown in the following corollary, which is proved in Appendix C.

Corollary 2: An upper bound for R^{RS} can be expressed as

$$R^{\mathrm{RS}} = \frac{\sum_{m=1}^{M}\frac{C_m^{\mathrm{S}}}{C_m^{\mathrm{A}}} + \sum_{k=1}^{K}\left(1-\frac{N_k^{\mathrm{A}}R_k^{\mathrm{T}}}{R(N_k^{\mathrm{A}})}\right)}{\sum_{m=1}^{M}\frac{N_m^{\mathrm{S}}}{C_m^{\mathrm{A}}}}. \tag{27}$$

We now develop a practical algorithm for the resource sharing method taking into account the discrete time slots, as presented in Table II. The main idea of the algorithm is similar to the traffic offloading case. In each iteration, we pick up the SBS with the minimum average per-user throughput and allocate one time slot to it from the AP with the largest capacity.

C. The Hybrid Method

Now, we begin to investigate the hybrid method. The optimization problem in (9) can be rewritten as

$$\max\ R^{\mathrm{HB}}, \tag{28}$$

subject to

$$\frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}} \geq R^{\mathrm{HB}},\ \forall m, \tag{28a}$$

$$\frac{R\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)\left(1 - \sum_{m=1}^{M} L_{mk}\right)}{\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)} \geq R_k^{\mathrm{T}},\ \forall k, \tag{28b}$$

$$N_{mk} \leq N_{mk}^{\max},\ \forall m, k. \tag{28c}$$

If we relax both N_{mk} and L_{mk} into continuous variables and ignore the constraint (28c), we have the following corollary to express an upper bound of the maximum average per-user throughput, which is proved in Appendix C.

Corollary 3: An upper bound for R^{HB} can be expressed as

$$R^{\mathrm{HB}} = \max_{\{N_{mk}\}} \frac{\sum_{m=1}^{M} \frac{C_m^{\mathrm{S}}}{C_m^{\mathrm{A}}} + \sum_{k=1}^{K} \left\{ 1 - \frac{R_k^{\mathrm{T}} \cdot \left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)}{R\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)} \right\}}{\sum_{m=1}^{M} \frac{N_m^{\mathrm{S}}}{C_m^{\mathrm{A}}} - \sum_{m=1}^{M} \frac{\sum_{k=1}^{K} N_{mk}}{C_m^{\mathrm{A}}}}. \tag{29}$$

We can develop a joint resource sharing and traffic offloading algorithm for the hybrid method, as shown in Table III. In each iteration, we pick up the SBS with the minimum average per-user throughput and an overlapped AP with the largest capacity. Then we decide to offload one user to this AP or occupy its one time slot depending on which one is better. Specifically, traffic offloading is selected if $R^{\mathrm{TO}} > R^{\mathrm{RS}}$ and resource sharing is selected otherwise, where R^{TO} is given in (25) and

$$R^{\mathrm{RS}} = \frac{\sum_{m=1}^{M} \frac{C_m^{\mathrm{S}}}{C_m^{\mathrm{A}}} + \sum_{k=1}^{K} \left(1 - \frac{N_k^{\mathrm{A}} R_k^{\mathrm{T}}}{R(N_k^{\mathrm{A}})}\right)}{\sum_{m=1}^{M} \frac{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}}{C_m^{\mathrm{A}}}}. \tag{30}$$

We can see that all the three algorithms have the computational complexity of only $\mathcal{O}(M \cdot K)$. Therefore, they can be easily implemented in practical systems.

V. Performance Evaluation

In this section, numerical results are presented to evaluate the performance of the proposed algorithms. The transmit power at the SBS is 20 dBm and the noise power on both licensed and

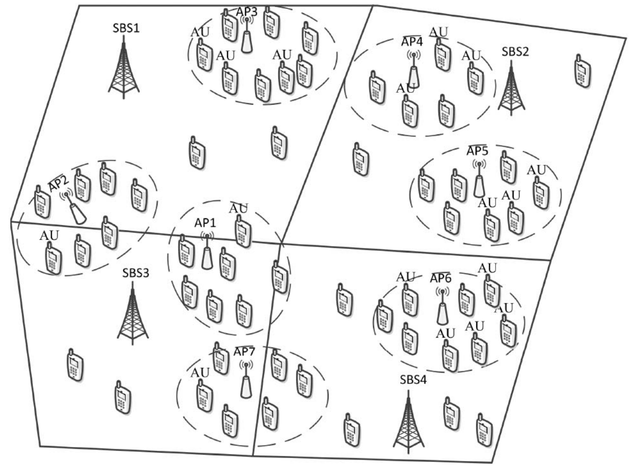
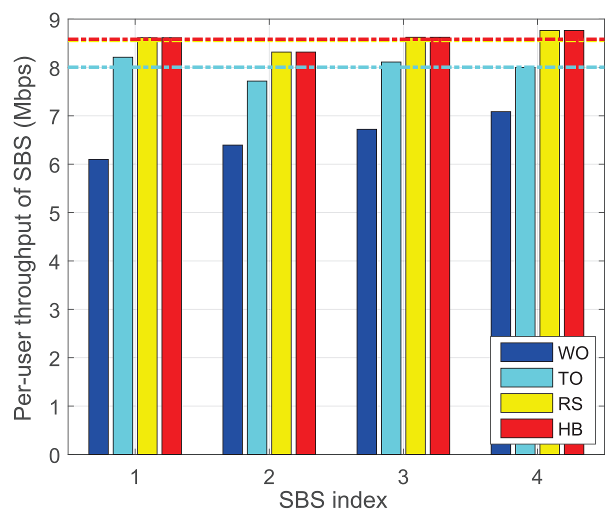
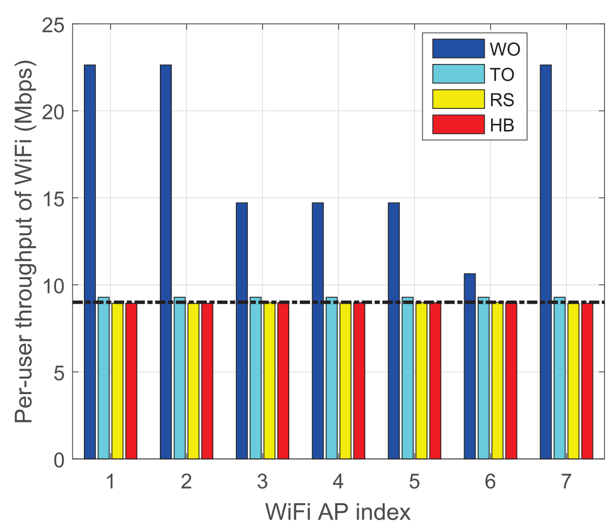


Fig. 4. Simulation model for the multi-BS scenario.

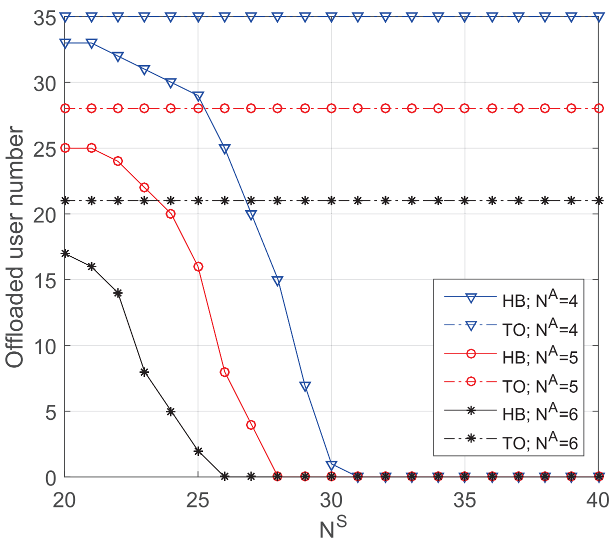


(a) Average per-user throughput of each SBS.

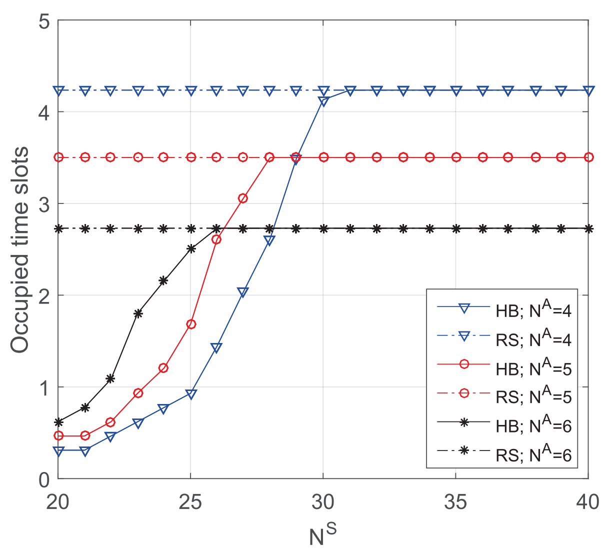


(b) Average per-user throughput of each WiFi.

Fig. 5. Average per-user throughput of each SBS and WiFi AP. $N^{\mathrm{S}} = 35$. $N^{\mathrm{A}} = \{4, 4, 6, 6, 6, 8, 4\}$.

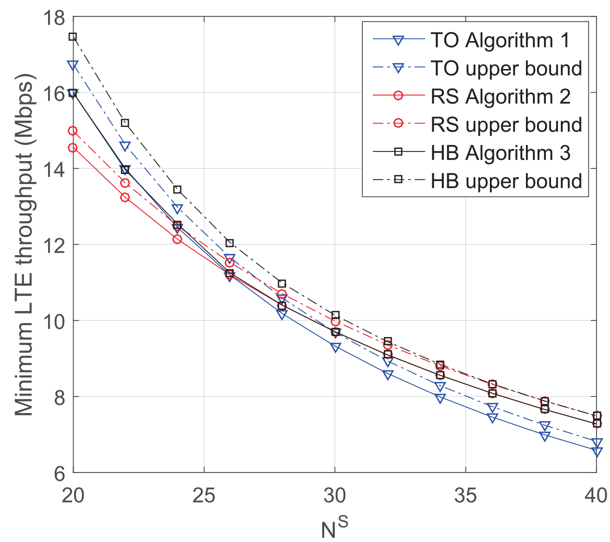


(a) Total number of offloaded users.

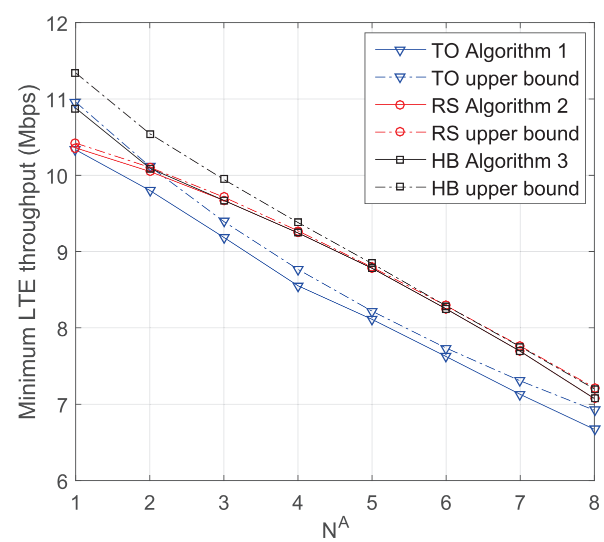


(b) Total number of occupied time slots.

Fig. 6. Total number of offloaded users and occupied time slots with different numbers of cellular users.



(a) Minimum average per-user LTE throughput with different numbers of cellular users. $N^{\mathrm{A}} = \{4, 4, 6, 6, 6, 8, 4\}$.



(b) Minimum average per-user LTE throughput with different numbers of WiFi users. $N^{\mathrm{S}} = 35$.

Fig. 7. Performance comparison of different methods.

unlicensed bands is -95 dBm. The path loss model is $15.3 + \alpha \times 10\log_{10}(d)$ dB, where d is in meter and α is 3.75 and 5 for licensed and unlicensed bands, respectively [29]. The LTE SBSs are distributed according to homogeneous PPP and the interference and rate model in [26] is adopted. The WiFi APs are deterministically deployed for given LTE SBS locations and both LTE and WiFi users are uniformly distributed.

The WiFi network is equipped with the IEEE 802.11n protocol working at the 5GHz band and we adopt the RTS/CTS mechanism in the simulations. Other WiFi parameters are listed in Table IV. Here, we assume the channel data rate of the IEEE 802.11n system is 130 Mbps, which is a typical value for 20 MHz bandwidth. However, similar results can be expected for other channel data rates. In the following figures, TO, RS, and HB stand for traffic offloading, resource sharing, and the hybrid method, respectively, while WO stands for the original SBS system without any of the three methods.

A. Single-BS Scenario

We first demonstrate the performance for a given SBS which is overlapped with one WiFi AP. The two constants, C^{S} and C^{A} in (5) and (6) can be calculated as 204 Mbps and 62 Mbps, respectively. The performance of average per-user LTE throughput in the single-BS scenario is depicted in Fig. 3, where $N^{\max}$ is set large enough. Fig. 3(a) plots the relationship between the average per-user LTE throughput and the number of cellular users, N^{S}, for different WiFi throughput threshold, R^{T}, where $N^{\mathrm{A}} = 4$. From the figure, when R^{T} is large (R^{T}=10 Mbps), (17) cannot be satisfied since the maximum number of users that WiFi can support, i.e., N^{T}, is small. Therefore, resource sharing always performs better than traffic offloading. On the other hand, both (18) and (19) can be satisfied due to large R^{T}, resulting in the same performance between the hybrid method and the resource sharing method in this situation. Comparing the three curves with R^{T}=8 Mbps, we find that traffic offloading performs better than resource sharing when N^{S} is relatively small while it is contrary for large N^{S}, which demonstrates Theorem 1. Moreover, the hybrid method performs better than the others since (18) and (19) cannot be satisfied for small N^{S}. But it achieves the same performance as resource sharing when N^{S} becomes large. Fig. 3(b) shows the relationship between the LTE throughput and the number of existing WiFi users, N^{A}, where $N^{\mathrm{S}} = 35$. When N^{A} is large enough, the hybrid method achieves the same performance as the resource sharing method, demonstrating Theorem 2. From both figures, the average per-user LTE throughput can be improved by the three methods.

B. Multi-BS Scenario

We now present the results for the multi-BS scenario, where 4 nearby SBSs share unlicensed spectrum with 7 WiFi APs, as shown in Fig. 4. Specifically, SBS1 is overlapped with AP 1 to AP 3 with maximum offloading numbers of 7, 11, 10, respectively, SBS2 is overlapped with AP 4 and AP 5, with maximum offloading numbers of 8 and 12, respectively, SBS3 is overlapped with AP 1, 2, and 7, with the same maximum offloading number of 7 to each AP, and SBS4 is overlapped with AP 1, AP 6, and AP 7 with maximum offloading numbers of 8, 8, 9, respectively. It is assumed that the per-user throughput threshold of each WiFi AP is the same, i.e., $R_k^{\mathrm{T}} = 9$ Mbps, $\forall k$, and each SBS has the same number of cellular users, i.e., $N_m^{\mathrm{S}} = N^{\mathrm{S}}, \forall m$. The C_m^{S} of the 4 SBSs are 213.5 Mbps, 223.8 Mbps, 235.2 Mbps, and 248 Mbps, and the C_m^{A} of the 4 SBSs are 73.4 Mbps, 86.3 Mbps, 100.9 Mbps, and 117.5 Mbps.

Fig. 5(a) illustrates the average per-user throughput of each SBS in the three methods where the dashed lines correspond to the upper bound of each method. From the figure, SBSs can achieve almost the same performance in each method, resulting from the maximization of the minimum average per-user throughput in the objective function. The performance upper bound of each method is also demonstrated. The performance of WiFi APs in each method is depicted in Fig. 5(b), where the dashed line shows the required minimum per-user throughput. As predicted, each WiFi AP achieves a per-user throughput that is a little more than the given threshold.

We plot the total number of the offloaded users, $\sum_{mk} N_{mk}$, and the total occupied time slots, $\sum_{mk} L_{mk}$, of the hybrid method in Fig. 6(a) and Fig. 6(b), respectively. We assume the WiFi APs have the same number of users, i.e., N^{A}. For a given N^{A}, the number of offloaded users in the traffic offloading method is fixed as $\sum_k \{N_k^{\mathrm{T}} - N_k^{\mathrm{A}}\}$, which serves as an upper bound for the hybrid method. Also, the number of occupied time slots in the resource sharing method is fixed for a given N^{A}, i.e., $\sum_{k=1}^{K}\left(1 - \frac{N_k^{\mathrm{A}} R_k^{\mathrm{T}}}{R(N_k^{\mathrm{A}})}\right)$, serving as the upper bound for the hybrid method. As N^{S} increases, fewer users will be offloaded and more time slots will be occupied in the hybrid method since resource sharing is more efficient for large N^{S}, as demonstrated in Theorem 1. For large enough N^{S}, no user will be offloaded and the hybrid method is degraded into the resource sharing method, as shown in Theorem 2.

Fig. 7(a) and Fig. 7(b) present the minimum average per-user LTE throughput with different numbers of cellular users and WiFi users, respectively. From Fig. 7(a), the hybrid method achieves a better performance than the others when N^{S} is small while it has the same performance as resource sharing for large N^{S}. Also, traffic offloading is first superior and then inferior to resource sharing as N^{S} increases. These phenomena are the same as in the single-BS scenario as shown in Fig. 3(a). A similar result can be found in Fig. 7(b) where $N_k^{\mathrm{A}} = N^{\mathrm{A}}, \forall k$. In both figures, the upper bounds for different methods in Corollaries 1-3 are validated.

VI. Conclusion

In this paper, we have investigated the coexistence of cellular and WiFi systems in unlicensed bands. First, to take advantage of both resource sharing and traffic offloading methods, we have proposed a hybrid method where small cell base stations can simultaneously offload traffic to WiFi APs and occupy several time slots on the unlicensed band. Then, to get some insights into the performance comparison, we have theoretically analyzed the LTE throughput of resource sharing, traffic offloading, and the hybrid method with the guarantee of minimum WiFi per-user throughput in the single-BS scenario. We find that traffic offloading achieves a better LTE performance than resource sharing when the number of existing WiFi users is below a threshold and the hybrid method has the same performance as the resource sharing method when the number of existing WiFi users is large enough. Moreover, in the multi-BS scenario, we have developed different traffic offloading and resource sharing algorithms for the three methods to maximize the minimum average per-user throughput among SBSs. We have also derived a closed-form performance upper bound for each method. Our analytical results have been demonstrated by numerical simulations.

In this work, we mainly consider the long-term average per-user LTE throughput as our performance metric, which may not guarantee the instantaneous user experience. As a future work, we will investigate the opportunistic traffic offloading and resource sharing according to the instantaneous channel and traffic status to further improve the user QoS. Moreover, to obtain the closed-form results for WiFi and LTE coexistence, we have assumed that each LTE user has the same traffic pattern and shares the same amount of wireless resource. It will be very interesting to extend our work into a more practical scenario with different traffic patterns for different users in the future.

Appendix A
Proof of Theorem 1

To prove traffic offloading is better than resource sharing, we need to prove

$$\frac{C^{\mathrm{S}}}{N^{\mathrm{S}} - N^*} > \frac{C^{\mathrm{S}} + C^{\mathrm{A}} L^*}{N^{\mathrm{S}}}, \tag{31}$$

where $L^* = 1 - \frac{R^{\mathrm{T}} N^{\mathrm{A}}}{R(N^{\mathrm{A}})}$ and $\frac{R(N^{\mathrm{A}}+N^*)}{N^{\mathrm{A}}+N^*} = R^{\mathrm{T}}$.

The above inequation can be equally written as

$$\frac{R^{\mathrm{T}} N^{\mathrm{A}}}{R\left(N^{\mathrm{A}}\right)} > 1 - \frac{C^{\mathrm{S}}}{C^{\mathrm{A}}} \frac{N^*}{N^{\mathrm{S}} - N^*}. \tag{32}$$

Denote $N^* = N^{\mathrm{T}} - N^{\mathrm{A}}$, we can rewrite (32) as

$$\begin{aligned} N^{\mathrm{A}} &< N^{\mathrm{T}} - \frac{1 - \frac{R^{\mathrm{T}}}{R(N^{\mathrm{A}})/N^{\mathrm{A}}}}{\frac{C^{\mathrm{S}}}{C^{\mathrm{A}}} + 1 - \frac{R^{\mathrm{T}}}{R(N^{\mathrm{A}})/N^{\mathrm{A}}}} N^{\mathrm{S}} \\ &= N^{\mathrm{T}} - \frac{1 - \frac{1}{\alpha}}{\left(1 - \frac{1}{\alpha}\right) + \frac{C^{\mathrm{S}}}{C^{\mathrm{A}}}} N^{\mathrm{S}}, \end{aligned} \tag{33}$$

where $\alpha = \frac{R(N^{\mathrm{A}})/N^{\mathrm{A}}}{R^{\mathrm{T}}}$. Since $R(N)/N$ is a decreasing function and $N^{\mathrm{A}} < N^{\mathrm{T}}$, we have $\alpha > 1$ and

$$\frac{1 - \frac{1}{\alpha}}{\left(1 - \frac{1}{\alpha}\right) + \frac{C^{\mathrm{S}}}{C^{\mathrm{A}}}} < \frac{1}{1 + \frac{C^{\mathrm{S}}}{C^{\mathrm{A}}}}. \tag{34}$$

Based on (34), we can conclude that (33) can be guaranteed if (17) is satisfied, which ends the proof.

Appendix B
Proof of Theorem 2

To prove the hybrid method is equivalent to the resource sharing method, we need to prove that (16) is maximized when $N = 0$, or equivalently, $f(N)$ in (16) is a non-increasing function, which can be further equivalent to prove that $f(N) \geq f(N+1)$ exists for all $N \geq 0$, as

$$\frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{C^{\mathrm{A}} R^{\mathrm{T}} \cdot (N^{\mathrm{A}}+N)}{R(N^{\mathrm{A}}+N)}}{N^{\mathrm{S}} - N} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{C^{\mathrm{A}} R^{\mathrm{T}} \cdot (N^{\mathrm{A}}+N+1)}{R(N^{\mathrm{A}}+N+1)}}{N^{\mathrm{S}} - N - 1}. \tag{35}$$

With simple mathematical calculation, (35) could be rewritten into

$$\begin{aligned} &\left(N^{\mathrm{S}} - N\right)\left(N^{\mathrm{A}} + N\right)\left(\frac{1}{R\left(N^{\mathrm{A}} + N + 1\right)} - \frac{1}{R\left(N^{\mathrm{A}} + N\right)}\right) \\ &\quad + \frac{N^{\mathrm{S}} - N}{R\left(N^{\mathrm{A}} + N + 1\right)} + \frac{N^{\mathrm{A}} + N}{R\left(N^{\mathrm{A}} + N\right)} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{C^{\mathrm{A}} R^{\mathrm{T}}}. \end{aligned} \tag{36}$$

Based on the fact that the throughput of WiFi decreases with the number of users, we have

$$\frac{1}{R\left(N^{\mathrm{A}} + N\right)} < \frac{1}{R\left(N^{\mathrm{A}} + N + 1\right)}. \tag{37}$$

Then, a sufficient condition for (36) can be expressed as

$$g(N) \triangleq \left(N^{\mathrm{S}} - N\right)\left(N^{\mathrm{A}} + N\right)\beta + \frac{N^{\mathrm{A}} + N^{\mathrm{S}}}{R\left(N^{\mathrm{A}} + N\right)} \geq \frac{C^{\mathrm{S}} + C^{\mathrm{A}}}{C^{\mathrm{A}} R^{\mathrm{T}}}, \tag{38}$$

where $\beta = \min\limits_{N} \left\{\frac{1}{R(N^{\mathrm{A}}+N+1)} - \frac{1}{R(N^{\mathrm{A}}+N)}\right\}$.

Since $\left(N^{\mathrm{S}} - N\right)\left(N^{\mathrm{A}} + N\right)\beta$ is quadratic, and $\frac{N^{\mathrm{A}}+N^{\mathrm{S}}}{R(N^{\mathrm{A}}+N)}$ is an increasing function of N, the minimum $g(N)$ is achieved when $N = 0$ or $N = N^{\mathrm{T}} - N^{\mathrm{A}}$, which is expressed in the left sides of (18) and (19) respectively. Therefore, if (18) and (19) are satisfied, (38) will be guaranteed for all $N > 0$, which ends the proof.

Appendix C

A. *Proof of Corollary 1*

It is easy to prove that max R^{TO} can be achieved when the following equation is satisfied

$$\frac{C_m^{\mathrm{S}}}{N_m^{\mathrm{S}} - \sum\limits_{k=1}^{K} N_{mk}} = R^{\mathrm{TO}}, \ \forall m. \tag{39}$$

Since the left side of (24b) decreases while R^{TO} in (39) increases with N_{mk}, "$\geq$" should be set equal in (24b), which can be further expressed as

$$\sum_{m=1}^{M} N_{mk} = N_k^{\mathrm{T}} - N_k^{\mathrm{A}}, \ \forall k, \tag{40}$$

where N_k^{T} is the maximum number of users that AP k can support with the minimum per-user throughput. According to (39) and (40), we have

$$\sum_{m=1}^{M}\sum_{k=1}^{K} N_{mk} = \sum_{m=1}^{M}\left(N_m^{\mathrm{S}} - \frac{C_m^{\mathrm{S}}}{R^{\mathrm{TO}}}\right), \tag{41}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} N_{mk} = \sum_{k=1}^{K}\left(N_k^{\mathrm{T}} - N_k^{\mathrm{A}}\right). \tag{42}$$

Combining (41) with (42), we can express R^{TO} in Corollary 1.

B. *Proof of Corollary 2*

From (26a), the maximum R^{RS} is achieved when

$$\frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum\limits_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}}} = R^{\mathrm{RS}}, \ \forall m. \tag{43}$$

We see that R^{RS} increases with L_{mk} while the left side of (26b) decreases with L_{mk}, therefore (26b) can be rewritten as

$$\frac{R_k\left(N_k^{\mathrm{A}}\right)\left(1 - \sum\limits_{m=1}^{M} L_{mk}\right)}{N_k^{\mathrm{A}}} = R_k^{\mathrm{T}}, \ \forall k. \tag{44}$$

Furthermore, (43) and (44) can be rewritten as

$$\sum_{m=1}^{M}\sum_{k=1}^{K} L_{mk} = \sum_{m=1}^{M} \frac{N_m^{\mathrm{S}} R^{\mathrm{RS}} - C_m^{\mathrm{S}}}{C_m^{\mathrm{A}}}, \tag{45}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} L_{mk} = \sum_{k=1}^{K}\left(1-\frac{R_k^{\mathrm{T}} N_k^{\mathrm{A}}}{R\left(N_k^{\mathrm{A}}\right)}\right), \tag{46}$$

respectively. From the above equations, we can obtain the R^{RS} in Corollary 2.

C. Proof of Corollary 3

The proof of the hybrid method is much similar to that of the traffic offloading and the resource sharing methods. First, the maximum R^{HB} is achieved when "$\geq$" in (28a) is set to "$=$". Thus, from (28a) we have

$$\sum_{m=1}^{M}\sum_{k=1}^{K} L_{mk} = \sum_{m=1}^{M}\left(\frac{N_m^{\mathrm{S}}}{C_m^{\mathrm{A}}} R^{\mathrm{HB}} - \frac{\sum_{k=1}^{K} N_{mk}}{C_m^{\mathrm{A}}} R^{\mathrm{HB}} - \frac{C_m^{\mathrm{S}}}{C_m^{\mathrm{A}}}\right). \tag{47}$$

Furthermore, since the left side of (28b) decreases with both L_{mk} and N_{mk} while R^{HB} increases with them, the "$\geq$" in (28b) should also be forced to "$=$". Therefore, we have

$$\sum_{m=1}^{M}\sum_{k=1}^{K} L_{mk} = \sum_{k=1}^{K}\left(1-\frac{R_k^{\mathrm{T}}\cdot\left(N_k^{\mathrm{A}}+\sum_{m=1}^{M} N_{mk}\right)}{R\left(N_k^{\mathrm{A}}+\sum_{m=1}^{M} N_{mk}\right)}\right). \tag{48}$$

Combining (47) and (48), we can obtain the R^{HB} as a function of N_{mk} only, as presented in Corollary 3.

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