Throughput-Power Tradeoff Association for User Equipments in WLAN/Cellular Integrated Networks

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***Abstract*—To meet the dramatic growth in mobile traffic, Wireless Local Area Networks (WLANs) have been integrated with cellular networks. We investigate the User Equipment (UE) association problem in WLAN/cellular integrated networks from game-theoretic perspective, by taking into account throughput as well as power consumption. In the case of WLAN offloading, random uplink traffic from UEs inevitably brings contention and collisions into WLANs, and thus the capacity of a WLAN system is decreased. To eliminate such side effect, UEs are encouraged to deliver uplink traffic over contention-free cellular networks. However, UEs will consume much more power when their uplink traffic is delivered over cellular networks instead of WLANs. Observing the above contradiction between throughput and power consumption, we define a utility function to reconcile the contradiction and formulate the UE association problem as a game. An incentive mechanism is involved to encourage UEs with enough energy to redirect their uplink traffic over cellular networks. We prove that such game is an exact potential game with at least one pure strategy Nash equilibrium. Then, a distributed algorithm is proposed for each UE to determine its uplink association. Finally, extensive numerical simulations validate the feasibility and effectiveness of the proposed association strategy.**

***Index Terms*—WLAN/cellualr integrated networks, UE association, potential game, decoupled UE association strategy, traffic redirection**

I. Introduction

IN recent years, the increasing use of wireless connectivity by mobile User Equipments (UEs) such as smart-phones has led to an exponential surge in mobile traffic, which keeps the cellular network's resources under heavy pressure. To meet the dramatic growth of mobile traffic, Wireless Local Area Networks (WLANs) have been integrated with cellular networks. In this case, UEs are provided with alternative wireless connectivity by the widely deployed and low-cost Access Points (APs) supporting the IEEE 802.11a/b/g/n standards. WLAN/cellular integrated networks have drawn many attentions from both academia and industry [1] [2]. Particularly, they would play an important role in the evolution towards 5G mobile networks where multiple Radio Access Technologies (RATs) are supposed to coexist to improve the network capacity and wireless coverage [3] [4].

In WLAN/cellular integrated networks, one of the essential problems that need to be addressed is the UE association problem. A UE can select a WLAN AP or cellular Base Station (BS) to associate with for data transmission. Moreover, the AP or BS selected for its downlink is not necessary the same as that for the uplink of the UE. There are two kinds of association strategies, termed coupled and decoupled association strategies respectively. The former is popular in the case of conventional WLAN offloading [5] [6], where the same AP or BS is involved to serve both the downlink and uplink traffic for a UE. A typical example is the WLAN-first strategy [7], which indicates that UEs prefer to associate with the WLAN AP in both downlink and uplink directions. However, in WLANs, the basic mechanism to access the medium is the Distributed Coordination Function (DCF), which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [8]. Random uplink traffic from UEs inevitably brings contention and collisions, and thus decreases a WLAN's throughput significantly, especially when the WLAN load is heavy. The decoupled strategy [9] [10] can be applied to eliminate such side effects, where uplink traffic from UEs is redirected to contention-free cellular networks instead of WLANs. Hence, downlink throughput in WLANs can be increased.

However, current UE association strategies in WLAN/cellular integrated networks, either coupled or decoupled, still face the following challenges: (1) Most existing work concerns maximizing throughput of the system, whereas UE preference such as power consumption is not fully considered. Particularly, more transmit power will be consumed when uplink traffic is redirected to cellular networks to eliminate contention and collisions in WLANs. This is not what energy limited UEs expected. (2) In WLAN/cellular integrated networks, a central manager is necessary to implement a centralized UE association strategy. However, it's difficult to deploy and maintain a central manager in integrated networks [4]. Besides, if the central manager breaks down, the association strategy fails. Therefore, distributed association strategies are desired. (3) Besides, UEs are selfish. In practice, UEs prefer to uplink associate with the WLAN AP when a nearby WLAN is available. In order to improve the WLAN's capacity, an incentive mechanism that encourages UEs to redirect their uplink traffic to cellular BSs is necessary.

To address the above challenges, we study the UE association problem in WLAN/cellular integrated networks from

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the perspective of game theory. The focus of this paper is on distributed UE association strategies where both downlink and uplink are taken into account. The basic idea is to make UEs perform the association strategy for balancing their throughput and power consumption. For example, a UE with enough energy is encouraged to transmit uplink traffic to a cellular BS. As compensation, it will get more downlink WLAN throughput. To the best of our knowledge, this is the first work to consider throughput-power tradeoff association for UEs in WLAN/cellular integrated networks. Our main contributions can be summarized as follows.

- We define a utility function for each UE by taking into account throughput as well as power consumption. Combined with an incentive mechanism, the utility function encourages each UE to make association decision for uplink based on not only its energy status but also WLAN throughput reward for downlink.
- We derive downlink throughput of a WLAN, where random number of UEs transmit their uplink traffic through the WLAN.
- We model the uplink UE association problem in WLAN/cellular integrated networks as a game, and prove that such game is an exact potential game with at least one pure strategy Nash Equilibrium (NE).
- We develop a distributed association strategy for UEs, and prove its convergence. Through extensive simulations, we find that the proposed strategy can effectively balance downlink throughput and uplink power consumption for UEs. Besides, compared to the WLAN-first strategy, WLAN's downlink throughput is significantly improved.

It should be noted that traffic redirection is needed when a UE changes the point that it associates with. However, traffic redirection in WLAN/cellular integrated networks has been well studied in [10]–[12], which can be applied to our work directly.

The rest of the paper is organized as follows. We give an overview of related work in Section II. In Section III, we present the system model with a utility function and an incentive mechanism. In Section IV, we analyze downlink throughput in a WLAN and uplink transmit power when a UE associates with a WLAN AP or cellular BS, which are two metrics that determine the UE's utility. In section V, we formulate the UE association problem as an potential game and propose a distributed association strategy to achieve the NE. Numerical results are presented and analyzed in Section VI. Finally, we conclude our work in Section VII.

II. Related Work

In WLAN/cellualr integrated networks, the UE association problem has received significant attention in recent years. Existing association strategies for UEs can be divided into two categories, i.e., coupled and decoupled association strategies.

The pioneer work of coupled association strategies was the WLAN-first strategy [7], which has been widely employed in WLAN offloading. The WLAN-first access strategy was also considered as a baseline access strategy among network selection approaches [3]. Authors in [13] proposed an enhanced power-friendly access network selection strategy, which could prolong the battery life of mobile UEs. In [14], the interaction among UEs was modeled as a non-cooperative congestion game, where players (i.e., UEs) selfishly selected the access network that minimizes their perceived selection cost. [15] investigated a general performance evaluation framework for network selection strategies in 3G-WLAN interworking networks. However, almost all of the above work ignores the negative influence of uplink traffic from UEs on the WLAN's capacity [10]. This is one focus of our work.

It has been shown that decoupled association strategies might result in more performance benefits where joint downlink-uplink optimization is considered. [9] proposed a decoupled association strategy, where UEs located in the WLAN's coverage downlink associated with its target AP, while uplink associated with the cellular BS. Three integration options have been presented in [10] to provide the enhanced WLAN's capacity by diverting uplink traffic destined to WLAN APs via cellular networks. As another kind of solutions for the UE association problem, researches in [16]–[18] focused on multi-homing mechanisms where UEs simultaneously accessed multiple wireless networks. However, more uplink transmit power should be consumed when a UE redirects its uplink traffic to a cellular BS. In order to encourage more UEs to redirect their uplink traffic to cellular BSs, an incentive mechanism is necessary, which is lacking in the above work.

Some studies related with spectral-energy tradeoff have been considered in the literature. Ge *et al.* in [33] indicated that the trade-off between spectrum and energy efficiency of two-tier femtocell networks can be adjusted by configuring different numbers of open channels in a femtocell. New spatial spectrum and energy efficiency models for random cellular networks have been proposed in [34]. Authors in [35] analyzed the spectral-energy efficiency tradeoff for cognitive radio networks. The above researches focused on the performance of the system, while we mainly focus on the performance of UEs. Besides, the studies in [33]–[35] mainly considered the configuration and allocation of channels belonging to a homogeneous network, which made their proposals not easy to be extended for heterogeneous networks (e.g., WLAN/ cellular integrated networks) directly.

In wireless networks, multiple UEs share limited radio resources. UEs can either cooperate or compete with each other to achieve their objectives. To analyze the interaction and competition among rational and selfish UEs, game theory has been widely adopted to model individual or group behaviour of UEs for multiple access in wireless networks [19]. Authors in [20] investigated the problem of joint base station selection and resource allocation through an exact potential game model. In [21], a college admissions game was used to analyze the problem of uplink user association in wireless small cell networks. A bargaining game based access network selection scheme for call requests in integrated networks has been proposed in [22]. Game theory is an effective tool to analyze the mutual influence among UEs in our proposed problem.

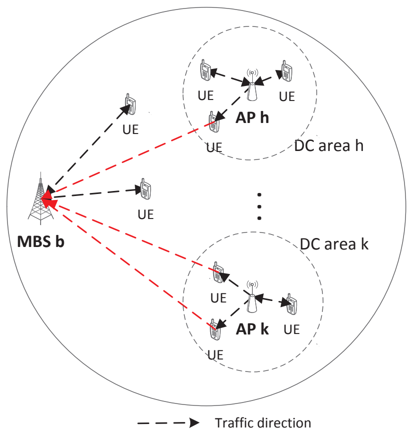


Fig. 1. Illustration of a WLAN/cellular integrated network

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Definition
R	Physical transmission rate in WLAN
L	Payload size of a packet in WLAN
R_{AP}	Downlink throughput of WLAN AP
P_i^u	Uplink transmit power consumed by UE i
$P_{i,max}$	Maximum allowed P_i^u of UE i
P_i^l	P_i^u when UE i uplink associates with MBS b
P_i^w	P_i^u when UE i uplink associates with WLAN AP k
λ	Uplink traffic generation rate (packets/slot)
r^u	Uplink traffic generation rate (bps)
$r_i^d(r_i^u)$	Downlink(Uplink) throughput of UE i
T_{slot}	Duration time of a slot in WLAN
α	Incentive factor adopted by WLAN
N	Number of UEs accommodated by WLAN k
n	Number of UEs uplink associating with WLAN k
w_i	Weight factor of UE i

III. System Model

A. Network Model

As shown in Fig. 1, we consider bidirectional transmission in a WLAN/cellular integrated network, where several WLAN APs are overlaid in the macrocell. The MBS of the macrocell network is located at the center of the cell, and WLAN APs are deployed around the MBS. All the networks in the cell are assumed to be operated by the same service provider. The 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) [27] and IEEE 802.11g are used as the specific technologies for cellular networks and WLANs respectively in this paper. UEs are equipped with both WLAN and LTE radio interfaces, and are able to connect to both networks simultaneously [18].

There are 3 non-overlapping channels for WLAN in 2.4GHz, and more non-overlapping channels for WLAN in 5 GHz [37], we assume that the neighbour WLAN APs can be assigned with non-overlapping channels. Thus there is no interference among the MBS and APs. It should be noted that similar assumptions have been adopted in [38] [39]. The area covered by both the cellular network and a WLAN is referred to as *Double-Coverage (DC) area*. The integral system includes two kinds of UEs, which are either covered or not covered by the WLAN AP. As for UEs that are not covered by the WLAN AP, they will have no choice but to downlink and uplink associate with the MBS. Hence, in this paper, we focus on the uplink association problem of UEs that are located in DC areas. Without loss of generality, we consider DC area k, which is under the coverage of both WLAN AP k and MBS b. We denote the UEs located in DC area k by set $\mathcal{N} = \{1, 2, ..., N\}$.

In this paper, decoupled UE association is focused. UEs in set $\mathcal{N}$ downlink associate with WLAN AP k. However, each UE will choose to uplink associate with the AP or BS, from which it can obtain higher benefits. Decoupled UE association in WLAN/cellular integrated networks can be implemented by augmenting MPTCP [10]. MPTCP operates at the transport layer and is able to schedule uplink traffic on LTE TCP subflows and downlink traffic on WLAN TCP subflows. The specific implementation of MPTCP is out the scope of this paper. Besides, the amount of necessary uplink traffic, such as TCP ACKs and control signaling, is relatively small. Therefore, this kind of traffic can be neglected in analysis.

Similar to [9], we consider a full buffer traffic model for downlink traffic of each UE. That is to say, there is always data waiting to be transmitted in the downlink buffer for each UE [7]. The UE's uplink traffic generation rate may fluctuate over time. Using the real-time uplink traffic generation rate in analysis will lead to fluctuations in uplink power consumption and WLAN throughput, which will further result in unstable UE association. Based on the above consideration, we adopt the average uplink traffic generation rate in analysis. We assume that each UE generates uplink packets with an average rate, λ (packets/slot), or equivalently $r^u = \frac{\lambda \cdot L}{T_{slot}}$ (bps), where L (bits/packet) and T_{slot} (seconds/slot) are the payload size and duration time of a backoff slot in the WLAN respectively. Same uplink traffic model has been adopted in [7].

As many symbols are used in this paper, we summarize the important ones in Table I. The superscripts and subscripts 'l', 'w' , 'u' and 'd' denote LTE network, WLAN, uplink direction and downlink direction, respectively.

B. Utility Function

The operational time of a UE in between battery chargings is considered to be a significant factor in the UE perceived satisfaction [23]. Thus except the obtained throughput, UEs concern regulating the energy usage. In this work, the optimization objective of each UE is to maximize the revenue gain, which equals revenue minus cost [26]. We define a utility function for UEs to reflect their revenue gains by taking into account throughput as well as power consumption. The utility function of UE i ($i \in \mathcal{N}$) is

$$U_i = \left(\frac{1}{1 + e^{-1.5 r_i^d}} - 0.5 \right) + f(r_i^u, r^u) - w_i \cdot \frac{P_i^u}{P_{i,max}}, \quad (1)$$

where r_i^d is the downlink throughput obtained from the WLAN AP, r_i^u is the uplink throughput achieved from the WLAN AP or the cellular BS according to its association decision, and r^u is the average uplink traffic generation rate. P_i^u and $P_{i,max}$ denote the consumed uplink transmit power and the allowed maximum transmit power consumed by UE i respectively.

$P_{i,max}$ is used to normalize P_i^u. In this paper, we model an uplink UE association game to analyze the mutual influence from UEs. Since only the UEs located in DC areas are considered as the players in the game, we only consider this type of UEs' influence on the utility function.

The first item is a concave function with respect to r_i^d, which denotes the benefit that UE i obtains from downlink data transmission. Due to adopting a full buffer traffic model, downlink traffic of each UE can be viewed as best-effort traffic [24]. Such benefit function first increases significantly when the downlink throughput is at low level. Then its gradient gradually decreases and the benefit changes smoothly as its downlink throughput increases. The second item denotes the benefit that UE i obtains from uplink data transmission, which is a step function as follows:

$$f(r_i^u, r^u) = \begin{cases} 0 & r_i^u < r^u, \\ 1 & r_i^u \geq r^u. \end{cases} \tag{2}$$

For uplink transmission, the benefit function (2) means the uplink service rate should be guaranteed. For example, when the uplink service rate obtained from the WLAN AP can not satisfy the UE's uplink rate requirement, the UE will attempt to switch its uplink association to the MBS. Similar benefit functions have been defined in [24]. We add the utilities of downlink and uplink traffic flows together to reflect UEs' revenue, similar to the approach used in [25].

The last item denotes the cost of UE i when uplink transmit power P_i^u is consumed to fulfill its uplink traffic transmission. We normalize the satisfaction from achievable throughput in the revenue function. Correspondingly, we also normalize the power consumption with P/P_{max}, and ω_i is defined as the price parameter of UE i to reflect the tradeoff between achieved throughput and power consumption. For instance, when the UE's residual battery capacity is low, it should pay more attention to power consumption and choose a larger weight factor from $[\underline{w}, \overline{w}]$. On the contrary, a UE with enough energy should choose a smaller weight factor to indicate its expectation for higher throughput.

C. Incentive Mechanism

It has been proved that the WLAN's capacity can be enhanced by decreasing the number of uplink traffic flows destined to the WLAN AP [9]. Researches have observed high power overheads in cellular network, which contributes to the fact that cellular interfaces are less power-efficient than WiFi interfaces [40]. Thus, under the premise of guaranteeing the uplink rate requirement, more transmit power will be consumed when a UE's uplink traffic is redirected to the cellular network from the WLAN. In the utility function, the cost of a UE is directly related to its uplink power consumption. As compensation, reward should be allocated to UEs performing such uplink traffic redirection.

In a WLAN, UE's downlink traffic is coordinated by the WLAN AP. In this case, UEs can achieve differentiated downlink throughput through a buffer based scheme at the WLAN AP. Such scheme can be implemented as follows, which is similar to that in [9]. Each downlink flow builds a buffer in the target AP. Every time when the WLAN AP occupies the channel, it will choose a non-empty buffer and send the first packet in the buffer. Thus downlink throughput for each UE is determined by the probability that the target AP chooses its corresponding buffer.

Based on the above buffer based scheme, we propose an incentive mechanism. Let R_{AP} denote total downlink throughput of WLAN AP k. We define a pre-determined ratio $\frac{\alpha}{N}$, where $\alpha \in [0, 1]$ is referred to as an *incentive factor* and N is the number of UEs that WLAN AP k accommodates. A UE will be allocated additional downlink throughput, $\frac{\alpha}{N} R_{AP}$, if it redirects its uplink traffic to the cellular network through its LTE radio interface. Remaining downlink throughput of WLAN AP k will be equally shared by all UEs in $\mathcal{N}$. In other words, when a UE redirects its uplink traffic to the cellular network, the WLAN AP will choose its downlink buffer with $\frac{\alpha}{N}$ higher probability than the UEs that do not redirect their uplink traffic.

IV. Analysis of Throughput and Power Consumption in Integrated Networks

In this section, two key components of the utility function are analyzed and derived, namely achieved downlink throughput and consumed power for uplink transmission of UEs. These two components are also considered as important performance metrics to evaluate the effectiveness of the association strategies. Firstly, the downlink throughput of a WLAN is analyzed when bidirectional transmission is considered. Then we derive the downlink throughput and the uplink transmit power consumption for each UE when the decoupled UE association strategy is employed.

A. Analysis of Downlink Throughput

Each UE's data transmission is modeled as a queue, where the average arrival rate is λ (packets/slot). A UE is in the stable state if all arriving packets are transmitted with a finite delay, which is equivalent to the condition that the average service rate μ (packets/slot) is strictly greater than λ (packets/slot) [36]. We can say that the system is operating in the stable state when all UEs are in the stable state. Since each UE contends the channel for data transmission with the same priority, μ is same for all UEs, and the system being in the stable state is equivalent to the condition that $\mu > \lambda$.

A tuple (N, n) is used to represent the status of a WLAN. The status tuple means that N UEs are accommodated by the target WLAN AP, wherein n UEs uplink associate with the WLAN AP, and the other $(N - n)$ UEs uplink associate with the LTE MBS. When too many UEs uplink associate with the WLAN AP, contention and collisions would decrease the channel utilization of WLAN and make the system unstable. In this section, we focus on finding the maximal n that keeps the system stable for a specific N, and calculating the WLAN AP's throughput when the WLAN is stable. Hence, the following analysis is based on the assumption that the WLAN system is stable, namely $\mu > \lambda$.

The probability that there are packets waiting to be transmitted in each UE's uplink buffer is $\frac{\lambda}{\mu}$. Because the WLAN

AP contends for the channel to serve all accommodated UEs and there are always packets waiting to be transmitted in the downlink buffer for each UE, the probability that the WLAN AP has packets to be transmitted is 1. We denote the service rate of the WLAN AP by μ_{AP} (packets/slot).

In general, the downlink rate perceived by a UE depends on the actual "physical" conditions of the UE, i.e., position, assigned modulation scheme based on propagation conditions, etc. For ease of analysis, we consider a flat average rate for all UEs associating with the WLAN AP. However, the analyses in this paper can be extended to UEs with differentiated service rates.

For an arbitrary UE uplink associating with the WLAN AP, when this UE transmits in a time slot, a collision will happen if any other UEs or the WLAN AP transmit in the same time slot. Thus the collision probability for a packet being transmitted in a time slot by a UE is given by

$$\eta_u = 1 - (1 - \frac{\lambda}{\mu}\tau_u)^{n-1}(1 - \tau_d), \tag{3}$$

where τ_u, τ_d are the transmission probability of a packet from a UE and WLAN AP k, respectively. Similarly, the collision probability for a packet being transmitted in a time slot by the WLAN AP is given by

$$\eta_d = 1 - (1 - \frac{\lambda}{\mu}\tau_u)^n. \tag{4}$$

When the collision probability of a packet transmission is η, let $E(\eta)$ and $\overline{W}(\eta)$ denote the average transmission attempts and the average backoff time respectively. Therefore, we have $\tau_u = E(\eta_u)/\overline{W}(\eta_u)$ and $\tau_d = E(\eta_d)/\overline{W}(\eta_d)$. $E(\eta)$ and $\overline{W}(\eta)$ are given by [8]

$$E(\eta) = \frac{1 - \eta^{m+1}}{1 - \eta}; \tag{5}$$

$$\begin{aligned} \overline{W}(\eta) = (1-\eta)\frac{W}{2} + \cdots + \eta^{m'}(1-\eta)\frac{\sum_{i=0}^{m'} 2^i W}{2} + \\ \cdots + \eta^m \frac{\sum_{i=0}^{m'} 2^i W + (m - m')2^{m'} W}{2}, \end{aligned} \tag{6}$$

where m', m, W are the maximum backoff stage, the retransmission limit and the minimum backoff window size, respectively.

Under the DCF mode[1], the average duration time of a successful and collided transmission are given by T_s and T_c, respectively[2]. The average collision time of a frame, $T_c(\eta)$, can be written as [8]

$$\begin{aligned} \overline{T}_c(\eta) &= \eta(1-\eta) \cdot T_c + \cdots + \eta^m(1-\eta) \cdot mT_c \\ &= \frac{\eta[1 - (m+1)\eta^m + m\eta^{m+1}]T_c}{1 - \eta}. \end{aligned} \tag{7}$$

[1]Although this paper focuses on the DCF mode, the analysis can be extended to the request-to-send/clear-to-send (RTS/CTS) mode.

[2]In DCF mode, $T_s = T_{DIFS} + L/R + T_{SIFS} + T_{ACK}$ and $T_c = T_{DIFS} + L/R + T_{ACK\_TO}$, where R is physical transmission rate of UE when it is uplink transmitting to the WLAN AP. The $T_{DIFS}, T_{SIFS}, T_{ACK}$ and T_{ACK_TO} are DCF interframe space (DIFS), short interframe space (SIFS), transmission time of an ACK frame, and waiting time for an ACK timeout, respectively.

Given the above parameters, the WLAN AP's average downlink throughput is given by Lemma 1.

Lemma 1. *When a WLAN system is under a stable status* (N, n)*, the downlink throughput of the WLAN AP can be expressed as*

$$R_{AP} = \mu_{AP} \cdot \frac{L}{T_{slot}} = \frac{1 - [T_s + \frac{1}{2}\overline{T}_c(\eta_u)]n\lambda}{\overline{W}(\eta_d) + T_s + \frac{1}{2}\overline{T}_c(\eta_u)} \cdot \frac{L}{T_{slot}}, \tag{8}$$

which is a function of n*.*

Proof: When a WLAN system is under stable status (N, n), the average service time of a packet from the WLAN AP consists of four parts, namely 1) the transmission time of such frame, 2) the transmission time of $\frac{n\lambda}{\mu_{AP}}$ frames of n UEs, 3) the time that the channel is sensed busy due to collisions, 4) the average backoff time of the WLAN AP. Thus we have

$$\frac{1}{\mu_{AP}} = T_s + \frac{n\lambda}{\mu_{AP}}T_s + \frac{1}{2}\overline{T}_c(\eta_d) + \frac{n\lambda}{2\mu_{AP}}\overline{T}_c(\eta_u) + \overline{W}(\eta_d). \tag{9}$$

Further, the service rate of the WLAN AP is

$$\mu_{AP} = \frac{1 - [T_s + \frac{1}{2}\overline{T}_c(\eta_u)]n\lambda}{\overline{W}(\eta_d) + T_s + \frac{1}{2}\overline{T}_c(\eta_u)}. \tag{10}$$

Then substitute μ_{AP} into $R_{AP} = \mu_{AP} \cdot \frac{L}{T_{slot}}$, we obtain Eq. (8).

Similar to Eq. (9), the average service time of a packet from a UE can be expressed as

$$\begin{aligned} \frac{1}{\mu} &= \left[\frac{(n-1)\lambda}{\mu} + 1 + \frac{\mu_{AP}}{\mu}\right] T_s + \overline{W}(\eta_u) \\ &+ \frac{1}{2}\left[\left(\frac{(n-1)\lambda}{\mu} + 1\right)\overline{T}_c(\eta_u) + \frac{\mu_{AP}}{\mu}\overline{T}_c(\eta_d)\right]. \end{aligned} \tag{11}$$

Given n, the Eqs. (3) and (4), along with (9) and (11) compose nonlinear equations, which could be solved numerically to obtain η_u, η_d, μ and μ_{AP}. In other words, all of these parameters can be expressed as implicit functions of n. Thus R_{AP} is a function of n, we complete the proof. □

Remark 1: Since the collision probabilities are increasing functions of n [8], μ and μ_{AP} decrease with the increase of n. There exists a specific value n_0 such that $\mu < \lambda$ when $n > n_0$. In this case, congestion occurs in the WLAN such that due to accommodating too many uplink traffic flows, the rate requirements of UEs' uplink traffic flows cannot be satisfied. Besides, R_{AP} can be pre-calculated offline and be applied to different scenarios where different number of UEs are accommodated by the WLAN AP.

With the incentive mechanism, UE's achieved downlink throughput will be determined by its uplink association and WLAN's downlink throughput. We define an indicative function s_i for UE i $(i \in \mathcal{N})$, which is given by

$$s_i = \begin{cases} 1, & \text{UE i uplink associates to WLAN AP } k \\ 0, & \text{UE i uplink associates to MBS } b \end{cases}. \tag{12}$$

Then downlink throughput achieved by UE i can be expressed as

$$r_i^d = \frac{1}{N}\left[1 + \frac{\sum_{i\in\mathcal{N}} s_i}{N}\alpha - s_i \cdot \alpha\right] \cdot R_{AP}(\sum_{i\in\mathcal{N}} s_i), \tag{13}$$

where N is the number of UEs in $\mathcal{N}$. It can be seen that $\sum_{i\in\mathcal{N}} r_i^d = R_{AP}(\sum_{i\in\mathcal{N}} s_i)$.

B. Analysis of Uplink Transmit Power Consumption

The uplink transmit power consumption for each radio interface consists of two parts. One is a fixed circuit power consumption, and the other is a dynamic part, which scales with the UE's service rate. Due to uplink open loop power control [28] of LTE, the target Signal to Noise Ratio (SNR) at the BS is a constant value γ. Let $P_{i,tx}$ denote the dynamic part of transmit power consumption of UE i. We have the following equation [28]:

$$\gamma = \frac{P_{i,tx} h_{i,b}}{B\sigma^2},$$

where B is the bandwidth allocated by MBS b to UE i for satisfying its uplink rate requirement, σ^2 is the noise power density, and $h_{i,b}$ denotes the channel gain from UE i to MBS b. On the other hand, according to the Shannon formula, we have $r^u = Blog_2(1+\gamma)$. Combining the equation of γ and r^u, we can deduce the expression of $P_{i,tx}$ as follows:

$$P_{i,tx} = \frac{\gamma\cdot\sigma^2}{h_{i,b}}\cdot\frac{r^u}{log_2(1+\gamma)}.$$

When UE i uplink associates with the MBS, total consumed power for uplink transmission of UE i is given by

$$P_i^l = \frac{\gamma\cdot\sigma^2}{h_{i,b}}\cdot\frac{r^u}{log_2(1+\gamma)} + P_c^l, \tag{14}$$

where P_c^l is the fixed circuit power consumption for LTE radio interface.

In practice, WiFi cards generally use fixed emitted power P^w. Due to collisions, a packet will be averagely transmitted $E(\eta^u) = \frac{1-(\eta^u)^{m+1}}{1-\eta^u}$ times until it's successfully received by the WLAN AP. Since the probability that a frame has been dropped after m retransmissions is negligible, $(\eta^u)^{m+1}$ can be ignored in $E(\eta^u)$. The ratio of time during which UE i is in transmission state is $\frac{r^u}{R(1-\eta^u)}$, where η^u is a function of n. When UE i chooses to uplink associates with the WLAN AP, consumed power for uplink transmission of UE i is given by

$$P_i^w = \frac{r^u P^w}{(1-\eta^u(n))R} + P_c^w, \tag{15}$$

where P_c^w is the fixed circuit power consumption for WLAN radio interface.

V. User Association Strategy From Game-theoretic Perspective

In this section, we investigate the distributed association strategy for UEs from game-theoretic perspective based on the previously defined utility function. Firstly, the UE association problem is formulated as a game. The game has been proved to be an exact potential game, and there exists at least one pure strategy NE. Finally, UEs determine their uplink association according to a distributed algorithm, which is based on the best-response-dynamics [29].

A. Game Model for UEs

In our focused problem, when a UE changes its uplink association, the WLAN's capacity as well as the utilities of other UEs are affected. As a result, some UEs may change their uplink association as reactions. We resort to game theory to analyze such kind of mutual influence from UEs and formulate a game for the uplink UE association problem as follows.

Definition 1 (**Uplink UE Association Game**). Consider DC area k, an uplink UE association game is defined as

$$<\mathcal{N}, (S_i)_{i\in\mathcal{N}}, (U_i)_{i\in\mathcal{N}}>,$$

where $\mathcal{N} = \{1, 2, \dots, N\}$ is the set of players, namely UEs located in DC area k. $(S_i)_{i\in\mathcal{N}}$ is the set of pure strategies. S_i represents the set of actions for player i, which is defined according to the indicative function in expression (12). $(U_i)_{i\in\mathcal{N}}$ indicates the set of utility functions where $U_i : S \to \mathbb{R}$ is a function from the set of all action profiles $S = \prod_{i\in\mathcal{N}} S_i$ to real numbers. The utility function, U_i, has been defined in expression (1).

In this game, "1" and "0" are defined as the pure strategy of uplink association with WLAN AP k and LTE MBS b respectively. $S_i = \{0, 1\}$. We denote by set S_{-i} the action profiles for all UEs except the ith UE and by $\mathbf{s} = (s_i, \mathbf{s}_{-i})$ a tuple action profile, where s_i and $\mathbf{s}_{-i}$ corresponds to the element in S_i and S_{-i} respectively. For an arbitrary UE i, each part of its utility function will be analyzed as follows.

The first part of U_i is directly determined by UE i's downlink throughput. For an arbitrary vector $\mathbf{x}$, the expression $||\mathbf{x}||_0$ is defined as the zero norm of $\mathbf{x}$, which is the number of non-zero elements in the vector. In fact, the action profile $\mathbf{s}$ can be viewed as a vector $(s_1, \dots, s_i, \dots, s_N)$. Hence, combining with the definition of s_i $(i \in \mathcal{N})$, the zero norm of vector $\mathbf{s}$ can be expressed as $||\mathbf{s}||_0 = \sum_{i\in\mathcal{N}} s_i$. In other words, $||\mathbf{s}||_0$ is equivalent to the parameter 'n' in Lemma 1, which is the number of UEs uplink associating with WLAN AP k in set $\mathcal{N}$. Based on Eq. (13), downlink throughput obtained by UE i can be expressed as

$$r_i^d(s_i, \mathbf{s}_{-i}) = \frac{1}{N}\left[1 + \frac{||\mathbf{s}||_0}{N}\alpha - s_i\cdot\alpha\right]\cdot R_{AP}(||\mathbf{s}||_0). \tag{16}$$

According to Remark 1 in Section IV, $\mu < \lambda$ when $||\mathbf{s}||_0 < n_0$, which is equivalent to that $r_i^u < r^u$ when $||\mathbf{s}||_0 < n_0$. Hence, the second part of U_i can be expressed as

$$f(r_i^u, r^u) = 1 + s_i\{f(||\mathbf{s}||_0, n_0) - 1\}, \tag{17}$$

which means that $f(r_i^u, r^u) = 0$ if $s_i = 1$ and $||\mathbf{s}||_0 < n_0$, otherwise $f(r_i^u, r^u) = 1$. The function $f(x, y)$ is a step function defined as Eq. (2).

On the other hand, the last part of U_i is determined by UE i's consumed power for uplink transmission. Based on Eqs. (14) and (15), UE i's consumed power for uplink transmission can be expressed as

$$P_i^u = P_i^l + s_i\{\frac{r^u P^w}{(1-\eta^u(||\mathbf{s}||_0))R} - P_i^l\}. \tag{18}$$

From Eqs. (17)-(19), we can find that each part of the utility function U_i is a specific function of s_i and $||\mathbf{s}||_0$. That is to say, each UE's utility function only depends on its own strategy and the number of UEs choosing the strategy "1".

Before we prove the existence of a pure strategy NE of the uplink UE association game, we give the formal definition of a potential game [29] as follows.

Definition 2 (**Potential Game**)**.** A strategic game $\mathcal{G} =< \mathcal{N}, (S_i)_{i\in\mathcal{N}}, (U_i)_{i\in\mathcal{N}} >$ is called an *exact potential game* if there exists a function $\Phi : S = \prod_i S_i \to \mathbb{R}$ such that for any $i \in \mathcal{N}$ and any $(s_i, \mathbf{s}_{-i}), (s_i^*, \mathbf{s}_{-i}) \in \mathcal{N}$, we have

$$U_i(s_i, \mathbf{s}_{-i}) - U_i(s_i^*, \mathbf{s}_{-i}) = \Phi(s_i, \mathbf{s}_{-i}) - \Phi(s_i^*, \mathbf{s}_{-i}), \quad (19)$$

wherein the vector $\mathbf{s}_{-i}$ denotes the vector of the strategies of all players except the ith one.

The property of the uplink UE association game and the existence of a pure strategy NE will be illustrated in the following lemma.

Lemma 2. *The uplink UE association game is an exact potential game, and has at least one pure strategy NE.*

Proof: Let us denote the potential function as $\Phi(\mathbf{s})$. For the convenience of expression, we define

$$\mu_1(||\mathbf{s}||_0) = \frac{1}{1 + e^{-1.5 r_i^d(1,\mathbf{s}_{-i})}} + f(||\mathbf{s}||_0, n_0), \quad (20)$$

and

$$\mu_0(||\mathbf{s}||_0) = \frac{1}{1 + e^{-1.5 r_i^d(0,\mathbf{s}_{-i})}} + 1. \quad (21)$$

Even though $\mu_1(0)$ and $\mu_0(N)$ have no values, we define $\mu_1(0) = f(||\mathbf{s}||_0, n_0)$ and $\mu_0(N) = 1$ for consistency. We propose that potential function is chosen as follows:

$$\begin{aligned}\Phi(\mathbf{s}) = &\sum_{j=0}^{||\mathbf{s}||_0} \mu_1(j) + \sum_{j=||\mathbf{s}||_0}^{N} \mu_0(j) \\ &+ \sum_{i=1}^{N} \frac{w_i \cdot s_i}{P_{i,max}} (P_i^l - P_i^w(||\mathbf{s}||_0)).\end{aligned} \quad (22)$$

When an arbitrary UE i changes its strategy unilaterally from $s_i = 1$ to $s_i = 0$, the change of the function value is

$$\begin{aligned}\Phi(1, \mathbf{s}_{-i}) - \Phi(0, \mathbf{s}_{-i}) = &\sum_{j=0}^{1+||\mathbf{s}_{-i}||_0} \mu_1(j) + \sum_{j=1+||\mathbf{s}_{-i}||_0}^{N} \mu_0(j) \\ &- \left(\sum_{j=0}^{||\mathbf{s}_{-i}||_0} \mu_1(j) + \sum_{j=||\mathbf{s}_{-i}||_0}^{N} \mu_1(j) \right) + w_i \frac{P_i^l - P_i^w(||\mathbf{s}||_0)}{P_{i,max}} \\ &+ \sum_{j=1, j\neq i}^{N} w_j \frac{(P_j^w(||\mathbf{s}_{-j}||_0) - P_k^w(1 + ||\mathbf{s}_{-j}||_0)) \cdot s_j}{P_{j,max}},\end{aligned} \quad (23)$$

where $||\mathbf{s}_{-j}||$ means the number of UEs in the set $\mathcal{N}/\{j\}$ which choose to uplink associate with WLAN AP k.

According to the analysis in [30], in the IEEE 802.11 DCF, when the minimum back-off window $W \gg 1$, we can make an accurate approximation $\eta^u(n) \approx \eta^u(n+1)$, namely change in collision probability η^u is negligible if only one UE alters its uplink association. Then from Eq. (15), we have $\frac{P_i^w(n) - P_i^w(n+1)}{P_{i,max}} \approx 0$. The last item in Eq. (23) can be neglected, and we have

$$\begin{aligned}&\Phi(1, \mathbf{s}_{-i}) - \Phi(0, \mathbf{s}_{-i}) = \\ &= \left(\mu_1(||\mathbf{s}||_0) - w_i \frac{P_i^w(||\mathbf{s}||_0)}{P_{i,max}} \right) - \left(\mu_0(||\mathbf{s}||_0) - w_i \frac{P_i^l}{P_{i,max}} \right) \\ &= U_i(1, \mathbf{s}_{-i}) - U_i(0, \mathbf{s}_{-i}).\end{aligned} \quad (24)$$

Based on Definition 2, the uplink UE association game is an exact potential game. According to corollary 3.1 in [29], this game has at least one pure strategy NE. This completes the proof. □

B. Distributed Association Algorithm for UEs

Algorithm 1: Distributed Association Algorithm for UE i

Initialize N; α; $||\mathbf{s}||_0$; s_i^n: current action; l_i: order number;
Initialize P_i^l and $P_i^w(||\mathbf{s}||_0)$ according to (14) and (15);
while *the stopping-condition is not satisfied* **do**
  for $k = 1 : N$ **do**
    if $l_i = k$ **then**
      $||\mathbf{s}_{-i}||_0 = ||\mathbf{s}||_0 - s_i^n$;
      $s_i^p = \underset{s\in S_i}{argmax}\, U_i(s, \mathbf{s}_{-i})$;
      if $s_i^p \neq s_i^n$ **then**
        $s_i^n = s_i^p$;
        send a message including this change to the WLAN AP;
      end
    end
    update $||\mathbf{s}||_0$ from the WLAN AP;
  end
end
UE i executes its uplink association according to s_i^n.

Given any initial WLAN status (N, n), all UEs in DC area k are assumed to downlink associate with the WLAN AP. By exploring the property of the exact potential game, we propose a distributed association algorithm for UEs based on best-response-dynamics. In the best-response-dynamics process, a) only one player acts at each time step, and b) the acting player executes its best response, $B_i(\mathbf{s}_{-i}) = \underset{s_i}{argmax}\, U_i(s_i, \mathbf{s}_{-i})$, given the most recent actions of the other players.

In order to implement step a), the WLAN AP coordinates UEs' sequential actions by randomly selecting a UE and giving a unique order number from $[1, N]$ to this UE. The process continues until each UE has its own order number. Then each UE can sequentially updates its action according to its order number. However for step b), if each UE executes its best response whenever its optimal action changes, frequent association switches and switching back and forth will emerge.

In an actual association process, e.g., association with the LTE MBS, the following information exchange will be required. A UE will send an association request to the MBS.

Then the MBS send back an association response (request acknowledgement) after the decision of admission control. After synchronization and resource allocation, the association process completes. An actual association process incurs not only more information exchange, but also more time delay. However when a UE decides its preferred action in each step, it concerns the parameter $||\mathbf{s}||_0$ instead of the specific $\mathbf{s}$. Hence, we propose to use a simplified interaction process between the UEs and the WLAN AP as follows. If UE i prefers to change its action according to its current best response, it will send a message including this change to the WLAN AP. Whereafter, the WLAN AP records the current optimal association actions for all UEs, updates and broadcasts new $||\mathbf{s}||_0$. This step continues until no UE will change its action.

The proposed distributed association strategy for an arbitrary UE is presented in Algorithm 1. The UE obtains the parameters in *Line* 1 from the WLAN AP. *Lines* 4-14 means an iteration cycle during which all UEs can update their actions once time. The stopping condition in *Line* 3 is that $||\mathbf{s}||_0$ keeps unchanged during one iteration cycle.

Since each UE sequentially updates its action, the interval between the time that two UEs updating their actions should be properly configured. A small interval might result in uncompleted interaction process while a large interval might reduce the convergence rate. The interval can be just set as the time required to complete *Lines* 5-13 for a UE.

For the convergence of Algorithm 1, we have Lemma 3. The convergence speed is also evaluated by the simulations in Section VI.

Lemma 3. *The proposed distributed association algorithm converges to a NE, for any initial strategies within a finite number of iterations.*

Proof: Since the uplink association game for UEs is an exact potential game, a NE point maximizes the potential function. Besides, the potential function will increase whenever a UE updates its action during *Lines* 5-13 in Algorithm 1. Since the number of possible combinations is limited, the proposed algorithm will converge to a NE within a finite number of iterations. □

Algorithm 1 will converge to a person-by-person maximum of the potential function regardless of the UEs' playing order and the initial condition of the game. Each UE may change its uplink association in the last step of Algorithm 1. The proposed simplified interaction process can avoid unnecessary associations, and reduce signalling overhead and time overhead through avoiding executing actual association processes.

C. Price of Anarchy

One useful notion for evaluating the performance of a NE is the *price of anarchy* [29]. Since the final NE due to players' distributed behaviors is not necessarily social pareto optimal, PoA refers to the price for the lack of a centralized controller. Thus, PoA can be used to study the efficiency of a distributed method by assigning a performance metric to each outcome and calculating the ratio between them.

A common measure of efficiency of each outcome is the welfare function $W : S \to \mathbb{R}$, i.e., the sum of all players' utilities. In this manuscript, given $\mathbf{s} \in S$, the welfare function can be expressed as $W(\mathbf{s}) = \sum_{i=1}^{N} U_i(\mathbf{s})$. Let $\hat{\mathbf{s}} \in S$ denote the social optimum point, i.e., $\hat{\mathbf{s}} = argmax_{\mathbf{s}\in S} W(\mathbf{s})$. In addition, let $\bar{\mathbf{s}}$ be an arbitrary strategy profile obtained via the proposed distributed method, namely a NE in this manuscript. Then for the potential game, the PoA for the NE point obtained from our game will be defined as

$$PoA(\bar{\mathbf{s}}) = \frac{W(\hat{\mathbf{s}})}{W(\bar{\mathbf{s}})} \geq 1.$$

Similar definition of PoA has been adopted in [41].

In order to evaluate PoA, $W(\hat{\mathbf{s}})$ should be calculated. However, calculating $W(\hat{\mathbf{s}})$ through traversing S is impractical because the complexity will be $O(2^N)$. Fortunately, we can reduce the complexity significantly through the following method. Given $\mathbf{s} = (s_1, \ldots, s_i, \ldots, s_N)$, $W(\mathbf{s})$ can be expressed as:

$$\begin{aligned} W(\mathbf{s}) &= \mu_1(||\mathbf{s}||_0) \cdot ||\mathbf{s}||_0 + \mu_0(||\mathbf{s}||_0) \cdot (N - ||\mathbf{s}||_0) \\ &- \sum_{i=1}^{N} \frac{w_i \cdot P_i^l}{P_{i,max}} + \sum_{i=1}^{N} w_i \frac{P_i^l - P_i^w(||\mathbf{s}||_0)}{P_{i,max}} \cdot s_i. \end{aligned} \quad (25)$$

Fixed $||\mathbf{s}||_0$, the former three items of $W(\mathbf{s})$ are constants, and the last item is a linear combination of s_i. Let $e_i = w_i \frac{P_i^l - P_i^w(||\mathbf{s}||_0)}{P_{i,max}}$, and we can rewritten $W(\mathbf{s})$ as follows:

$$W(\mathbf{s}) = \phi(||\mathbf{s}||_0) + \sum_{i=1}^{N} e_i \cdot s_i,$$

where $\phi(||\mathbf{s}||_0)$ is a function of $||\mathbf{s}||_0$. Then $W(\hat{\mathbf{s}})$ can be solved through the following steps:

1) We can divide S into $N+1$ subsets, which are denoted by $X_0, X_1, \ldots, X_N$. The zero norm of elements in X_n is n.
2) Without loss of generality, we limit the solution domain of maximizing $W(\mathbf{s})$ to X_n. Thus maximizing $W(\mathbf{s})$ in X_n is equivalent to maximizing $\sum_{i=1}^{N} e_i \cdot s_i$ when $||\mathbf{s}||_0 = n$. Then: a) sorting the coefficients e_i in decreasing order, and the indexes of the sorted coefficients are $n_1, n_2, \cdots, n_N$; b) solution of maximizing $W(\mathbf{s})$ in X_n is: $s_{n_1} = \cdots = s_{n_n} = 1$ and $s_{n_{n+1}} = \cdots = s_{n_N} = 0$. The maximal value of $W(\mathbf{s})$ in X_n is $W(n) = \phi(n) + \sum_{i=1}^{n} e_{n_i}$.
3) Step 2 is repeated for each subset. Let $n^* = \underset{n\in\mathcal{N}}{argmax}\ W(n)$, thus $W(\hat{\mathbf{s}}) = W(n^*)$.

The complexity of the above steps is $O(N^2)$.

The PoA will be evaluated to study the degree of optimality of the game in the next section.

VI. Numerical results and discussions

The performance of the proposed distributed association strategy, which is denoted as UAGT in the rest of the paper, is evaluated in this section. To the best of our knowledge, this is the first work to consider throughput-power tradeoff association for UEs. We adopt a typical coupled and a typical decoupled association strategy in the literature for comparison. The former is the widely applied WLAN-first strategy [7] in WLAN/cellular integrated networks. And the latter is the association strategy [9] [10] redirecting all UEs' uplink traffic to cellular networks, which is denoted as UTCFA in the rest of this paper. Simulation results validate the feasibility and effectiveness of the proposed distributed association strategy.

TABLE II
SIMULATION PARAMETERS

Network	Parameters	Value
Cellular	Coverage Radius	300 m
	Target SNR at MBS (γ)	25 dB
	Pathloss	$15.3 + 37.6 * \log_{10}(d)$ dB
	Shadowing Deviation	4 dB
	Noise Power Density (σ^2)	-174 dBm/Hz
WLAN	Transmit Rate (R)	54 Mbps
	Coverage Radius	40 m
	Payload Size (L)	500 Bytes/frame
	Maximum Backoff Stage (m')	6
	Retry Limit (m)	7
	Time Slot (T_{slot})	9 µs
	Initial Backoff Window (W)	32

A. Simulation Setup

The default system parameters and configurations are listed in Table III, which are selected based on 3GPP LTE specification [31] and IEEE 802.11g standard [32].

For simulations, we consider a macrocell with the MBS at the center. In the macrocell, we randomly deploy a WLAN AP. UEs are uniformly distributed within WLAN's coverage. In the simulations, WLAN load is represented by the number of UEs accommodated by the WLAN AP. Parameter d in the pathloss model of cellular network means the distance between a UE and the MBS in meters. Maximum allowed power consumption of each UE is set to be 250 mW. Fixed circuit power consumption $P_c^l = P_c^w = 100$ mW, and fixed emitted power of WiFi cards $P^w = 200$ mW. Duration time of DIFS, SIFS, and ACK are 28 µs, 10 µs and 2 µs, respectively. Average uplink traffic generation rate is $\lambda = 0.001$ (packets/slot). As for the utility function, UE's weight factor w_i is uniformly distributed in range $[0, 1]$. All statistical results are averaged, via 10,000 simulation runs, over possible locations of WLAN AP and UEs.

B. Results and Discussions

We use "step" to represent the procedure during which a UE chooses its best action. In other words, a step is corresponding to *Lines* 5-13 in Algorithm 1. The potential function with respect to the step number is shown in Fig. 2. In the simulation, 20 UEs are deployed in the DC area and initially uplink associate with the WLAN AP. In the sequential steps, UEs update their preferred actions according to their orders, which are coordinated by the WLAN AP. As seen from Fig. 2, the proposed distributed algorithm improves the potential function whenever a UE changes its preferred action. The algorithm converges with a quite fast speed, only within 40 steps in the simulation. We also find that the incentive factor α affects the value of the potential function, however it does not affect the convergence speed.

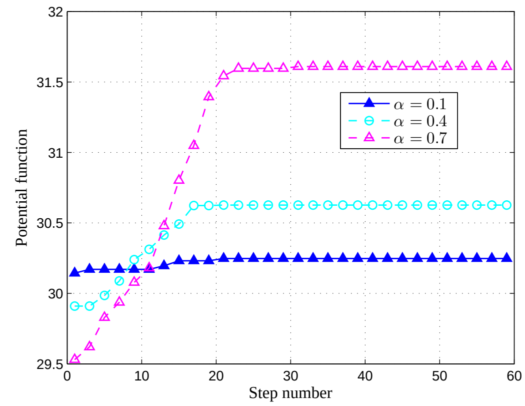


Fig. 2. Convergence of the proposed distributed algorithm when $N = 20$.

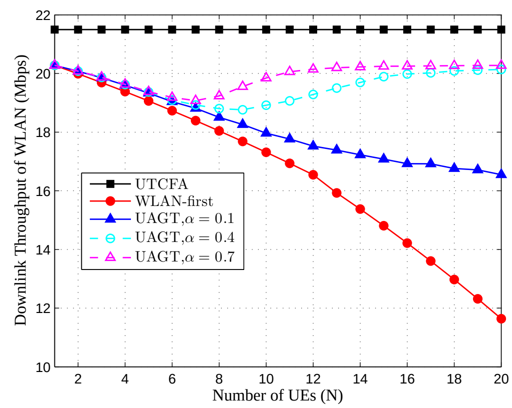


Fig. 3. Total downlink throughput of WLAN as WLAN load varies

In Fig. 3, we evaluate WLAN's average downlink throughput as WLAN load varies. As the WLAN-first strategy introduces most contention and collisions in the WLAN, it achieves the lowest average downlink throughput. In this case, average downlink throughput of the WLAN also decreases most quickly as WLAN load increases. On the contrary, the UTCFA strategy achieves highest average downlink throughput in the WLAN, as it reduces contention and collisions dramatically by redirecting all uplink traffic from UEs to the cellular network. Moreover, average downlink throughput of the WLAN is almost constant as WLAN load varies. When the proposed UAGT strategy is adopted, WLAN's downlink throughput under a light WLAN load is close to that when applying the WLAN-first strategy. Besides, the downlink throughput is almost not affected by the incentive factor α. However under a relatively heavy WLAN load, larger α will result in higher WLAN's downlink throughput. The above results can be explained with Eq. (2) as follows. Under a light WLAN load, UEs can obtain relatively high downlink throughput even though they uplink associate with the WLAN AP. If a UE redirects its uplink traffic, the increase in revenue due to more downlink throughput is not apparent, while higher cost will be incurred because more power consumption is needed. Hence, few UEs would be willing to do so. The situation is reversed

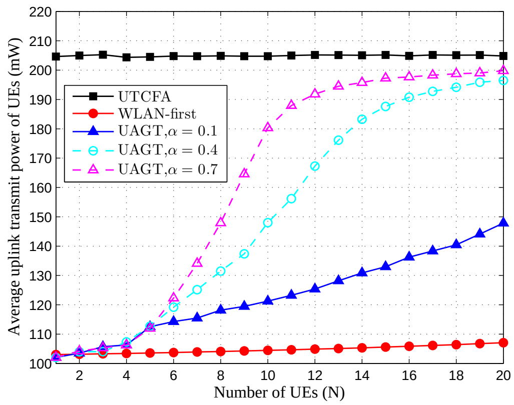


Fig. 4. Average uplink power consumption per UE as WLAN load varies

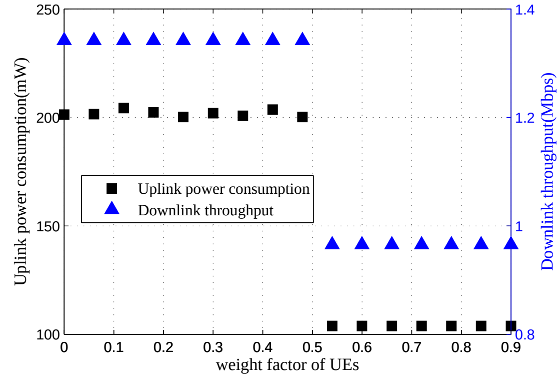
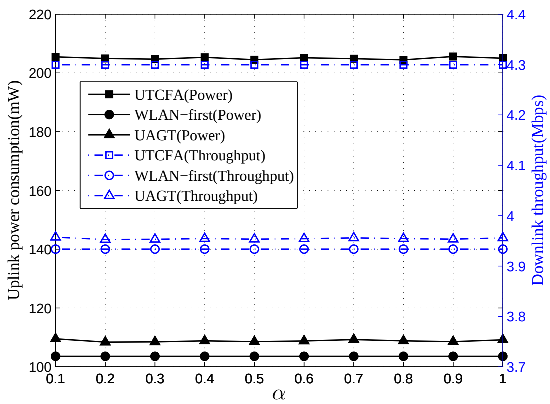
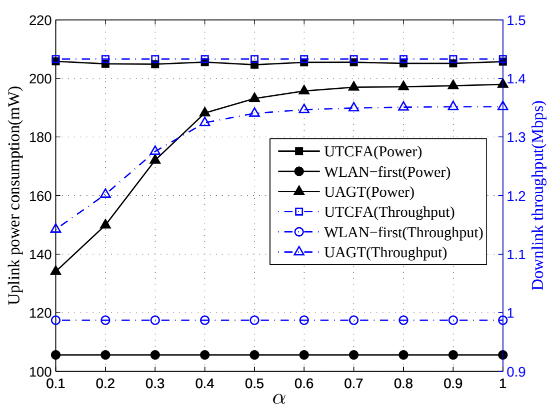


Fig. 6. Uplink power consumption and downlink throughput of 16 UEs sorted by weight factors ($\alpha = 0.4$).



(a) In the case of light WLAN load ($N = 5$).



(b) In the case of heavy WLAN load ($N = 15$).

Fig. 5. Average downlink throughput and uplink power consumption per UE as incentive factor α varies.

when the load of WLAN load high, since more UEs uplink associating with the WLAN AP would cause low downlink throughput per UE. Besides, $\frac{\alpha}{N}$ of total downlink throughput will be allocated to a UE if it redirects its uplink traffic to the cellular network. Hence, a larger α will encourage more UEs to uplink associate with the MBS.

Fig. 4 plots average uplink transmission power consumption per UE as WLAN load varies. From this figure, we obtain the following results: 1) Average uplink transmit power consumed by UEs using the UAGT strategy is between that using the two baseline strategies. 2) Applying the WLAN-first strategy, average uplink transmit power consumption per UE will increase as WLAN load increases, however the increasing rate is negligibly small. Therefore, the assumption $P_i^w(n) \approx P_i^w(n+1)$ is reasonable. 3) Under a light WLAN load, the proposed UAGT and WLAN-first strategies lead to almost equal average uplink transmit power consumption for each UE. Under a relatively heavy WLAN load, a larger α will lead to higher average uplink transmit power consumption per UE with the proposed UAGT strategy. The reasons of the last result can refer to the interpretation of Fig. 3. Combining Fig. 3 and 4, we can conclude that there is a natural contradiction between WLAN's downlink throughput and UEs' uplink power consumption. The proposed UAGT strategy can effectively balance downlink throughput and average uplink transmission power consumption for UEs.

In Fig. 5, we depict average downlink throughput and uplink power consumption per UE achieved by different association strategies as incentive factor α varies. As shown in Fig. 5(a), under a light WLAN load, the proposed UAGT strategy results in similar average downlink throughput and uplink power consumption per UE compared with the WLAN-first strategy despite of incentive factor α. The reason is that UEs can obtain enough downlink throughput in this case, even though they uplink associate with the WLAN AP. However, Fig. 5(b) indicates that the situation will be quite different under a heavy WLAN load. For the proposed UAGT strategy, average downlink throughput and uplink power consumption per UE increases at first and then keeps almost unchanged with the increase of α. When $\alpha \geq 0.4$, performance of UEs is close to that when applying UTCFA strategy. From Fig. 5, we can also see that with proper α, e.g., 0.6, the WLAN-first strategy and UTCFA strategy can be considered as two extreme cases of the proposed UAGT strategy under light and heavy WLAN load, respectively.

Fig. 6 shows the distribution of uplink power consumption and downlink throughput of 16 UEs with different weight factors w. The weight factors are uniformly taken from a range of from 0 to 0.9. Generally, we can see that UEs will achieve

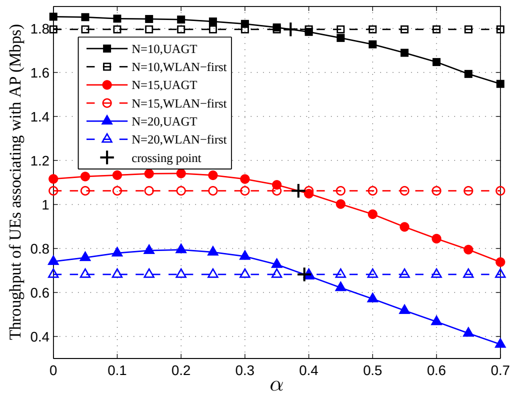


Fig. 7. Average downlink throughput for each UE uplink associating with the WLAN AP under different WLAN load as incentive factor α varies

more throughput by consuming more uplink transmit power despite of weight factors. UEs with smaller weight factors ($w < 0.5$) would prefer to strive for higher downlink throughput at the expense of more uplink power consumption, which redirect their uplink traffic to the cellular network through their LTE radio interfaces. On the contrary, UEs with larger weight factors ($w > 0.5$) would prefer to consume much less transmit power by delivering uplink traffic through WLANs, which also achieve much lower downlink throughput. From Fig. 6, we can conclude that the weight factor has a decisive impact on the UE uplink association strategy. Therefore, UEs should set their weight factors properly based on their energy status as well as the network status.

Fig. 7 shows average downlink throughput that each UE can obtain when it uplink associates with the WLAN AP. From this figure, we draw the following conclusion: if we apply the UAGT strategy with suitable incentive factor (e.g., $\alpha \in [0, 0.36]$ in our simulations), UEs that choose to uplink associate with the WLAN AP will achieve higher downlink throughput than that when applying the WLAN-first strategy. This can be explained through Eqs. (13) and (16). When N UEs are deployed in DC area and the WLAN-first association strategy is applied, each UE's downlink throughput is $\frac{1}{N}R_{AP}$. In addition, when the proposed UAGT strategy is applied, if UE i uplink associates with the WLAN AP, its downlink throughput would be $r_i^d = \frac{1}{N}\left[1 + (\frac{||\mathbf{s}||_0}{N} - 1)\alpha\right] \cdot R_{AP}(||\mathbf{s}||_0)$. Let $r_i^d \geq \frac{1}{N}R_{AP}$, we have $0 \leq \alpha \leq \left(1 - \frac{R_{AP}(N)}{R_{AP}(||\mathbf{s}||_0)}\right) / \left(1 - \frac{||\mathbf{s}||_0}{N}\right)$. The right side of the inequality decreases as α increases. Hence, given N, there exists a threshold α_0. When α is set as $\alpha \leq \alpha_0$, UEs uplink associating with the WLAN AP would achieve higher downlink throughput when the UAGT strategy is applied.

In addition, we have numerically evaluated the values of PoA to study the degree of optimality of the game. The PoAs are evaluated and averaged via 10,000 independent simulations, where 15 UEs are deployed in DC area. The mean values of PoAs under different association strategies are shown in Table III. We can see that the PoAs under UAGT are quite close to the optimum bound '1'. Hence, low PoA values mean that the proposed game has a fair degree of optimality. In addition, the proposed association strategy is superior to the WLAN-first and UTCFA strategies, since the proposed UAGT strategy results in the highest social welfare.

TABLE III
POAS UNDER DIFFERENT ASSOCIATION STRATEGIES

Association strategy	Price of anarchy
WLAN-first	1.6283
UTCFA	2.2127
UAGT, $\alpha = 0.1$	1.1413
UAGT, $\alpha = 0.4$	1.0367
UAGT, $\alpha = 0.7$	1.3082

VII. CONCLUSIONS

In this paper, we attempted to propose a distributed association strategy for UEs in WLAN/cellular integrated networks by taking into account throughput as well as power consumption. To do so, an uplink UE association game was formulated based on a utility function, which reconciles the contradiction between downlink throughput and uplink power consumption. We proved such game is an exact potential game with at least one pure strategy NE. Based on best-response-dynamics, an efficient distributed association algorithm has been proposed, which encourages UEs with enough energy to redirect their uplink traffic through cellular network interfaces. Numerical simulation results validated that the proposed distributed association strategy can balance UE's throughput and power consumption effectively.

As future work, we will study the UE association problem in non-cooperative WLAN/cellular integrated networks.

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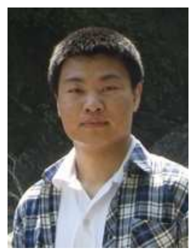

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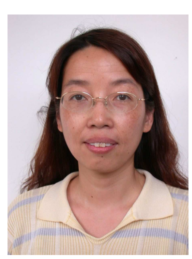

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