AN ENERGY-AWARE AUCTION FOR HYBRID ACCESS IN HETEROGENEOUS NETWORKS UNDER QOS REQUIREMENTS

Fei Shen⋆, Pin-Hsun Lin+, Luca Sanguinetti⋆‡, Merouane Debbah⋆†, Eduard A. Jorswieck+

⋆Large Networks and System Group (LANEAS), CentraleSupélec, Université Paris-Saclay, Gif-sur-Yvette, France

+Technische Universität Dresden, Communications Laboratory, Dresden, Germany

‡Dipartimento di Ingegneria dell'Informazione, University of Pisa, Pisa, Italy

†Mathematical and Algorithmic Sciences Lab, Huawei France, Paris, France

ABSTRACT

We consider a heterogeneous network (HetNet) in which multiple small cell base stations (SBSs) aim to offload a quantity of macro cell user equipments (MUEs) to reduce the energy consumption of the network while guaranteeing the QoS requirements of all UEs. We design an ascending-bid auction mechanism to achieve this goal. Unique and closed form solutions for the demand and supply quantities of offloading MUEs are derived. When the MBS has knowledge about the utilities and strategies of the SBSs, the proposed auction can be formulated as a Stackelberg game where the clinching bid price is obtained in closed form. Numerical results verify the theoretical analysis for different scenarios and show that the proposed auction clinches fast at the unique clinching price, thereby resulting in a win-win solution that improves the energy consumption of the HetNet.

Index Terms— ascending-bid auction, hybrid access, heterogeneous network, QoS requirement

1. INTRODUCTION

Heterogeneous networks (HetNets) are considered as a key technology for 5G [1]. This paper investigates the user equipment (UE) and base station (BS) association for a network with a single macrocell base station (MBS) and multiple small cell base stations (SBSs), where each UE has a rate-based QoS requirement to be guaranteed by the serving BS.

The three basic access control mechanisms for HetNets are closed, hybrid and open access [2, 3]. Among them, the hybrid access is considered as the most promising for reducing the energy consumption of the network. Since the transmit power of each UE is highly related to the total number of UEs served in each cell, it is important for the MBS to stimulate the SBSs for the hybrid access. When multiple SBSs exist, auction is a powerful tool to model, analyze, and solve the problem for offloading the quantity of macrocell UEs (MUEs) in the hybrid access.

There exist several works in which resource allocation is performed using game theory and auction [4, 5]. The user-cell association for massive MIMO networks is considered in [6] and addressed using non-cooperative game theory. In [7], the user association and spectrum allocation problems are addressed to stabilize the HetNet and to minimize the transmission delay. In [8, 9], two auction mechanisms for allocating the received power among a group of UEs subject to a constraint on the interference are proposed for

relay selection and relay power allocation, leading to a weighted max-min fair allocation. To motivate an efficient and fair resource allocation for spectrum-sharing femtocell networks, Vickrey-Clarke-Groves (VCG) auction is proposed to ensure that small cell user equipments (SUEs) submit their utilities truthfully despite of their selfish nature [10]. The single cluster of macro-femtocell hybrid access is discussed in [11, 12] where a Stackelberg game is designed to maximize the system energy consumption. A compensation framework is proposed for motivating the hybrid access in conjunction with a time division multiple access (TDMA) strategy [13].

In this work, the multiple SBSs are modelled as bidders that compete among each other to offload a certain number of MUEs and receive the corresponding compensation paid by the MBS. Two different scenarios are envisaged. In the first one, we assume that the MBS and SBSs belong to different operators and thus have no knowledge of the utilities and strategies of each other. In this context, a low-complexity ascending-bid auction is proposed, in which each SBS bids for the demand quantity of the offloading MUEs only based on their local information and the given bid price. The fast convergence of the clinching price at market clearance is guaranteed. In the second scenario, we assume that the MBS and SBSs belong to the same operator and exploit the knowledge of the utilities and strategies to formulate a Stackelberg game. This allows us to compute the clinching price in closed-form without the need of any iterative procedure.

The outline of the paper is as follows. In order to motivate the energy-aware hybrid access for the two-tier HetNet, an ascending-bid auction is proposed in Sec. 2. The utilities of the MBS and SBSs are provided as functions of the bid price and the quantity of offloading MUEs in Sec. 3.1. Unique and closed form solutions for the demand and supply quantities of offloading MUEs are derived in Sec. 3.2 by maximizing the utilities of the MBS and SBSs, respectively. A Stackelberg game is analyzed in Sec. 4 wherein a closed-form clinching price is derived. Numerical results are given in Sec. 5 to assess the performance of the proposed solutions and validate the analysis.

2. NETWORK MODEL

2.1. System model

We consider the uplink of a two-tier HetNet in which the MBS and SBSs operate over different frequency bands. We denote by M the number of MUEs that are served by the MBS and assume that N SBSs serve L_i SUEs each. We assume also that all UEs and BSs are equipped with a single antenna and that a certain QoS require-
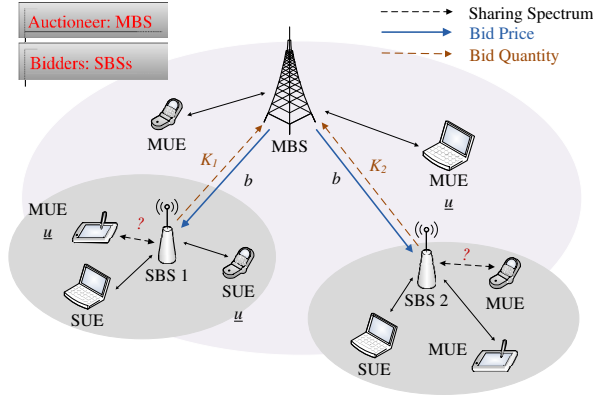
Fig. 1. The considered system model.

ment $\underline{u}$ must be guaranteed to each UE (no matter it is served by the MBS or by the SBSs). Within this setting, we are interested in reducing the energy consumption of the network. To this end, we assume that the MBS is willing to compensate a given SBS for offloading a quantity of MUEs. Clearly, when $N > 1$ this gives rise to a competition among the SBSs, which is modelled and solved in this work through an ascending-bid auction mechanism as described in the next section.

We consider a block flat-fading channel model and denote by α_i the channel gain of a generic UE i. Call S_i the total number of UEs associated to the MBS or SBS serving UE i. Then, for a given S_i the uplink power required by UE i to meet the rate requirement $\underline{u}$ is given by [14] as

$$p_i[S_i] = \frac{1 - 2^{-\underline{u}}}{\alpha_i} \frac{1}{S_i(2^{-\underline{u}} - 1) + 1}. \tag{1}$$

We denote the Shannon rate $\log(1 + SINR_i)$ as the criterion of the rate requirement $\underline{u}$ measured in [bit/s/Hz]. When all the UEs meet the rate requirement $\underline{u}$ with equality, $p_i[S_i]$ is derived in a simple expression as (1) where the CSI or SINR of other UEs is contained in $\underline{u}$.

From the above equation, it follows that a positive power allocation and the feasibility of achieving $\underline{u}$ for all UEs in the HetNet are ensured only if the total number S_i in the network is such that

$$0 \le S_i \le \frac{1}{1 - 2^{-\underline{u}}}. \tag{2}$$

2.2. Auction-based Hybrid Access

In a generic ascending-bid auction mechanism, the auctioneer calls a bid price and the bidders respond with demand quantities by maximizing their own utilities. Meanwhile, the auctioneer optimizes the supply at the given bid price in each round. The process iterates with increasing bid prices until the market clears or the demand is no less than the supply [15].

The ascending-bid auction mechanism used in this work to offload MUEs operates as follows. The MBS acts as the auctioneer, which announces a bid price b to all the SBSs (the bidders) and calls for demand quantities $\{K_i^\star; i = 1, \ldots, N\}$. Each $K_i^\star$ corresponds to the maximum number of MUEs that can be offloaded by SBS i in order to maximize its own utility function U_i^S while taking into account that the reward from the MBS is $bK_i^\star$. At the same

time, the MBS optimizes its supply quantity by computing the optimal number $K^\star$ of offloading MUEs by maximizing its own utility U^M. If the sum of the demand quantities is less than the supply, i.e., $\sum_{i=1}^N K_i^\star < K^\star$, then the auctioneer increases the bid price b by a given quantity Δb. The process continues until the market clinches or, equivalently, until the following condition is satisfied $\sum_{i=1}^N K_i^\star = K^\star$. The above ascending-bid auction mechanism is summarized in Algorithm 1.

Algorithm 1 Auction-based Hybrid Access

1: Input M, N, $\underline{u}$, $\{L_i\}$, Δb, U^M and $\{U_i^S\}$.
2: Output $K^\star$, $\{K_i^\star\}$, $b^\star$.
3: Set $b = 0$;
4: **repeat**
5:     Set $b = b + \Delta b$;
6:     Compute $K_i^\star = \arg \max_{K_i \in 0, 1, \ldots, M} U_i^S$;
7:     Compute $K^\star = \arg \max_{K \in 0, 1, \ldots, M} U^M$;
8: **until** $\sum_{i=1}^N K_i^\star = K^\star$

When the auctioneer MBS has no knowledge about the utility and strategies of the SBSs, the auction is run as shown in Algorithm 1 until the market clears.

3. AUCTION FORMULATION AND SOLUTION

Next, we introduce the utility functions of MBS and SBSs for the propsoed auction framework and then provide its solution in a closed form. The bid b is provided by the auctioneer MBS for the quantity of offloading MUEs.

3.1. Auction Formulation

The utility functions U^M and U_i^S commonly take the following form `Utility = Revenue − Cost`. In this work, we assume that U^M is computed as

$$U^M = v^M - bK, \tag{3}$$

where v^M denotes the `Revenue` for the power saving for each remaining MUE due to the offloading of K MUEs and bK accounts for the total price (or cost) paid by the MBS to all SBSs. Denote $\mathcal{M}$ and $\mathcal{M} - \mathcal{K}$ to be the sets of MUEs served by the MBS before and after using the hybrid access, respectively. Thereby, we obtain

$$
\begin{aligned}
v^M &= \lambda^M \left(p_i[M] - p_i[M - K] \right) \frac{\alpha_i}{1 - 2^{-\underline{u}}} \\
&= \lambda^M \left(\frac{1}{M(2^{-\underline{u}} - 1) + 1} - \frac{1}{(M - K)(2^{-\underline{u}} - 1) + 1} \right),
\end{aligned}
\tag{4}
$$

where λ^M denotes the equivalent revenue per unit of power saving of a single MUE i that remains in the service range of MBS. For each remaining MUE i in the system the term $\frac{1 - 2^{-\underline{u}}}{\alpha_i}$ remains the same for both sets $\mathcal{M}$ and $\mathcal{M} - \mathcal{K}$ in (1). Therefore, $\frac{1 - 2^{\underline{u}}}{\alpha_i}$ is multiplied to ease the calculation. Note that both the `Revenue` and `Cost` of the MBS are increasing functions with respect to K, i.e., the supply quantity of offloaded MUEs.

The utility of SBS i is modelled as:

$$U_i^S = v_i^S + bK_i - E_i \tag{5}$$

where v_i^S accounts for the utility of the L_i SUEs, bK_i is the compensation received from the MBS, and E_i is the cost of additional energy of each registered SUE when additional K_i MUEs are offloaded to the SBS i. We let $v_i^S = \lambda_1 L_i \underline{u}$ with λ_1 being the revenue per unit of achievable rate whereas E_i is computed as

$$E_i = \lambda_2 \frac{p_i[L_i + K_i]}{p_i[L_i]} = \lambda_2 \frac{L_i(2^{-\underline{u}} - 1) + 1}{(L_i + K_i)(2^{-\underline{u}} - 1) + 1} \qquad (6)$$

with λ_2 being the revenue per unit of power loss denoted by the ratio of power consumption for a single registered SUE. Observe that E_i is an increasing function of K_i. The utility U_i^S is a function of only the local information of each SBS and of the bid price b from the MBS. Therefore, there is no need of information exchange among SBSs.

3.2. Auction Solution

As depicted in Algorithm 1, for a given b the demand quantity of SBS i at each iteration is obtained as the solution of the following problem:

$$K_i^\star = \arg \max_{K_i \in \{0,1,\ldots,M\}} U_i^S, \qquad (7)$$

where U_i^S takes the form

$$U_i^S = \lambda_1 L_i \underline{u} + bK_i - \lambda_2 \frac{(L_i(2^{-\underline{u}} - 1) + 1)}{(L_i + K_i)(2^{-\underline{u}} - 1) + 1}. \qquad (8)$$

The solution of the above problem can be obtained in a closed form as follows.

Proposition 1. *For a given bid price b, the solution to (7) is*

$$K_i^\star = \left\lfloor \frac{L_i(2^{-\underline{u}} - 1) + 1}{1 - 2^{-\underline{u}}} - \sqrt{\frac{(L_i(2^{-\underline{u}} - 1) + 1)\lambda_2}{b(1 - 2^{-\underline{u}})}} \right\rfloor. \qquad (9)$$

Proof. K_i^* in (9) is obtained by checking $\frac{\partial U_i^S}{\partial K_i} = 0$ by integer optimization and showing that U_i^S is a convex function of K_i. The optimal quantity K_i is obtained by solving the first derivative of (8) with respect to K_i, i.e.,

$$\frac{\partial U_i^S}{\partial K_i} = b + \frac{\lambda_2(L_i(2^{-\underline{u}} - 1) + 1)(2^{-\underline{u}} - 1)}{((L_i + K_i)(2^{-\underline{u}} - 1) + 1)^2} = 0,$$

$$K_i = \frac{L_i(2^{-\underline{u}} - 1) + 1}{1 - 2^{-\underline{u}}} - \sqrt{\frac{(L_i(2^{-\underline{u}} - 1) + 1)\lambda_2}{b(1 - 2^{-\underline{u}})}}. \quad (10)$$

Now we show that the utility function U_i^S in (8) admits global maximum by checking the second derivative,

$$\frac{\partial^2 U_i^S}{\partial^2 K_i} = \frac{-2(L_i(2^{-\underline{u}} - 1) + 1)(2^{-\underline{u}} - 1)^2((L_i + K_i)(2^{-\underline{u}} - 1) + 1)}{((L_i + K_i)(2^{-\underline{u}} - 1) + 1)^4}. \qquad (11)$$

Given the restriction in (2), $\frac{\partial^2 U_i^S}{\partial^2 K_i} < 0$. The integer-valued optimization result is achieved by using $\lfloor \rfloor$. $\qquad \square$

As seen, for a given b the computation of $K_i^\star$ requires knowledge of local information as it only depends on the parameters L_i, $\underline{u}$, and λ_2, which are independent of other SBSs.

The MBS determines the optimal supply of offloading MUEs by solving the following problem:

$$K^\star = \arg \max_{K \in \{0,1,\ldots,M\}} U^M \qquad (12)$$

with

$$U^M = \lambda^M \left(\frac{1}{M(2^{-\underline{u}} - 1) + 1} - \frac{1}{(M-K)(2^{-\underline{u}} - 1) + 1} \right) - bK.$$

Proposition 2. *For a given bid price b, the solution to (12) is*

$$K^\star = \left\lfloor M + \sqrt{\frac{\lambda^M}{b(1 - 2^{-\underline{u}})}} - \frac{1}{1 - 2^{-\underline{u}}} \right\rfloor. \qquad (13)$$

Proof. The proof follows the same procedure as that for Proposition 1 and is thus omitted for space limitations. $\qquad \square$

With the constraint on the total number of offloading MUEs $K \in \{0,1,\ldots,M\}$, the bid price b should be provided in the following range.

Corollary 1. *The rate requirement $\underline{u}$ can be ensured provided that the bid price b is such that $b_{\min} \leq b \leq b_{\max}$ with*

$$b_{\max} = \frac{\lambda^M(1 - 2^{-\underline{u}})}{(M(2^{-\underline{u}} - 1) + 1)^2}, \qquad (14)$$

and

$$b_{\min} = \max\left(\lambda^M(1 - 2^{-\underline{u}}), \frac{\lambda_2(1 - 2^{-\underline{u}})}{L_i(2^{-\underline{u}} - 1) + 1} \right). \qquad (15)$$

Proof. $\lambda^M(1 - 2^{-\underline{u}}) \leq b \leq \frac{\lambda^M(1-2^{-\underline{u}})}{(M(2^{-\underline{u}}-1)+1)^2}$ is proved by ensuring $0 \leq K \leq M$. $\frac{\lambda_2(1-2^{-\underline{u}})}{L_i(2^{-\underline{u}}-1)+1} \leq b$ is to ensure $0 \leq K_i \leq M$, therefore Corollary 1 is proved. $\qquad \square$

4. CLINCHING PRICE-STACKELBERG GAME

If the MBS and SBSs belong to the same operator, then it is possible for the MBS to gain knowledge about the utilities and strategies of the SBSs. The proposed ascending-bid auction can be formulated as a Stackelberg game. The MBS acts as the leader by providing the clinching bid price b^* and the SBSs act as the followers by deciding the bid quantity of offloading MUEs given b^*.

We now proceed computing the clinching bid price in a closed form. If the MBS acquires the information of the SBSs, then it can predict the bid b^* without iterations. As described before, the auction mechanism is clinched if the market clears or, equivalently, if the supply is equal to the total demand, which amounts to saying that $K^\star = \sum_{i=1}^N K_i^\star$. Then, from the results of Propositions 1 and 2 it follows that:

Proposition 3. *The clinching bid price b^* can be obtained from the following equation*

$$b^* = \left(\frac{\sqrt{\lambda^M} + \sum_{i=1}^N \sqrt{\lambda_2(L_i(2^{-\underline{u}} - 1) + 1)}}{\sqrt{\frac{1}{1-2^{-\underline{u}}}}(1 + \sum_{i=1}^N L_i(2^{-\underline{u}} - 1) + 1) - M\sqrt{1 - 2^{-\underline{u}}}} \right)^2.$$
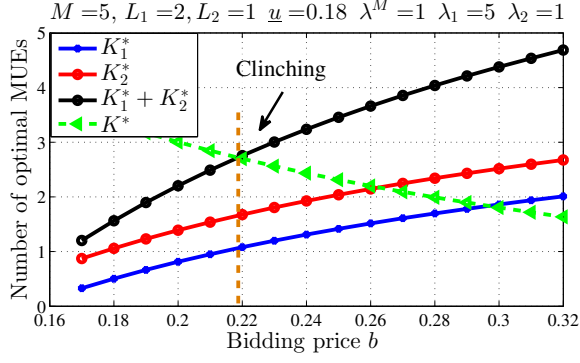
Fig. 2. Illustration of clinching bid price at market clearance with $\underline{u} = 0.18$.
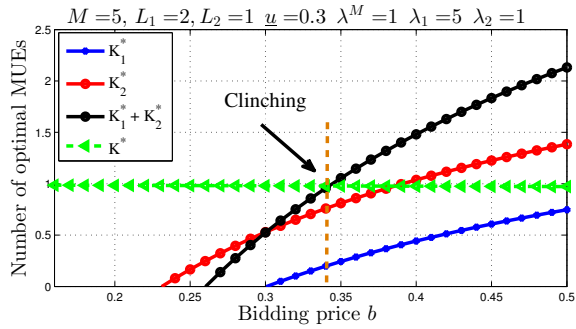

Fig. 3. Illustration of clinching bid price at market clearance with $\underline{u} = 0.3$.

Proof. Imposing $K^{\star} = \sum_{i=1}^{N} K_i^{\star}$ and solving with respect to b yields the above result (after simple calculus). $\square$

If the MBS and SBSs belong to different operators, then the ascending-bid auction is run as shown in Algorithm 1. This is illustrated in the next section.

5. NUMERICAL RESULTS

In order to illustrate the outcome of the proposed auction-based hybrid access, the scenario where two small cells exist within the coverage of the macrocell is simulated. However, the results are extendable to multiple small cells.

In the following, the identical rate requirement is set in the range such that it is achievable for all possible numbers of UEs in the two-tier system no matter in the macrocell or the small cell.

We illustrate when the MBS has no knowledge about the SBSs, how the number of MUEs in both demand and supply changes with the bid price for different network parameters. In each round of the auction, both the auctioneer MBS and the bidders SBSs optimize their supply and demand quantities of offloading MUEs by maximizing their own utilities, respectively. U^M is a decreasing function while U_i^F is an increasing function of b. The higher the bid price, the more compensation the MBS will pay to the SBSs and thus the lower its supply of MUEs. In contrast, the higher b, the more MUEs the SBSs are willing to serve. There exists a unique clinching price b^*
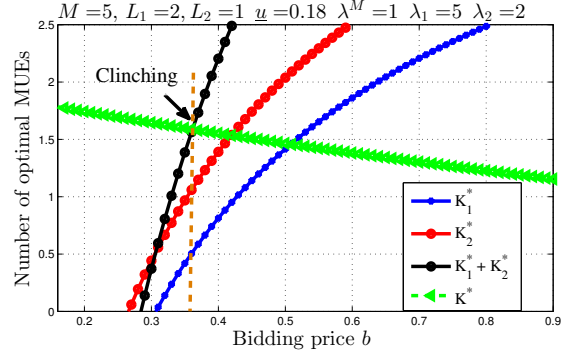

Fig. 4. Illustration of clinching bid price at market clearance with $\lambda_2 = 2$.

such that the market clears with $K^* = \sum_{i=1}^{N} K_i^*$. And the step size Δb can be chosen for fast convergence. We can see from the figures that the bid price clinches only after few iterations, which shows the fast convergence of Algorithm 1.

By comparing Fig. 2 and Fig. 3, we observe that when the rate requirement $\underline{u}$ of each UE increases, the clinching bid price b^* is higher and the market clearance quantity K^* decreases. This is because the higher rate requirement, the less the acceptable number of UEs in each cell. Moreover, the SBSs need more compensation from the MBS in order to stimulate the acceptance of the additional MUEs.

When λ_2 increases as shown in Fig. 4, the clinching bid price b^* also becomes higher and the market clearance quantity K^* decreases as well. The reason is that λ_2 shows the importance of the energy loss for the SBSs when concerning to serve additional MUEs. If λ_2 becomes higher, then less K_i^* MUEs could be served in order to make sure that the loss in power of the registered SUEs is not significant.

The theoretical analysis of b^*, K_1^*, K_2^* and K^* are verified by the simulation results. Both the utilities of the MBS and SBSs are maximized. Since there is no overhead on information exchange among different cells, the proposed ascending-bid auction is a low-complexity mechanism to apply for the hybrid access in HetNets.

After optimizing the offloading quantity of MUEs, the MBS can decide the exact MUEs with the shortest distance to the corresponding SBS in order to minimize the total energy consumption of the two-tier HetNet. However, this is beyond the scope of the current work. Therefore, the comparison of energy reduction remains in our future work.

6. CONCLUSION

In order to motivate the energy-aware hybrid access in the two-tier macro-small cell network, a novel ascending-bid auction-based algorithm is proposed.. The MBS in the macro- cell acts as the auctioneer and the SBSs in the small cells act as the bidders. The bid price is provided by the MBS to all the SBSs. The optimal supply and demand quantities and the clinching price are derived in closed form solutions. Numerical results illustrate that the auction clinches at the unique clinching price and the utilities of both the MBS and the SBSs are maximized, showing that the auction algorithm results in a win-win solution.

7. REFERENCES

[1] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Commun. Mag*, vol. 46, no. 9, pp. 59–67, 2008.

[2] H.-S. Jo, P. Xia, and J. Andrews, "Open, closed, and shared access femtocells in the downlink," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, p. 363, 2012.

[3] G. de la Roche, A. Valcarce, D. Lopez-Perez, and J. Zhang, "Access control mechanisms for femtocells," *Communications Magazine, IEEE*, vol. 48, no. 1, pp. 33–39, January 2010.

[4] G. Bacci, E. Belmega, P. Mertikopoulos, and L. Sanguinetti, "Energy-aware competitive power allocation for heterogeneous networks under qos constraints," *Wireless Communications, IEEE Transactions on*, vol. 14, no. 9, pp. 4728–4742, Sept 2015.

[5] O. Naparstek and A. Leshem, "Fully distributed optimal channel assignment for open spectrum access," *Signal Processing, IEEE Transactions on*, vol. 62, no. 2, pp. 283–294, Jan 2014.

[6] D. Bethanabhotla, O. Bursalioglu, H. Papadopoulos, and G. Caire, "Optimal user-cell association for massive mimo wireless network," in *arXiv:1407.6731 [cs.NI]*.

[7] B. Zhuang, D. Guo, and M. L. Honig, "Energy-efficient cell activation, user association, and spectrum allocation in heterogeneous networks," in *arXiv:1509.04805 [cs.IT]*.

[8] J. Huang, R. A. Berry, and M. L. Honig, "Auction-based spectrum sharing," *Mob. Netw. Appl.*, vol. 11, no. 3, pp. 405–418, Jun. 2006.

[9] J. Huang, Z. Han, M. Chiang, and H. Poor, "Auction-based resource allocation for cooperative communications," *Selected Areas in Communications, IEEE Journal on*, vol. 26, no. 7, pp. 1226–1237, September 2008.

[10] F. Wang, W. Liu, X. Chen, and W. Wang, "Auction-based resource allocation for spectrum-sharing femtocell networks," in *Communications in China (ICCC), 2012 1st IEEE International Conference on*, Aug 2012, pp. 416–421.

[11] F. Shen, M. Zhang, and E. Jorswieck, "User-centric energy aware compensation framework for hybrid macro-femtocell networks," in *IEEE Global Communications Conference-Globecom 2013*, Dec 2013, pp. 3089–3094.

[12] F. Shen and E. Jorswieck, "User-centric compensation framework with universal pricing for hybrid femtocell networks," in *Wireless Communications Signal Processing (WCSP), 2012 International Conference on*, Oct 2012, pp. 1–6.

[13] Y. Chen, J. Zhang, and Q. Zhang, "Utility-aware refunding framework for hybrid access femtocell network," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 5, pp. 1688–1697, 2012.

[14] F. Shen and E. Jorswieck, "Universal non-linear cheat-proof pricing framework for wireless multiple access channels," *Wireless Communications, IEEE Transactions on*, vol. 13, no. 3, pp. 1436–1448, March 2014.

[15] L. M. Ausubel, "An efficient ascending-bid auction for multiple objects," *American Economic Review*, vol. 94, no. 5, pp. 1452–1475, 2004.