Opportunistic User Association for Multi-Service HetNets Using Nash Bargaining Solution

Dantong Liu, Yue Chen, Kok Keong Chai, Tiankui Zhang, and Maged Elkashlan

***Abstract*—We propose an opportunistic user association for multi-service HetNets aiming to guarantee quality of service (QoS) of human-to-human (H2H) traffic while providing fair resource allocation for machine-to-machine (M2M) traffic. We classify H2H traffic as primary service and M2M traffic as secondary service. The opportunistic user association is formulated as an optimization problem, which can be resolved by Nash Bargaining Solution (NBS). Simulation results show that the proposed algorithm can enable network operators to support fair resource allocation for M2M traffic without jeopardizing QoS of H2H traffic.**

***Index Terms*—HetNets, user association, Nash bargaining solution, multi-service, QoS.**

I. Introduction

WITH the fast development of Internet of Things (IoT) applications, machine-to-machine (M2M) traffic grows explosively. A great amount of M2M traffic uses cellular networks as backhaul to Internet [1], which generates increasing pressure for wireless network operators. The key problem is how to support more M2M traffic fairly without affecting quality of service (QoS) of conventional human-to-human (H2H) traffic.

Based on the concept of small cell, heterogeneous networks (HetNets) proposed by 3GPP is able to achieve more spectrum-efficient and energy-efficient communications [2]. Thus HetNets provide a promising architecture for supporting mixed H2H and M2M traffic. User association in HetNets refers to associating users with a serving base station (BS). The most existing research on user association in HetNets has focused on user association without service classification [3], [4]. In [3], the off-loading benefits of user association in HetNets is demonstrated in terms of capacity improvement by using range extension and inter-cell interference coordination. In [4], user association is proposed in HetNets to maximize the sum rate via convex optimization. In [5], bandwidth allocation is proposed to support the QoS of constant and variable bit rate services in the coexistence of cellular and wireless local area networks (WLANs).

While the aforementioned laid a solid foundation in understanding user association, the impact of service classification

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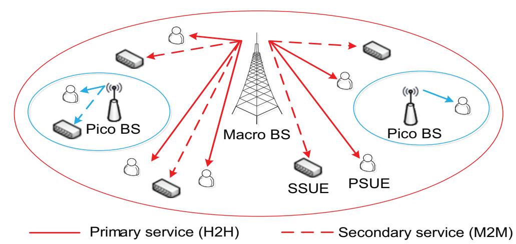

Fig. 1. Opportunistic user association in multi-service HetNets.

on user association in HetNets is less well understood. Our work aims to bridge the gap between user association and QoS support for multi-service traffic in HetNets. With this in mind, we propose opportunistic user association to classify the H2H traffic as primary service with higher priority, and the M2M traffic as secondary service with lower priority. The proposed opportunistic user association aims at utilizing radio resources to support fair resource allocation for secondary service without jeopardizing QoS of the primary service.

We formulate the opportunistic user association as a bargaining problem, where different BSs compete for serving users. Nash Bargaining Solution (NBS) from cooperative game theory is well suited for resource allocation among competing players [6], [7]. Inspired by the low complexity two-band partition [8], we first develop a NBS based two-player bargaining algorithm for two BSs to negotiate user association. We then develop a multi-player bargaining algorithm with the aid of the Hungarian method that groups BSs into pairs to optimize user association in HetNets.

II. System Model

We focus on the 2-tier downlink HetNet where tier 1 is modeled as macrocell and tier 2 as picocell. Fig. 1 details the system model for opportunistic user association in multi-service HetNets. We have M BSs, where BS_1 is a macro BS, and BS_m is a pico BS ($m \in \{2, 3, \cdots, M\}$). All the BSs share the same frequency band. It is worth mentioning that the proposed opportunistic user association can be extended to multi-tier HetNets. We have N user equipments (UEs), where UE_n ($n \in \{1, 2, \cdots, K\}$) requests secondary service (e.g. M2M traffic), denoted as secondary service UE (SSUE), and UE_n ($n \in \{K+1, K+2, \cdots, N\}$) requests primary service (e.g. H2H traffic), denoted as primary service UE (PSUE). We assume that each UE is associated with a single BS at any time. We also assume that the BSs have the capability to differentiate between PSUE and SSUE.

To formulate the user association, we define association matrix $\mathbf{X}$ as

$$x_{mn} = \begin{cases} 1, & \text{if } \mathrm{UE}_n \text{ is associated with } \mathrm{BS}_m \\ 0, & \text{otherwise} \end{cases}. \quad (1)$$

The downlink signal-to-interference-plus-noise-ratio (SINR) of UE_n associated with BS_m is

$$SINR_{mn} = \frac{P_m g_{mn}}{\sum\limits_{i \in \{1,2,\cdots,M\}, i \neq m} P_i g_{in} + \sigma^2}, \quad (2)$$

where P_m is the transmit power of BS_m, g_{mn} is the channel power gain between UE_n and BS_m, where pathloss and shadowing are considered, and σ^2 is the noise power level.

Since the effective load of BS_m is defined as the number of UEs associated with it $\sum_{n=1}^{N} x_{mn}$, each UE receives a fraction $1 \Big/ \sum_{n=1}^{N} x_{mn}$ of all the radio spectrum when associated with BS_m [4]. Therefore, UE_n's data rate associated with BS_m is

$$r_{mn} = \left(\sum\nolimits_{n=1}^{N} x_{mn} \right)^{-1} W \log_2 \left(1 + SINR_{mn}\right), \quad (3)$$

where W is the operating frequency band.

III. Proposed NBS Based Opportunistic User Association

A. Problem Formulation

According to cooperative game theory, the bargaining problem is outlined as follows [6]. Assume M players compete for resources and the minimal payoff of each player $m \quad (m \in \{1,2,\cdots,M\})$ is $U_m^{\min}$, where $\mathbf{U}^{\min} = \left(U_1^{\min},\cdots,U_m^{\min},\cdots,U_M^{\min}\right)$. Assume $\mathbf{U} = (U_1,\cdots,U_m,\cdots,U_M)$ is a closed and convex subset of $\Re^M$ to present the set of feasible payoff allocation that players can get when they cooperate. Since the minimal payoff of each player must be guaranteed, $\left\{U_m \in \mathbf{U} | U_m \geq U_m^{\min}, \forall m \in \{1,2,\cdots,M\}\right\}$ is a nonempty set. Then $\left(\mathbf{U}, \mathbf{U}^{\min}\right)$ is a M person bargaining problem. As such, the NBS of the bargaining problem satisfies [7]

$$\begin{aligned} &\mathbf{U}* = \arg\max_{\mathbf{U}} \prod_{m=1}^{M} \left(U_m - U_m^{\min}\right), \\ &\text{s.t.} \qquad U_m \geq U_m^{\min}. \end{aligned} \quad (4)$$

Based on [7], if U_m is a concave upper-bounded function which has convex support, there exists a unique and optimal NBS.

In opportunistic user association, we model the BSs as players in the bargaining problem and define the payoff of BS_m as the sum utility of all the UEs associated with it

$$U_m = \sum_{n=1}^{N} x_{mn} \mu_{mn}, \quad (5)$$

where u_{mn} is the utility of UE_n associated with BS_m,

$$\mu_{mn} = \begin{cases} b \ln\left(r_{mn}\right), & \forall n \in \{1, 2 \cdots, K\} \\ -\exp\left(\frac{-a r_{mn}}{r_n^{\min}}\right), & \forall n \in \{K+1,\cdots,N\} \end{cases}. \quad (6)$$

in which a is PSUE's satisfactory factor ($a > 1$), and the proper value of a has been justified in [9] and the reference therein. b is SSUE's utility coefficient ($0 < b < 1$), and $r_n^{\min}$ is the required minimum data rate of PSUE.

According to (6), PSUE's utility is negative if the data rate is less than $r_n^{\min}$, otherwise it asymptotically approaches zero. To encourage user fairness, SSUE's utility is a logarithm function which is concave with diminishing benefits, widely used to construct utility functions [10].

Substituting (3) and (6) into (5), the payoff of BS_m is

$$U_m = \sum_{n=1}^{K} x_{mn} b \ln\left(r_{mn}\right) + \sum_{n=K+1}^{N} -x_{mn} \exp\left(\frac{-a r_{mn}}{r_n^{\min}}\right). \quad (7)$$

Then the optimization problem of opportunistic user association is formulated as

$$\begin{aligned} \max_{\mathbf{X}}. \quad & U = \prod_{m=1}^{M} \left(U_m - U_m^{\min}\right), \\ \text{s.t.} \quad & U_m \geq U_m^{\min}, \ \forall m \\ & x_{mn} = \{0,1\}, \ \forall m,n \\ & \textstyle\sum_{m=1}^{M} x_{mn} = 1, \ \forall n, \end{aligned} \quad (8)$$

where U is the NBS utility, and $U_m^{\min}$ is the minimal payoff of BS_m. Here we set $U_m^{\min} \to 0$, which means PSUE's data rate is larger than the required minimum data rate. $\sum_{m=1}^{M} x_{mn} = 1$ indicates each UE must be associated with a single BS.

To sum up, the bargaining problem of opportunistic user association in HetNets is described as follows. Each BS_m has the payoff U_m, which is concave and upper-bounded, since its Hessian matrix is negative semidefinite. The optimization goal is to determine $\mathbf{X}$ to maximize all U_m simultaneously under the constraint $U_m \geq U_m^{\min}$. It is crucial to design a simple and fast method to find the optimal, unique, and fair $\mathbf{X}$.

B. Algorithm for Two-BS Case

In this subsection, we focus on the two-player bargaining algorithm for two BSs ($M = 2$). We then proceed in the next subsection with the multi-player bargaining algorithm for multiple BSs. In the two-player bargaining algorithm, BS_1 and BS_2 are arbitrary parts of BSs in HetNets. They can be modeled as a macro BS and a pico BS, or two macro BSs, or two pico BSs. Inspired by the low complexity algorithm in [8], the so-called two-band partition is applied to determine the opportunistic user association. It is shown in [8] that the two-band partition is near-optimal for the optimization goal of weighted rate maximization.

The proposed two-band UE partition in opportunistic user association is described in Table I. In opportunistic user association, the two-player bargaining is to maximize the NBS utility $U = \left(U_1 - U_1^{\min}\right)\left(U_2 - U_2^{\min}\right)$. Similar to [8], the constraint $x_{mn} = \{0,1\}$ is relaxed to continuous values with $0 \leq x_{mn} \leq 1$. Then the Lagrangian function of (8) as a function of x_{mn} is

$$L = \prod_{m=1}^{2} \left(U_m - U_m^{\min}\right) + \sum_{n=1}^{N} \lambda_n \left(\sum_{m=1}^{2} x_{mn} - 1 \right), \quad (9)$$

where λ_n is the Lagrangian multipliers. By taking the Karush-Kuhn-Tucker (KKT) condition and substituting (5) into (9), the derivative of (9) with respect to x_{mn} is

$$\frac{\mu_{1n} + \sum\limits_{n=1}^{N} x_{1n} \frac{d\mu_{1n}}{dx_{1n}}}{U_1 - U_1^{\min}} = \frac{\mu_{2n} + \sum\limits_{n=1}^{N} x_{2n} \frac{d\mu_{2n}}{dx_{2n}}}{U_2 - U_2^{\min}}. \quad (10)$$

TABLE I
TWO-BAND UE PARTITION

Step 1. Initialization Initialize the user association and guarantee BS_m's minimal payoff. Set $U_{\max}(0) = U$, and calculate A_m and B_m. Set $i = 1$.
Step 2. Sort the UEs Sort UEs from largest to smallest according to $f(\mu_{1n}, \mu_{2n})$.
Step 3. For $n = 1, \cdots, N-1$ Calculate $U(n)$, where UE_1,..., UE_n is associated with BS_1, and UE_{n+1},..., UE_N is associated with BS_2. **end**
Step 4. Choose the two-band partition $\aleph = \arg\max_n U(n)$ **which generates the largest** U **satisfying the constraints.** Set $U_{\max}(i) = U(\aleph)$.
Step 5. Update user association If $U_{\max}(i) \leq U_{\max}(i-1)$, the iteration ends; Otherwise, update A_m and B_m according to the new partition, set $i = i + 1$, and go to ***step 2***.

The left and right side of (10) can be interpreted as the marginal benefits of UE_n for BS_1 and BS_2, respectively. When UE_n is only associated with one BS, (10) becomes inequality. If the left side of (10) is greater than the right side, UE_n should be associated with BS_1 and vice versa with BS_2. Substitute (7) into (10), and take the difference between the left and right sides of (10), we define $f(\mu_{1n}, \mu_{2n})$ as difference of marginal benefits of UE_n for BS_1 and BS_2

$$f(\mu_{1n}, \mu_{2n}) = \frac{(\mu_{1n} + A_1 + B_1)}{U_1 - U_1^{\min}} - \frac{(\mu_{2n} + A_2 + B_2)}{U_2 - U_2^{\min}}, \quad (11)$$

where

$$A_m = \sum_{n=K+1}^{N} \left(\frac{-a r_{mn} x_{mn}}{\sum\limits_{n=1}^{N} x_{mn} r_n^{\min}} \right) \exp\left(\frac{-a r_{mn}}{r_n^{\min}} \right), m \in \{1, 2\}, \quad (12)$$

and

$$B_m = \sum_{n=1}^{K} x_{mn} \left(-b \Big/ \sum\nolimits_{n=1}^{N} x_{mn} \right), m \in \{1, 2\}. \quad (13)$$

Thus we can decide whether UE_n should be associated with BS_1 or BS_2 by checking whether $f(\mu_{1n}, \mu_{2n})$ is greater or less than zero. With fixed A_m and B_m, we sort the index of UEs to make $f(\mu_{1n}, \mu_{2n})$ decrease in n, such that $f(\mu_{1n}, \mu_{2n})$ is a monotonic function of n. Then (11) is similar to the weighted maximization in [8], and the two-band UE partition is near-optimal to the optimization problem in (8) with $M = 2$.

It is worthy mentioning that due to the continuous relaxation of x_{mn}, in the end, the UE_n with $f(\mu_{1n}, \mu_{2n}) = 0$ will be associated with BS_1 and BS_2 simultaneously. We call this UE_n as boundary UE, and all the other UEs are associated with either BS_1 or BS_2, which is similar with the approach in [11]. As shown in [8], given the number of UEs is much larger than the number of BSs, the boundary UE can be associated with either BS arbitrarily without affecting the system performance.

This two-band UE partition has the complexity of $O(N^2)$ for each iteration, which can be further improved by the binary search algorithm with a complexity of $O(N \log_2 N)$. According to simulations, this two-band UE partition converges within three rounds.

TABLE II
MULTI-PLAYER BARGAINING ALGORITHM

Step 1. Initialize the user association Associate all UEs to BSs.
Step 2. Group coalition If the number of BSs is odd, a dummy BS is created, and no BS bargains UEs with this dummy BS. The coalition is grouped by the Hungarian method.
Step 3. Bargain in each coalition Bargain the user association using the two-band UE partition in Table I.
Step 4. Repeat Go to *Step 2*, until no improvement is achieved i.e.,$\mathbf{b} = \mathbf{0}_{M \times M}$.

C. Algorithm for Multi-BS Case with Coalition

For the multiple BSs case, the most recent literature has focused on solving the user association problem among multiple BSs in a centralized manner [4]. Note that the centralized way such as brute force will incur high computational complexity with $O(M^N)$. Note that M and N are number of BSs and UEs, respectively. Such computation is essentially impossible even for a modest size HetNet.

In this letter, we propose a two-step iterative algorithm. We first group BSs into pairs called coalitions. We then for each coalition execute the two-player bargaining algorithm in Table I. The BSs are regrouped and re-bargained until convergence. By doing so, the computational complexity is greatly reduced. The proposed multi-player bargaining algorithm is shown in Table II.

Grouping BSs into pairs is an assignment problem, which we can efficiently solve using the Hungarian method [12]. We formulate the problem in detail as below.

The benefit for the *i*th BS bargaining UEs with the *j*th BS is defined as b_{ij}, which is the element of the matrix $\mathbf{b}$,

$$b_{ij} = \max_{i,j \in \{1,\cdots,M\}} \left(U\left(\tilde{U}_i, \tilde{U}_j\right) - U\left(\widehat{U}_i, \widehat{U}_j\right), 0\right), \quad (14)$$

where $\tilde{U}_i$ and $\tilde{U}_j$ are the payoff of BS_i and BS_j after bargaining, $\widehat{U}_i$ and $\widehat{U}_j$ are the payoff of BS_i and BS_j before bargaining. Obviously, $b_{ii} = 0 \, \forall i$ and $\mathbf{b}$ is symmetric. The proposed two-band UE partition in Table I calculates each $b_{ij} \, \forall i, j$. The total computational complexity is $O(M^2 N \log_2 N)$.

We define the coalition assignment matrix $\mathbf{h}$, with elements representing whether there is a coalition between two BSs

$$h_{ij} = \begin{cases} 1, & \text{if } \mathrm{BS}_i \text{ bargains with } \mathrm{BS}_j \\ 0, & \text{otherwise} \end{cases}. \quad (15)$$

Then the assignment problem is how to group the bargaining pair so as to maximize the overall benefit, which is formulated as

$$\begin{aligned} &\max_{\mathbf{h}}. \textstyle\sum_{i=1}^{M} \sum_{j=1}^{M} h_{ij} b_{ij}, \\ &\text{s.t.} \sum_{i=1}^{M} h_{ij} = 1, \forall j \ \sum_{j=1}^{M} h_{ij} = 1, \forall i \ h_{ij} \in \{0, 1\}, \forall i, j. \end{aligned} \quad (16)$$

Taking into account the minimization goal of the Hungarian method, the optimization goal of (16) is modified as $\min\limits_{\mathbf{h}} \sum\limits_{i=1}^{M} \sum\limits_{j=1}^{M} -h_{ij} b_{ij}$. The Hungarian method is detailed in [12].

The complexity of Hungarian method is $O(M^3)$, so the overall complexity for each round of the proposed multi-player

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Bandwidth	10 MHz	Transmit power of macro BS	46 dBm
Noise power	-174 dBm/Hz	Transmit power of pico BS	30 dBm
a	10 [9]	Log-normal shadowing fading	10 dB [13]
b	0.005	PSUE's required min data rate	1 Mbps

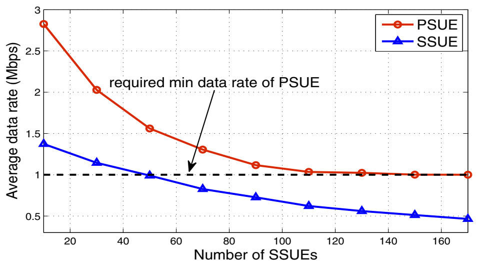

Fig. 2. Average date rate versus number of SSUEs.

bargaining algorithm is $O\left(M^2N\log_2 N + M^3\right)$. Simulations show that the multi-player bargaining algorithm converges within six rounds.

IV. SIMULATION RESULTS

We simulate the downlink of a HetNet, where pico BSs are symmetrically located along a circle with radius as 120m and macro BS in the center. The UEs are randomly distributed in the HetNets area. The basic simulation parameters are shown in Table III.

The pathloss between macro BS and UE and between pico BS and UE is $128.1 + 37.6\log_{10}d\,(km)$ and $140.7 + 36.7\log_{10}d\,(km)$ [13], respectively.

Fig. 2 shows the average date rate versus number of SSUEs when 1 macro and 1 pico BS are simulated. Assuming there are 30 PSUEs, the figure indicates that the increase of SSUEs does not affect QoS of PSUEs, since the average data rate of PSUE can always fulfill the minimum data rate requirement.

We then set 20 PSUEs and 80 SSUEs. We define $1 - \exp\left(-10r_n/r_n^{\min}\right),\ n = \{K+1, K+2\cdots, N\}$ [9] to weight the satisfaction degree of PSUEs. We validate the fairness among SSUEs by Jain's fairness index $FI = \left(\sum_{n=1}^{K} r_n\right)^2 \Big/ \left(K\sum_{n=1}^{K} r_n^2\right),\ n = \{1, 2, \cdots, K\}$, where r_n is transmission rate of UE_n.

Fig. 3 and Fig. 4 are a comparison with the reference algorithm [4] which aims to maximize the sum rate without service classification. Both figures show that in the scenario with more picocells, the proposed opportunistic user association outperforms the reference algorithm in terms of QoS support. The proposed algorithm not only fulfills the minimum data rate requirement of PSUEs, but also improves the fairness among SSUEs.

V. CONCLUSIONS

We proposed an opportunistic user association for multi-service HetNets, where H2H traffic is classified as primary service and M2M traffic as secondary service. The opportunistic user association optimization is modeled as a bargaining problem, which is resolved by NBS. We showed that for each iteration, the proposed opportunistic user association had a low computational complexity of $O\left(M^2N\log_2 N + M^3\right)$. Simulations indicate that the proposed algorithm can support fair resource allocation for M2M traffic without jeopardizing QoS of H2H traffic. In the future work, we will evaluate the performance of the proposed algorithm in the more general scenario with multiple co-channel marcocells.

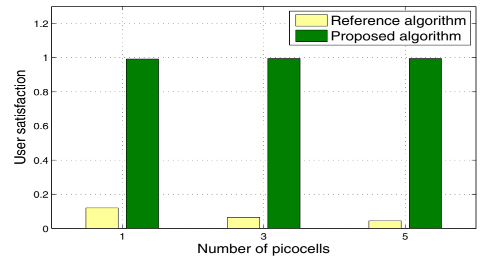

Fig. 3. Average satisfaction of PSUE versus number of picocells.

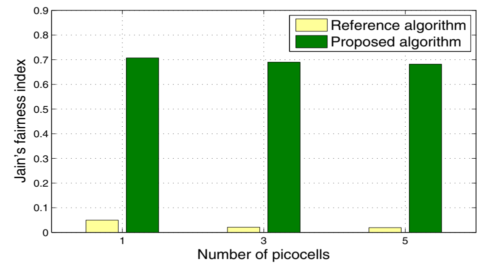

Fig. 4. Jain's fairness index of SSUE versus number of picocells.

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