A Reverse Auction Framework for Access Permission Transaction to Promote Hybrid Access in Femtocell Network

Yanjiao Chen§, Jin Zhang§, Qian Zhang§, Juncheng Jia†,
§Department of Computer Science and Engineering, Hong Kong University of Science and Technology
†Department of Electrical and Computer Engineering, University of Waterloo
Email: {chenyanjiao, jinzh, qianzh}@ust.hk, j6jia@bbcr.uwaterloo.ca

Abstract—**Femtocell refers to a new class of low-power, low-cost base stations (BSs) which can provide better coverage and improved voice/data Quality of Service (QoS). Hybrid access in two-tier macro-femto network is regarded as the most ideal access control mechanism to enhance overall network performance. But the implementation of hybrid access is hindered by a lack of market that can motivate ACcess Permission (ACP) trading between Wireless Service Providers (WSPs) and private femtocell owners. In this paper, we propose a reverse auction framework for fair and efficient ACP transaction. Unlike strict outcome (the demand of bidder must be fully satisfied) in most of the existing works on auction design, the proposed auction model allows range outcome, in which WSP accepts partial demand fulfillment and femtocell owners makes best-effort selling. We first propose a Vickery-Clarke-Grove (VCG) based mechanism to maximize social welfare. As the VCG mechanism is too time-consuming, we further propose an alternative truthful mechanism (referred to as suboptimal mechanism) with acceptable polynomial computational complexity. The simulation results have shown that the suboptimal mechanism generates almost the same social welfare and the cost for WSP as VCG mechanism.**

I. INTRODUCTION

Femtocell is a newly emerging technology addressing the problem of poor indoor coverage and wireless capacity limitation. In the two-tier macro-femtocell network, where the macrocell network is run by WSPs and the femtocell network by large pool of home owners, it is important to choose the proper access control mechanism, which decides what kind of users have the right to access the femtocell BSs. There are three mainstream access control mechanisms [1]: 1) *Closed access*. Only registered users (femto users) can access the femtocell. 2) *Open access*. Any users, registered and unregistered (macro users), can access the femtocell. 3) *Hybrid access*. Registered users can access the femtocell and unregistered users can access the femtocell with certain restriction.

Among the three access control mechanisms, hybrid access is the most desirable trade-off because both femtocell owners and WSP benefit from increased utility without impairing the interest of each other (which is Pareto improvement [2]). One of the key challenges for implementing hybrid access is a lack of market mechanism for femtocell owners and WSPs to trade ACP of femtocell BSs. That is to say, while WSPs are willing to ”buy” ACP from femtocell owners so that macro users can access femtocell BSs, it remains a problem how to make the deal to satisfy the need of both sides.

A sophisticatedly designed auction mechanism can properly serve the need of both WSP and femtocell owners. On the one hand, every femtocell owners has a fair opportunity to compete for selling its ACPs. One the other hand, a truthful auction incites femtocell owners to reveal their true valuation for the ACP, easing the price discovery for WSPs. Auction has been widely applied to wireless communication, especially spectrum auction [3]–[7]. The femtocell ACP auction has some unique features, which distinguish it from spectrum auction in several aspects:

1) For spectrum trading, forward auction (one-seller-multi-buyer) [3] [4] and double auction (multi-seller-multi-buyer) [5]–[7] are often used when there is one spectrum owner (such as FCC) or comparable number of sellers and buyers. For femtocell ACP trading, more often than not, WSPs are outnumbered by femtocell owners, i.e., one WSP has to deal with multiple femtocell owners. Therefore, reverse auction (one-buyer-multi-seller) should be considered and its truthfulness and other properties should be carefully examined.
2) The coverage area of two femtocells may overlap, i.e., different femtocell owners may try to peddle ACPs in the same region. This needs to be taken into consideration as WSPs want to buy just the right quota of ACPs to meet their needs in a certain area.

To better address the above-mentioned issues, in this paper, we propose a reverse auction model, which considers the scenario of a single WSP (who manages the macrocell network) and multiple femtocell owners (who runs private femtocell BSs). To deal with cell overlapping, we further partition femtocell coverage into smaller granularity of the same size (referred to as locations). The quantity of ACP traded in each location satisfies the demand of WSP and the total quantity of ACP that is sold by one femtocell owner is bounded by its capacity. Most existing works on spectrum auction only consider the strict outcome, where the bidders only accept the results that fully satisfy their bidding requirement. This means if the WSP is only interested in buying some of the ACP from a femtocell owner but not the entire package, the

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femtocell owner actually refuses to sell any ACP at all. We deem it is not sensible for femtocell owner to do so. In this paper, we assume that femtocell owners consent to take range outcome, trying their best to sell as many ACP as possible. It may also happen that in some area where few femtocell BSs exist, the demand of WSP cannot be fully satisfied. We assume that WSP is willing to accept partial fulfillment results as best effort to satisfy its user demand.

We initially apply VCG [8] [9] [10] mechanism for the auction design, which is optimal in terms of social welfare. Although the computational complexity of VCG mechanism can be polynomial concerning our model, it still costs a prohibitive amount of time. Therefore, we propose a truthful alternative mechanism, referred to as suboptimal. The suboptimal mechanism sacrifices a little social welfare but greatly reduces the computational complexity. We examine the effectiveness through simulation results, showing that the social welfare gap and the expenditure difference for WSP between the VCG and the suboptimal mechanism are negligible.

The paper makes the following key contributions.

- By carrying out the proposed auction framework for femtocell ACP transaction, hybrid access mechanism can be successfully realized in femtocell networks. The utility of both WSP and femtocell owners increases.
- Apart from the VCG-based mechanism, we propose a suboptimal auction mechanism, which is truthful, cost-saving for WSP and has low computational complexity. While most of the previous works only focused on strict outcome, our work extend to range outcome and provides both WSP and femtocell owners with more flexible choice.
- We conduct extensive simulations to analyze the performance of the proposed mechanisms. The results have shown that the suboptimal mechanism not only closely approximates VCG mechanism in terms of social welfare, but also saves the budget for WSP.

The rest of the paper is organized as follows. In Section 2, we describe the auction model in detail. We study the properties of VCG mechanism in reverse auction in Section 3 and propose a suboptimal mechanism in Section 4. Simulation results are presented in Section 5. We finally summarize our work in Section 6.

II. HYBRID ACCESS AUCTION MODEL

In this section, we give the detailed model of hybrid access reverse auction. We begin with the scenario description and then discuss the feasible allocation that the auction results should engender.

A. Model Description

We consider a network of one WSP and N femtocell owners as shown in Fig.1. The WSP considers buying ACP within a regional area that contains K locations. To begin with, all femtocell owners submit their bids to WSP. The bid of femtocell owner i includes three parts: 1) Its valuation for unit ACP, denoted by b_i; 2) Its total ACP capacity, denoted by c_i; 3) Its location availability information. Then, WSP works out the auction result that generates feasible allocation, which we will discuss later in II-B. After that, WSP computes the price for each femtocell owner in each location. Finally, WSP announces the final result and pays the winning femtocell owners corresponding price.

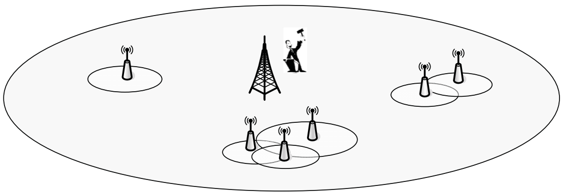

Fig. 1. System model for two-tier macro-femto network.

B. Feasible Allocation

We define the strict outcome and range outcome as follows.

Definition 1: Strict outcome is the auction results that satisfy: 1) The demand of WSP is fulfilled in every location; 2) A femtocell owner either sells all of its ACP or no ACP at all. Range outcome is the auction results that violate either one of the above requirements.

In case of strict outcome, the winner determination can be represented by a vector consisting of 1 and 0. However, in case of range outcome, femtocell owners may sell different quantities of ACP in different locations. Therefore, we use a matrix $\mathbf{A}$ to denote the final results of the auction, $\mathbf{A} = (A_1, A_2, ..., A_N)$, in which $A_i = (a_{i1}, a_{i2}, ..., a_{ik})$ and a_{ik} is the quantity of traded ACP of femtocell owner i in location k. According to the definition of ACP, a_{ik} is a continuous variable. The outcome $\mathbf{A}$ is feasible only if it satisfies the following constraints.

1) Availability: A femtocell can only provide ACP within its coverage. Let matrix $\{Avail_{i,k}\}_{i=1,...,N}^{k=1,...,K}$ denote the availability of each femtocell in each location. If $Avail_{i,k} = 1$, femtocell i covers the location k. Otherwise, $Avail_{i,k} = 0$.

2) Capacity of femtocell: The total quantity of ACP that each femtocell sell in all its covered locations should be no more than its capacity,

$$\sum_{k \in S(i)} a_{ik} \leq c_i, \tag{1}$$

in which and $S(i)$ is the set of locations it covers.

III. VCG-BASED REVERSE AUCTION

In this section, we apply the VCG mechanism to the hybrid access auction. We first describe the VCG mechanism in detail. Then we give a brief analysis of its computational complexity.

A. VCG Mechanism

The well-known VCG mechanism ensures truth-telling of bidders and tries to maximize social welfare with feasible allocation. It works as follows in the reverse auction.

- Given the bids of femtocell owners, WSP works out the feasible allocation that minimizes the total valuation,

$$\mathbf{A}^* = \arg\min_{A} \sum_{i=1}^{n} (\sum_{k \in S(i)} a_{ik}) b_i, \quad s.t.\ \mathbf{A}^*\ satisfies\ allocation\ constraints. \tag{2}$$

  Since VCG mechanism is truthful, $b_i = v_i$, in which v_i is the true valuation of femtocell owner i

  Let $V(N)$ denote the total minimum valuation, i.e.,

$$V(N) = \sum_{i=1}^{n} (\sum_{k \in S(i)} a^*_{ik}) b_i. \tag{3}$$

  The winners are those who have been assigned at least one ACP in one of its covered locations.
- For each winning femtocell owner i, compute the minimum valuation (under the condition of feasible allocation) excluding its bid. Let $V(N \backslash i)$ denote the minimum valuation without femtocell owner i,

$$V(N \backslash i) = \min \sum_{j=1, j \neq i}^{n} (\sum_{k \in S(j)} a'_{jk}) b_j. \tag{4}$$

- The price that WSP pays to femtocell owner i, denoted by p_i, for the total traded ACP is:

$$p^*_i = V(N \backslash i) - \sum_{j \neq i} (\sum_{k \in S(j)} a^*_{jk}) b_j. \tag{5}$$

- WSP purchased ACP from femtocell owners according to allocation $\mathbf{A}^*$ at the price p^*_i.

The running time of the VCG mechanism depends mostly on finding the feasible allocation that minimizes the total valuation of ACP. It can be easily proved that the problem can be solved by linear programming, for which there are two mainstream algorithms.

The simplex algorithm starts from any vertex of the feasible region and keeps moving towards another vertex that generates better objective value until the current vertex is optimal. Simplex algorithm is an exponential-time algorithm [11].

Karmarkar's Algorithm, belonging to the interior point method, generates a sequence of points inside the feasible region and finally approaches the optimal vertex [12]. Karmarkar's Algorithm is bounded by $O(N^4K^4L)$, in which L is the number of encoded bits of a_{ik}. Therefore, in VCG-based reverse auction, to determine the winners has a time complexity of $O(N^4K^4L)$ time and to determine the payment takes $O(N^5K^4L)$ time. When the number of femtocell owners and the number of locations are huge, the computational complexity of VCG-based auction is considerably high. We will see in the next section that the proposed suboptimal auction design can significantly reduce the computational complexity to $O(NK)$ and $O(N^2K)$.

IV. SUBOPTIMAL AUCTION DESIGN

In order to reduce the computational complexity and at the same time reserve the truthfulness in the reverse auction, we propose a suboptimal mechanism based on greedy algorithm in this section.

A. Main Algorithm

The suboptimal auction consists of two stages: winner determination and price determination. The winner determination is illustrated in Algorithm 1 and the price determination in Algorithm 2.

Algorithm 1 Suboptimal Allocation Algorithm (Winner Determination)

```
$Ca_{jk} = c_j, j = 1, 2, ..., n, k \in S(j)$;
$Demand_k = d_k, k = 1, 2, ..., K$;
$L$ = Sorted list of $b$ in ascending order;
while $Demand_k > 0$ for some $k$ and $L \neq \phi$ do
    $j = next(L)$;
    for all $k \in S(j)$ do
        if $Demand_k > 0$ then
            $a_{jk} = min\{Demand_k, Ca_{jk}\}$;
            $Demand_k = Demand_k - a_{jk}$;
            $Update(Ca)$.
        end if
    end for
end while
```

Winner Determination

The greedy algorithm is used for winner determination to generate a feasible allocation.

- WSP sorts the femtocell owners in a non-descending order according to their bids. Let L denote the sorted list.
- WSP iteratively checks each bidder in L. In each iteration, WSP addresses the next bidder i in L. For each location that is covered by bidder i, WSP examines whether the demand in the location is satisfied. If so, WSP will skip this location and go on looking at the next location in i's coverage. If not, WSP purchases ACPs from femtocell owner i within the location. The order of locations to be checked is pre-determined by WSP according to its own will. The number of traded ACPs is then determined by two factors: the extra demand in the location and the residual capacity of femtocell.
- After each iteration, the demand of WSP in each location and the quantity of available ACPs of each femtocell owner are updated.

It is likely that in some locations, the demand of WSP cannot be satisfied either because the femtocell are sparse and providing limited ACP or due to the high traffic pressure of macrocell in these locations. In this case, WSP accepts partial fulfillment as best effort to meet the needs of its users.

Price Determination

The algorithm for price determination searches for the critical bidder of each femtocell owner in each location.

Definition 2: Given $\{c_i\}_{i=1}^N$, $\{S(i)\}_{i=1}^N$, $\{b_i\}_{i=1}^N$ and $\{d_k\}_{k=1}^K$, a critical bidder $Critical_{ik}$ for femtocell owner i in location k is the bidder who can offer ACPs in location k and if femtocell owner i bids lower than $Critical_{ik}$ does, WSP will buy ACP from femtocell owner i in location k.

Algorithm 2 Price Determination for Femtocell Owner i

```
$Critical_{ik} = -1, k \in S(i)$;
$L' = L \setminus \{i\}$;
while $Demand_k > 0$ for some $k$ and $L' \neq \phi$ do
    $j = next(L')$;
    for all $k \in S(j)$ do
        if $Demand_k > 0$ then
            $a_{jk} = min\{Demand_k, Ca_{jk}\}$;
            $Demand_k = Demand_k - a_{jk}$;
            $Update(Ca)$;
            if $k \in S(i)$ and $Demand_k \leq 0$ then
                $Critical_{ik} = j$;
            end if
        end if
    end for
end while
if $Critical_{ik} == -1$ for some $k \in S(i)$ then
    $Critical_{ik} = \{j \neq i : b_j = \max_{k \in L \setminus \{i\}} b_k\}$;
end if
return $p_i = \sum_{k \in S(i)} a_{ik} \times v_{Critical_{ik}}$.
```

Otherwise, WSP will buy nothing from femtocell owner i in location k.

The winning femtocell owner is paid the price according to the bid of their critical bidder. Due to range provision, each winner may have different critical bidder in different locations, thus receiving different unit prices for ACP in different locations. The algorithm finds critical bidder for femtocell owner i in the following way.

- WSP sorts the femtocell owners other than i in a non-descending order.
- WSP executes the winner determination algorithm. If the demand in location k is fulfilled by the first j bidders, the critical bidder for femtocell owner i in location k is the jth bidder.

B. Properties

We analyze the suboptimal mechanism's properties regarding the truthfulness and computational complexity.

Lemma 1: A mechanism of reverse auction is truthful if it satisfies the following two conditions:

- Monotonicity: If a bidder wins by bidding b_i, it will also win by bidding b'_i, where $b'_i < b_i$;
- Critical Payment: The winning bidder is paid the price p_i, which is the highest bid the bidder can submit in order to win.

Theorem 1: The suboptimal mechanism is truthful.

Proof: It can be easily proved that the suboptimal mechanism satisfies both *Monotonicity* and *Critical Payment*. ■

Theorem 2: The running time of the winner determination algorithm is $O(NK)$ and the price determination algorithm is $O(N^2K)$.

Proof: During winner determination phase, each iteration runs fewer than N times and each time no more than K locations are checked. Therefore, the running time of the winner determination algorithm is $O(NK)$. During price determination phase, the winner determination algorithm is leveraged for computing the price for each winner, taking $O(NK)$ running time every round. There are no more than N winners. So the running time of the price determination algorithm is $O(N^2K)$. ■

V. SIMULATION RESULTS

In this section, we conduct comprehensive simulations to evaluate the performance of the proposed auction mechanisms. Femtocell BSs scatter within an area of 100×100. WSP intends to purchase ACP in 16 locations. WSP's valuation is fixed as 2000 and the femtocell owners' valuations follow a Gaussian distribution with mean 8 and variance 4.

A. Social Welfare

We can see from Fig.2 and Fig.3 that suboptimal mechanism is almost as good as optimal mechanism in terms of social welfare. Taking into consideration the computational complexity, the suboptimal mechanism is more preferable.

Fig.2 shows that social welfare decreases as WSP requires more ACPs in each location. The reason is that WSP has to buy more ACP from femtocell owners so that the total valuation of femtocell owner increases, pulling down the social welfare. If the density of femtocells increases, there will be more femtocell owners compete with each other to vender the ACP. WSP is able to select from a larger pool of bidders with relatively lower valuation. Therefore, social welfare increases along with the increase of femtocell density as shown in Fig.3.

B. Cost for WSP

Fig.4 and Fig.5 suggest that WSP has to spend nearly the same amount of money in case of optimal and suboptimal mechanism. Fig.6 shows the price WSP paid to each femtocell owner. With the increase of requirement in each location, WSP has to pay more to femtocell owners as shown in Fig.4 due to the fact that it has to buy more ACPs and also raises the price to attract femtocell owners with higher valuation. The disbursement of WSP abates as shown in Fig.5 where the density of femtocell increases, which drags down the price due to more fierce competition between femtocell owners.

C. Bidder Satisfaction

The number of winning femtocell owners indicates bidders' satisfaction. We can see from Fig.7 and Fig.8 that the number of winners is more or less the same in optimal and suboptimal mechanism. When the average requirement of WSP in each location increases, the number of winning bidders goes up as shown in Fig.7, corresponding to the demand-supply relationship between WSP and femtocell owners. The density of femtocell almost has no influence on the number of winning bidders as shown in Fig.8 because in the allocation results, the number of winning femtocell owners is rather stable while

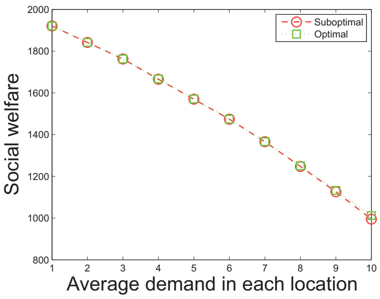

Fig. 2. Social welfare versus the average demand of WSP in each location.

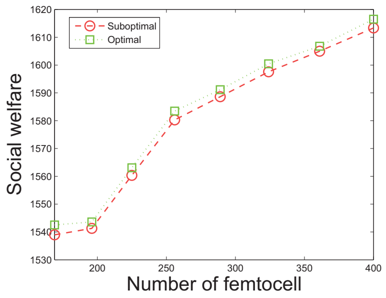

Fig. 3. Social welfare versus the density of femtocell.

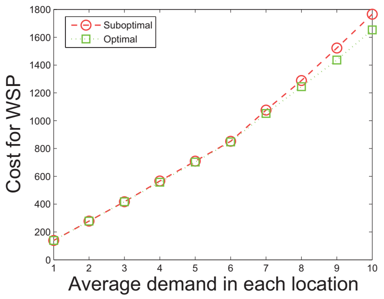

Fig. 4. Cost for WSP versus the average demand of WSP in each location.

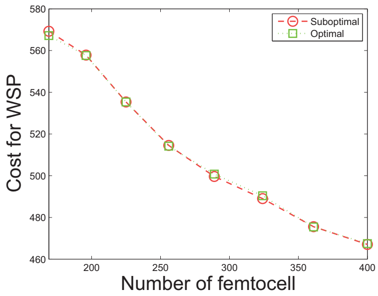

Fig. 5. Cost for WSP versus the density of femtocell.

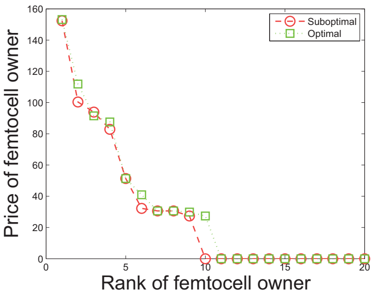

Fig. 6. Price paid to each femtocell owner.

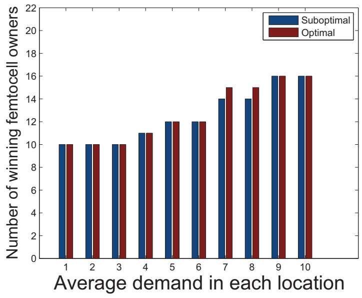

Fig. 7. Number of winning bidders versus the average demand of WSP in each location.

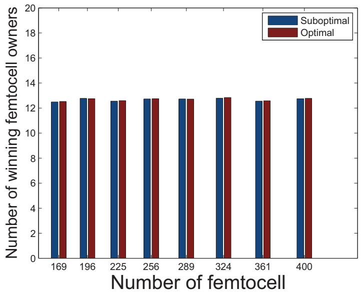

Fig. 8. Number of winning bidders versus the density of femtocell.

the quantity of trading ACP between WSP and each winning femtocell owner changes.

VI. CONCLUSIONS

In this paper, we propose a reverse auction model for a single WSP to purchase ACP from multiple femtocell owners. The successful transaction of ACP contributes to implementation of hybrid access, which enhances overall network performance and improves social welfare. The coverage of each femtocell is partitioned into locations of the same size to address the problem of coverage overlapping. Range outcome is accepted to allow femtocell owners to sell as many ACP as possible and WSP accepts partial fulfilment. Apart from VCG-based optimal mechanism, we propose a suboptimal mechanism to reduce computational complexity, which produces nearly the same social welfare and the cost for WSP as the VCG mechanism.

VII. ACKNOWLEDGEMENT

Hong Kong RGC grants 623209, 622410, Huawei-HKUST joint lab, and National Natural Science Foundation of China with grant no. as 60933012 and 61173156.

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