Distributed Delay-Energy Aware User Association in 3-tier HetNets with Hybrid Energy Sources

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***Abstract*—With tremendous attention for green communications, base station (BS) which is powered by both the power grid and renewable energy sources, is regarded as a promising paradigm to reduce energy consumption as well as provide uninterrupted service. In this paper, we propose dIstributed Delay-Energy Aware (IDEA) user association in 3-tier HetNets with hybrid energy sources. IDEA user association aims to reduce on-grid power consumption by maximizing the utilization of green power harvested from renewable energy sources, as well as enhance network quality of service by minimizing the average traffic delay. To this end, a convex optimization problem is formulated which enables a flexible tradeoff between average traffic delay and on-grid power consumption. We prove that the proposed IDEA user association converges to the globally optimal solution. We then address admission control for the case where the traffic load is heavy to ensure IDEA user association works when network traffic demand is over network capacity. Simulation results indicate that the proposed IDEA user association is able to adjust the loads of BSs and RSs along with the distributions of green power, substantially reduces on-grid power consumption and achieves comparable average traffic delay compared with the existing algorithm which aims to minimize average traffic delay.**

I. INTRODUCTION

Recently, motivated by the environmental concerns, green communication has drawn tremendous attention from both industry and academia. The conventional cellular networks which consume 60 billion kWh per year approximately are the major issue in green communication. Particularly, 80% of the energy in cellular networks is consumed by base stations (BSs), which generate over a hundred million tons of carbon dioxide annually [1].

Heterogeneous Networks (HetNets), where various small cells are densely underlaid in a macro-cellular network, is a promising technique to achieve more spectrum-efficient and energy-efficient communications in order to meet the requirements of 5G broadband wireless networks [2]. In contrast with the conventional macro BSs (MBSs), BSs in the "small cells" cover much smaller areas and hence require significantly lower transmit powers, which brings up about 50% reduction in overall energy consumption of all BSs as shown in [3].

User association in HetNets, which aims to associate users with proper serving BSs, has a great impact on the network performance. There have been a considerable amount of studies on energy-aware user association in HetNets, see [4], [5] and references therein. However [4] and [5] require ideal energy sources like power grid which supply continuous energy whenever needed. In practice, sometimes the direct connection to power grid is not readily available, especially in some undeveloped areas, since the infrastructure expenditure on power grid is prohibitively expensive [6]. In such a situation, energy harvesting provides a practical solution where BSs are capable of harvesting energy from the renewable energy sources, such as solar panels and wind turbines, thereby substantially reducing the operating cost of service providers.

Integrating energy harvesting capability into BSs poses many challenges to user association algorithms, due to the randomness of energy availability in renewable energy sources. Authors in [7] developed a traceable model for HetNets where all the BSs are assumed solely powered by renewable energy sources, and provided a fundamental characterization of regimes under which the HetNets with renewable energy powered BSs have the same performance as the ones with grid powered BSs. Yet, although the amount of renewable energy is potentially unlimited, the intermittent nature of the energy from renewable energy sources will result in highly random energy availability in BSs. Thus the BSs powered by hybrid energy sources are preferable than those solely powered by renewable energy sources in order to provide uninterrupted service [8] [9].

Furthermore, the aforementioned only focus on the 2-tier HetNets without relay stations (RSs), while in more general 3-tier HetNets, MBSs ensure basic coverage, pico BSs (PBSs) usually provide higher capacity in hotspot areas [10], and RSs are usually deployed near the macrocell edge to guarantee coverage. The mixed deployment of PBSs and RSs can address both the hotspot and cell edge coverage hole issues. In 3-tier HetNets, RSs are dedicated to forwarding data received from MBS to users and *vice versa*, and the signals transmitted via RSs consume resources from the backhaul link between MBS and RS, as well as the link between RS and user. Due to the backhaul link resource consumption, the existing user association algorithms in 2-tier HetNets cannot be directly extended to the 3-tier HetNets. As such RSs complicate the user association in HetNets.

In this paper, we propose dIstributed Delay-Energy Aware (IDEA) user association in 3-tier HetNets, where all the BSs and RSs are assumed powered by both the power grid and renewable energy sources. To the best of our knowledge, this is

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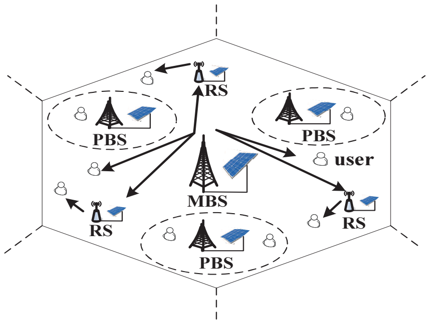

Fig. 1. IDEA user association in 3-tier HetNets with hybrid energy sources

the first work on user association in 3-tier HetNets with hybrid energy sources. We formulate the user association problem as a convex optimization problem to minimize the weighted sum of cost of average traffic delay and cost of on-grid power consumption. IDEA user association is proved to converge to the global optimum. We then bring in the admission control to ensure the proposed IDEA user association works in the heavy traffic load condition.

II. System Model

We focus on the 3-tier downlink HetNets where tier 1 is modeled as macrocell, tier 2 as picocell and tier 3 as RS. MBSs provide basic coverage, whereas PBSs and RSs are placed in the coverage area of each MBS to enhance capacity. All the BSs and RSs are assumed powered by both the power grid and renewable energy sources. Fig. 1 details the system model for IDEA user association in 3-tier HetNets with hybrid energy sources.

A. Traffic model

IDEA user association is carried out within a macrocell geographical area $\mathcal{L} \subset \mathbb{R}^2$ which is served by a set of RSs $\mathcal{R}$ and a set of BSs $\mathcal{B}$ including one MBS and several PBSs. Communication between MBS and users can be achieved by either direct transmission or cooperative transmission via the assistance of RS. In the cooperative transmission, backhaul link represents the communication link between MBS and RS, and access link represents the link between RS and user. RS in this model is a decode and forward relay which uses in-band backhaul, and we consider two-hop relay here. All the BSs and RSs are assumed to share the same frequency band with frequency reuse factor equalling to one. To facilitate our analysis, we define $\mathcal{K} = \mathcal{B} \cup \mathcal{R}$, and let $k \in \mathcal{K}$ index k-th BS or RS, where $k = 1$ indicates MBS, $k \in \{2, \cdots, |\mathcal{B}|\}$ indicate PBSs and $k \in \{|\mathcal{B}|+1, \cdots, |\mathcal{K}|\}$ indicate RSs. $x \in \mathcal{L}$ is used to denote a location. We assume that the traffic requests arrive according to a inhomogeneous Poisson point process with the arrival rate per unit area $\lambda(x)$ and the traffic size is independently distributed with mean $\mu(x)$. IDEA user association then is applied to decide which BS or RS within $\mathcal{L}$ will serve which user at location x.

Assuming a mobile user at location x is associated with k-th BS or RS, the transmission rate to this user $r_k(x)$ can be generally expressed according to Shannon Hartley theorem [11]

$$r_k(x) = \log_2(1 + \mathrm{SINR}_k(x)), \tag{1}$$

where

$$\mathrm{SINR}_k(x) = \frac{p_k g_k(x)}{\sum_{m \in \mathcal{K}, m \neq k} p_m g_m(x) + \sigma^2}, \tag{2}$$

here p_k is the maximum transmission power of k-th BS or RS, and σ^2 is the noise power level. $g_k(x)$ is the channel gain between k-th BS or RS and user at location x, which includes pathloss, shadowing, and other factors, if any. Note that fast fading is not considered here since the time scale of user association is much larger than the time scale of fast fading. As such, $r_k(x)$ can be considered as a time-averaged transmission rate [12].

Here we assume high-capacity and constant-quality backhaul links [13], with the constant date rate from MBS to RS as $r_{1,k}, k \in \{|\mathcal{B}|+1, \cdots, |\mathcal{K}|\}$. This assumption can be justified by the fact that RSs are usually placed in locations with low shadowing and equipped with multiple antennas [13].

In doing so, the average traffic load density at location x of k-th BS or RS is derived as

$$\varrho_k(x) = \begin{cases} \frac{\lambda(x)\mu(x)h_k(x)}{r_k(x)}, & k \neq 1 \\ \frac{\lambda(x)\mu(x)h_k(x)}{r_k(x)} + \sum\limits_{m=|\mathcal{B}|+1}^{|\mathcal{K}|} \frac{\lambda(x)\mu(x)h_m(x)}{r_{1,m}}, & k = 1, \end{cases} \tag{3}$$

where $h_k(x)$ is the user association indicators. If user at location x is associated with k-th BS or RS, $h_k(x) = 1$, otherwise $h_k(x) = 0$. We assume at each time, one user can only associate with one BS or RS, and thus we have $\sum_{k \in \mathcal{K}} h_k(x) = 1$. $\varrho_k(x)$ represents the fraction of time required to deliver traffic load from k-th BS or RS to the user at location x.

Based on the traffic load density, the set $\mathcal{F}$ of the feasible traffic loads of BSs and RSs $\boldsymbol{\rho} = (\rho_1, \ldots, \rho_{|\mathcal{K}|})$ is given by

$$\mathcal{F} = \left\{ \boldsymbol{\rho} | \rho_k = \int_{\mathcal{L}} \varrho_k(x)\, dx,\ 0 \leq \rho_k \leq 1 - \varepsilon, \forall k \in \mathcal{K} \right\}, \tag{4}$$

where ε is an arbitrarily small positive constant to ensure $\rho_k < 1$, and authors in [11] have proved that the feasible set $\mathcal{F}$ is convex.

B. Power consumption model

We assume all the MBSs, PBSs and RSs in the HetNets are powered by hybrid energy sources: power grid and renewable energy sources. If the green power harvested from renewable energy sources is not sufficient, BSs and RSs will consume the power from power grid. Due to the disadvantage of "banking" green power [14], here we assume the green power cannot be stored.

Generally, BSs and RSs consist of two types of power consumptions: static power consumption and adaptive power consumption which is nearly linear to the the loads of BSs and RSs [15]. Static power consumption is the power consumption when BSs or RSs are idle without any traffic load. Here we adopt the linear approximation of power consumption model in [15], with P_k denoted as the power consumption of k-th BS or RS,

$$P_k = \Delta_k \rho_k p_k + P_k^s, \quad \forall k \in \mathcal{K}, \tag{5}$$

where Δ_k is the slop of load-dependent power consumption of k-th BS or RS, p_k is maximum transmission power of k-th BS or RS, and P_k^s is the static power consumption of k-th BS or RS. It is worthwhile mentioning that the small BSs such as PBSs and femto BSs or RSs may have smaller static power consumption than that of MBSs since they have neither big power amplifiers nor cooling equipments.

Then we denote P_k^g as the green power of k-th BS or RS harvested from renewable energy sources, and the on-grid power consumption of k-th BS or RS is expressed as

$$P_k^{grid} = \max\left(P_k - P_k^g, 0\right). \tag{6}$$

III. PROBLEM FORMULATION

In this section, a convex optimization problem is formulated with the aim to reduce on-grid power consumption by optimizing the utilization of green power harvested from renewable energy sources, as well as enhance network quality of service by minimizing the traffic delay of BSs and RSs. Our problem is to find the optimal loads of BSs and RSs $\boldsymbol{\rho}$ that minimizes the total system cost which is given by

Problem 1:

$$\min_{\boldsymbol{\rho}} \left\{ f\left(\boldsymbol{\rho}\right) = \varphi\left(\boldsymbol{\rho}\right) + \omega \phi\left(\boldsymbol{\rho}\right) | \boldsymbol{\rho} \in \mathcal{F} \right\}, \tag{7}$$

where $\varphi(\boldsymbol{\rho})$ is the cost of average traffic delay and $\phi(\boldsymbol{\rho})$ is cost of on-grid power consumption. $\omega > 0$ is the relative weight to balance the tradeoff between average traffic delay and on-grid power consumption.

A. Cost function of average traffic delay

We define the cost function of average traffic delay as

$$\varphi\left(\boldsymbol{\rho}\right) = \sum\nolimits_{k \in \mathcal{K}} \frac{\rho_k}{1 - \rho_k}. \tag{8}$$

We assume users associated with the same BS or RS are served on the round robin fashion. When we consider the system as M/GI/1 multi-class processor sharing system in [16], $\rho_k/(1-\rho_k)$ is equal to the average number of flows at k-th BS or RS, and $\sum_{k \in \mathcal{K}} \frac{\rho_k}{1-\rho_k}$ is the total number of flows in the system. According to the Little's law, minimizing the average number of flows is equivalent to minimizing the average delay experienced by a typical traffic flow.

B. Cost function of on-grid power consumption

We define the green traffic load as the maximum traffic load that can be supported by the green power harvested from renewable energy sources. Based on equation (5), the green traffic load of k-th BS or RS is derived as

$$\rho_k^g = \min\left(\frac{P_k^g - P_k^s}{\Delta_k p_k}, 1 - \varepsilon\right), \quad \forall k \in \mathcal{K}. \tag{9}$$

According to (6), on-grid power is only consumed when green power is not sufficient. Thus when the traffic load of k-th BS or RS exceeds the green traffic load, that is $\rho_k > \rho_k^g$, on-grid power will be consumed, which leads to the increase in the cost of on-grid power consumption. Otherwise when $\rho_k < \rho_k^g$, the cost of on-grid consumption will stay trivial. In doing so, the cost function of on-grid power consumption is designed as

$$\phi\left(\boldsymbol{\rho}\right) = \sum\nolimits_{k \in \mathcal{B}+\mathcal{R}} \phi_k\left(\rho_k\right) = \sum\nolimits_{k \in \mathcal{B}+\mathcal{R}} \delta \exp\left(\beta \frac{\rho_k}{\rho_k^g}\right), \tag{10}$$

where β represents the network sensitivity towards on-grid power consumption ($\beta > 0$), and δ aims to adjust the value of cost function ($\delta > 0$). The cost function of on-grid power consumption has the following property: when $\rho_k/\rho_k^g > 1$, $\phi_k(\rho_k)$ increases exponentially with the rise of ρ_k; when $0 < \rho_k/\rho_k^g < 1$, $\phi_k(\rho_k)$ remains small.

IV. IDEA USER ASSOCIATION

In this section, we present IDEA user association which achieves the global optimum in minimizing the total system cost $f(\boldsymbol{\rho})$. IDEA user association is implemented in an iterative manner: BSs and RSs periodically measure and advertise their loads, and then users make user association decision based on the advertised information to minimize $f(\boldsymbol{\rho})$. The BS, RS and user sides update iteratively until convergence. IDEA user association is totally distributed, although interaction among users, BSs and RSs may incur overhead on control information exchange, it does not require any centralized computation, as such there is no algorithmic complexity issue here.

In order to guarantee convergence, we assume that spatial load distributions in the HetNets area are temporally stationary, and the time scale of users making user association decision is faster than that of BSs and RSs advertising their loads. In this case, BSs and RSs advertise their load conditions after the system remains stationary. We also assume all the BSs and RSs are synchronized and advertise their loads at the same time, and the green power of every BS and RS is constant during the period of determining user association.

A. IDEA user association algorithm

The proposed IDEA user association consists of two parts.

User side: At the beginning of *i*-th time slot, users get the traffic loads $\boldsymbol{\rho}^{(i)}$ of all BSs and RSs via broadcast. And then the user at location x chooses the optimal BS or RS by

$$n^{(i)}\left(x\right) = \arg\max_{k \in \mathcal{K}} \upsilon_k\left(x\right), \tag{11}$$

where

$$\upsilon_k\left(x\right) = \begin{cases} r_k\left(x\right)/\Xi_k, \text{ if } k \in \{1, 2, \cdots, |\mathcal{B}|\} \\ r_k\left(x\right)/\Xi_k + r_{1,k}/\Xi_1, \text{ if } k \in \{|\mathcal{B}|+1, \cdots, |\mathcal{K}|\}, \end{cases} \tag{12}$$

and [1],

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[1] Due to the small coverage of RS [17], here we assume RS transmits to all its associated users by the constant transmission rate ($r_k, k \in \{|\mathcal{B}|+1, \cdots, |\mathcal{K}|\}$).

$$\Xi_k = \begin{cases} \Psi_k, \text{if } k \in \{1,2,\cdots,|\mathcal{B}|\} \\ \Psi_k + \Psi_1 r_k / r_{1,k}, \text{ if } k \in \{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}, \end{cases} \tag{13}$$

$$\Psi_k = \left(1 - {\rho_k}^{(i)}\right)^{-2} + \frac{\omega\beta\delta}{(\rho_k^g)} \exp\left(\beta \frac{\rho_k^{(i)}}{\rho_k^g}\right), \forall k \in \mathcal{K}. \tag{14}$$

Then the user association indicator is updated by

$$h_k^{(i)}(x) = \begin{cases} 1, & \text{if } k = n^{(i)}(x) \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

And $h_k^{(i)}(x)$ will be broadcasted to all the BSs and RSs.

BS and RS side: The updated user association indicators from the user side will change the traffic loads of BSs and RSs, and thus during the *i*-th period, the new traffic load of k-th BS or RS, is given by equation (16) on the top of next page. Based on the derived $T_k\left({\rho_k}^{(i)}\right)$, k-th BS or RS updates the next advertising traffic load as [11]

$${\rho_k}^{(i+1)} = \theta {\rho_k}^{(i)} + (1-\theta) T_k\left({\rho_k}^{(i)}\right), \ \forall k \in \mathcal{K}, \tag{17}$$

where $0 \leq \theta < 1$ is an exponential averaging parameter.

B. Proof of optimality

The objective function $f(\boldsymbol{\rho}) = \phi(\boldsymbol{\rho}) + \omega\varphi(\boldsymbol{\rho})$ is a convex function of $\boldsymbol{\rho}$ when $\boldsymbol{\rho}$ is defined on $[0, 1-\varepsilon]^{|\mathcal{K}|}$, since $\nabla^2 f(\boldsymbol{\rho}) > 0$ when $\boldsymbol{\rho} \in [0, 1-\varepsilon]^{|\mathcal{K}|}$. As such, there exists a unique optimal $\boldsymbol{\rho}*$ that minimizes $f(\boldsymbol{\rho})$.

We denote $\boldsymbol{\rho}^{(i)} = \left({\rho_1}^{(i)}, \cdots, {\rho_{|\mathcal{K}|}}^{(i)}\right)$ and $\mathbf{T}\left(\boldsymbol{\rho}^{(i)}\right) = \left(T_1\left({\rho_1}^{(i)}\right), \cdots, T_{|\mathcal{K}|}\left({\rho_{|\mathcal{K}|}}^{(i)}\right)\right)$. Since $\mathbf{T}\left(\boldsymbol{\rho}^{(i)}\right)$ is a continuous mapping defined on compact set $[0, 1-\varepsilon]^{|\mathcal{K}|}$ to itself. According to the Brouwer's fixed point theorem, there exists a solution $\mathbf{T}(\boldsymbol{\rho}*) = \boldsymbol{\rho}*$.

C. Proof of convergence

Lemma: When $\boldsymbol{\rho}^{(i)} \neq \boldsymbol{\rho}*$, $\mathbf{T}\left(\boldsymbol{\rho}^{(i)}\right) - \boldsymbol{\rho}^{(i)}$ is a descent direction of $f\left(\boldsymbol{\rho}^{(i)}\right)$.

Proof: This lemma can be proved by deriving $\left\langle \nabla f\left(\boldsymbol{\rho}^{(i)}\right), \mathbf{T}\left(\boldsymbol{\rho}^{(i)}\right) - \boldsymbol{\rho}^{(i)} \right\rangle < 0$. Let $h_k(x)$ and ${h_k}^T(x)$ be the user association indicators of k-th BS or RS that result in the traffic load ${\rho_k}^{(i)}$ and $T_k\left({\rho_k}^{(i)}\right)$, respectively.

$$\begin{aligned} &\left\langle \nabla f\left(\boldsymbol{\rho}^{(i)}\right), \mathbf{T}\left(\boldsymbol{\rho}^{(i)}\right) - \boldsymbol{\rho}^{(i)} \right\rangle \\ &= \sum_{k\in\mathcal{K}} \Xi_k \left(T_k\left(\rho_k^{(t)}\right) - \rho_k^{(i)}\right) \\ &= \Xi_1 \textstyle\int_{\mathcal{L}} [\lambda(x)\mu(x)(r_1(x))^{-1}\left(h_1^T(x) - h_1(x)\right) \\ &+ \sum_{k\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}} \lambda(x)\mu(x)(r_{1,k})^{-1}\left(h_k^T(x) - h_k(x)\right)]dx \\ &+ \sum_{k\in\mathcal{K},k\neq 1} \Xi_k \textstyle\int_{\mathcal{L}} \lambda(x)\mu(x)(r_k(x))^{-1}\left(h_k^T(x) - h_k(x)\right)dx \\ &= \textstyle\int_{\mathcal{L}} \lambda(x)\mu(x)[\sum_{k\in\mathcal{K}} (r_k(x))^{-1}\left(h_k^T(x) - h_k(x)\right)\Xi_k \\ &+ \sum_{k\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}} (r_{1,k})^{-1}\left(h_k^T(x) - h_k(x)\right)\Xi_1]dx. \end{aligned} \tag{18}$$

Note that

$$\begin{aligned} &\sum_{k\in\mathcal{K}} \tfrac{h_k^T(x)}{r_k(x)}\Xi_k + \sum_{k\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}} \tfrac{h_k^T(x)}{r_{1,k}}\Xi_1 \\ &< \sum_{k\in\mathcal{K}} \tfrac{h_k(x)}{r_k(x)}\Xi_k + \sum_{k\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}} \tfrac{h_k(x)}{r_{1,k}}\Xi_1 \end{aligned} \tag{19}$$

holds since ${h_k}^T(x)$ derived from equation (11)–(15) maximizes $\sum_{k\in\mathcal{K}} r_k(x)/\Xi_k + \sum_{k\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}} r_{1,k}/\Xi_1$. Hence $\left\langle \nabla f\left(\boldsymbol{\rho}^{(t)}\right), \mathbf{T}\left(\boldsymbol{\rho}^{(t)}\right) - \boldsymbol{\rho}^{(t)} \right\rangle < 0$. ■

Theorem: The traffic load $\boldsymbol{\rho}$ converges to $\boldsymbol{\rho}*$ that minimizes $f(\boldsymbol{\rho})$.

Proof: Since ${\rho_k}^{(i+1)} - {\rho_k}^{(i)} = \theta{\rho_k}^{(i)} + (1-\theta)T_k\left({\rho_k}^{(i)}\right) - {\rho_k}^{(i)} = (1-\theta)\left(T_k\left({\rho_k}^{(i)}\right) - {\rho_k}^{(i)}\right)$, and $0 \leq \theta < 1$, $\boldsymbol{\rho}^{(i+1)} - \boldsymbol{\rho}^{(i)}$ is also a descent direction of $f\left(\boldsymbol{\rho}^{(i)}\right)$. Due to the fact that $f\left(\boldsymbol{\rho}^{(i)}\right)$ is a convex function and also lower-bounded by 0, $f\left(\boldsymbol{\rho}^{(i)}\right)$ converges to $f(\boldsymbol{\rho}*)$. ■

V. ADMISSION CONTROL

Up till now, we consider the condition where the problem 1 is feasible, that is $\rho_k \leq 1-\varepsilon, \forall k \in \mathcal{K}$. However when the traffic loads are high, the problem 1 will not be feasible, and thus the admission control is required. In this section, we focus on the admission control with the objective to minimize the system cost which includes the cost of blocking traffic.

We assume the blocked traffic is routed to the *null* BS. We use $\mathcal{B}_0$ to denote all BSs including the *null* BS, and define $\boldsymbol{\rho}_0 = \left(\rho_0, \rho_1, \ldots, \rho_{|\mathcal{B}_0|+|\mathcal{R}|}\right)$. Note that ρ_0 is defined as $\rho_0 = \int_{\mathcal{L}} \lambda(x)\mu(x)\left(1 - \sum_{k\in\mathcal{K}} h_k(x)\right)dx$, where $1 - \sum_{k\in\mathcal{K}} h_k(x)$ means if a user does not associate with any BS or RS, this user is blocked. ρ_0 is the total amount of traffic that is blocked and ρ_0 can be larger than 1. The optimization problem is given by

Problem 2:

$$\min_{\boldsymbol{\rho}_0} \left\{f(\boldsymbol{\rho}_0) = \varphi(\boldsymbol{\rho}) + \omega\phi(\boldsymbol{\rho}) + \alpha\rho_0\right\}, \tag{20}$$

where $\alpha\rho_0$ is the cost of blocking traffic and α reflects the blocking cost per bit. With the similar proof, we can conclude that Problem 2 is also a convex optimization problem defined on a convex set. Hence the user association algorithm is similar as the algorithm in Section IV, only with the revised equation (11) (12),

$$n^{(i)}(x) = \arg\max_{k\in\mathcal{B}_0+\mathcal{R}} \upsilon_k(x), \tag{21}$$

where

$$\upsilon_k(x) = \begin{cases} \alpha^{-1}, & \text{if } k = 0 \\ r_k(x)/\Xi_k, & \text{if } k \in \{1,2,\cdots,|\mathcal{B}|\} \\ r_k(x)/\Xi_k + r_{1,k}/\Xi_1, & \text{if } k \in \{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}, \end{cases} \tag{22}$$

here α^{-1} acts as the threshold to determine whether particular user is blocked or not.

VI. SIMULATION RESULTS

To evaluate the performance of the proposed IDEA user association (IDEA UA), the downlink HetNets composed of 19 macrocells are simulated. In each macrocell, 3 PBSs are symmetrically located along a circle with radius as 150m and MBS in the center, and 3 RSs are symmetrically located in the macrocell edge. Users are dropped in a hotspot of 30m radius around the PBSs with a probability of 2/3 [10], and there are 580 users in total distributed in each macrocell area.

$$T_k\left(\rho_k^{(i)}\right)=\begin{cases}\min\left(\int_{\mathcal{L}}\left(\frac{\lambda(x)\mu(x)h_k^{(i)}(x)}{r_k(x)}+\sum\limits_{m\in\{|\mathcal{B}|+1,\cdots,|\mathcal{K}|\}}\frac{\lambda(x)\mu(x)h_m^{(i)}(x)}{r_{1,m}}\right)dx,1-\varepsilon\right), & \text{if } k=1\\ \min\left(\int_{\mathcal{L}}\frac{\lambda(x)\mu(x)h_k^{(i)}(x)}{r_k(x)}dx,1-\varepsilon\right), \quad \text{if} \quad k\neq 1 & \end{cases} \tag{16}$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Bandwidth	10 MHz
Inter site distance	500 m
Max. transmission power MBS	46 dBm
Max. transmission power PBS or RS	30 dBm
Noise power	-174 dBm/Hz
Pathloss between MBS and user	$128.1 + 37.6\log_{10}d\,(km)$ [18]
Pathloss between PBS and user	$140.7 + 36.7\log_{10}d\,(km)$ [18]
Pathloss between RS and user	$145.4 + 37.5\log_{10}d\,(km)$ [18]
Log-normal shadowing fading	10 dB [18]
Static power consumption of MBS	780 W [15]
Static power consumption of PBS or RS	13.6 W [15]
Slop of MBS load-dependent power	4.7 [15]
Slop of PBS load-dependent power	4.0 [15]
Slop of RS load-dependent power	2.7 [19]

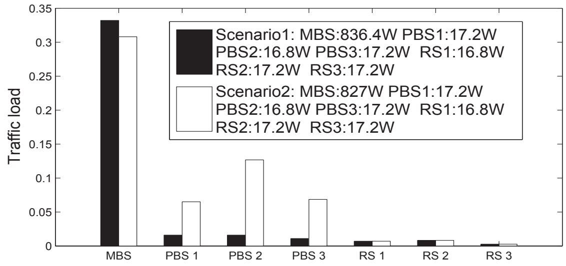

Fig. 2. Traffic load in different scenarios with different distributions of green power

We assume the green power of every BS and RS is constant during a snapshot of simulation. As for the traffic model, for the sake of simplicity, we simulate the file transfer requests follow a homogenous Poisson point process with arrival rate $\lambda(x) = \lambda$, but note that our model can still apply to the scenario with heterogeneous traffic distributions. Each request has exactly one file with mean file size μ as 100 kbits. The constant backhaul data rate is set as 4 bits/s/Hz [13]. Some basic simulation parameters are shown in Table I. The other parameters are preset as follows: $\delta = 10^{-7}$, $\beta = 12$, and $\theta = 0.98$ [11].

We first set the weight ω between cost of average traffic delay and on-grid power consumption as 1, and traffic arrival rate λ as $5*10^{-2}$. Fig. 2 shows the traffic loads of all the BSs and RSs in the proposed IDEA UA in different scenarios. In scenario 1, MBS has larger green power than that in scenario 2, and the green power of all the PBSs and RSs in scenario 1 is the same as that in scenario 2. This figure demonstrates that compared with scenario 2, traffic load of MBS is higher in scenario 1. It indicates that the proposed IDEA UA is able to adjust the traffic loads among BSs and RSs according to the distributions of green power, in order to make good use of renewable energy and reduce on-grid power consumption.

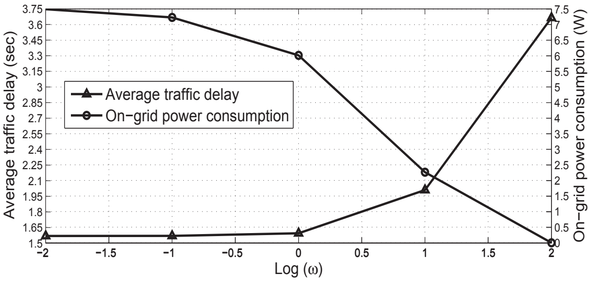

Fig. 3. Average traffic delay and on-grid power consumption with different values of weight ω

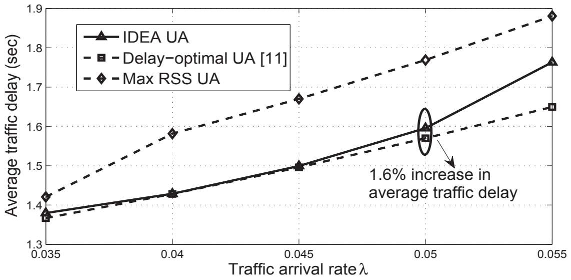

Fig. 4. Average traffic delay with different values of traffic arrival rate λ

Here we further evaluate the performance of the proposed IDEA UA in scenario 1. Fig. 3 demonstrates average traffic delay and on-grid power consumption with different values of weight ω, where with the increase of weight ω, the average traffic delay rises and the on-grid power consumption decreases. The larger weight ω will lead to more emphasis on the energy saving in order to minimize the on-grid power consumption, while the smaller weight ω will attach more importance to the traffic delay minimization. This figure indicates the weight ω in the proposed IDEA UA could adjust the tradeoff between average traffic delay and on-grid power consumption.

Then we compare the performance of the proposed IDEA UA with the delay-optimal UA in [11] and the conventional

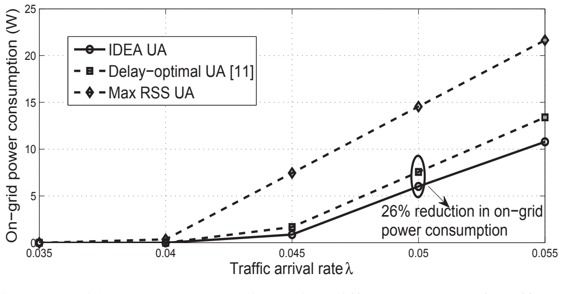

Fig. 5. On-grid power consumption with different values of traffic arrival rate λ

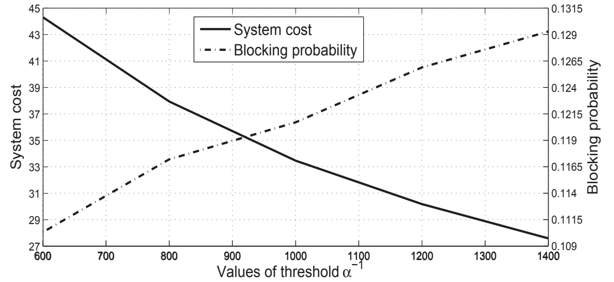

Fig. 6. System cost and blocking probability with different values of threshold α^{-1}

maximum received signal strength (max RSS) UA. In delay-optimal UA, user association is determined to minimize the average traffic delay. In max RSS UA, user will associate with the BS or RS from which it receives the highest RSS. Fig. 4 and Fig. 5 show the average traffic delay and on-grid power consumption with different values of traffic arrival rate λ, respectively. In max RSS UA, due to the large transmission power of MBS, majority of users will associate with MBS, which underutilizes the resources of PBSs and RSs. As such max RSS UA has the worst performance in terms of average traffic delay and energy saving compared with other two schemes. Fig. 4 indicates the proposed IDEA UA is slightly inferior to delay-optimal UA in terms of cost of average traffic delay. However the proposed IDEA UA obtains significant improvement in on-grid power saving as shown in Fig. 5. Hence the proposed IDEA UA achieves comparable average traffic delay compared with the delay-optimal UA, while substantially reducing the on-grid power consumption.

Here we evaluate the performance of the IDEA UA in the heavy traffic load condition with the traffic arrival rate λ as 0.1. Fig. 6 validates that the admission control enables the IDEA UA to work in heavy traffic load condition. It also indicates that the rise of the threshold reduces system cost which is the sum of cost of average traffic delay and cost of on-grid power consumption, and degrades the network performance by increasing the blocking probability.

VII. CONCLUSIONS

In this paper, we have proposed IDEA user association in 3-tier HetNets with hybrid energy sources, where all the BSs and RSs are assumed to be powered by both the power grid and renewable energy sources. The convex optimization problem we formulated is to minimize the weighted sum of cost of average traffic delay and cost of on-grid power consumption. IDEA user association has been proved to converge to the global optimum. The proposed IDEA user association allows for a flexible tradeoff between average traffic delay and on-grid power consumption by adjusting the value of weight ω. Admission control was also addressed to ensure the proposed IDEA user association works in the heavy traffic load condition. Simulation results validate the merit of the proposed IDEA user association in adapting the loads of BSs and RSs along with the distributions of green power. Results also show the potential of the proposed IDEA user association in substantially reducing on-grid power consumption and achieving comparable average traffic delay compared with the existing algorithm which aims to minimize the average traffic delay. IDEA use association provides insights into how BSs, RSs and users should associate in 3-tier HetNets with hybrid energy sources for the joint optimization of average traffic delay and on-grid power consumption.

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