A Bandwidth Trading Marketplace for Mobile Data Offloading

Stefano Paris*, Fabio Martignon†, Ilario Filippini‡ and Lin Chen†
*DIMM
University of Bergamo
stefano.paris@unibg.it
†LRI
Université Paris-Sud
{fabio.martignon, lin.chen}@lri.fr
‡DEI
Politecnico di Milano
filippini@elet.polimi.it

***Abstract*—The Radio Access Network (RAN) infrastructure represents the most critical part for capacity planning, which usually accounts for peak traffic conditions. A promising approach to increase the RAN capacity and simultaneously reduce its energy consumption is represented by the opportunistic utilization of third party WiFi access devices.**

In order to foster the utilization of unexploited Internet connections, we propose a new and open market, where a mobile operator can lease the bandwidth made available by third parties (residential users or private companies) through their access points to increase the network capacity and save large amounts of energy. We formulate the offloading problem as a reverse auction considering the most general case of *partial covering* of the traffic to be offloaded. We discuss the conditions (i) to offload the maximum amount of data traffic according to the capacity of third party access devices, (ii) to foster the participation of access point owners (individual rationality), and (iii) to prevent market manipulation (incentive compatibility). Finally, we propose a greedy algorithm that solves the offloading problem in polynomial time, even for large-size network scenarios.

***Index Terms*—WiFi Offloading, Heterogeneous Mobile Networks, Auction.**

I. INTRODUCTION

In recent years, the rapid growth of the bandwidth demand required by content-rich Internet services accessed by mobile users through their 3G/4G smart-phones has increased the pressure on mobile operators for upgrading their cellular networks. Consequently, mobile operators have increased the capacity of their radio access and backhaul networks through the development of new technologies and a pervasive deployment of new types of base stations. Nevertheless, mobile operators and their customers are experiencing a "bandwidth crunch" due to the steady growth of the demand required by real-time multimedia services and the limited capacity of the wireless access technology.

The Radio Access Network (RAN) infrastructure represents therefore the most critical part of the network for capacity planning, which usually accounts for peak traffic conditions. Furthermore, more than 80% of the overall energy consumption is due to the power consumed by the base stations forming the access section of mobile networks [1]. A promising approach to smoothly handle sudden peaks of bandwidth demand is represented by the utilization of Heterogeneous Mobile Networks, in which mobile operators can opportunistically exploit WiFi access networks to improve the QoS experienced by their customers, while reducing the power consumption of their networks by switching the underused base stations off.

In this paper, we investigate innovative policies and mechanisms to foster the deployment of Heterogeneous Mobile Networks as a means for mobile operators to increase their network capacity and save large amounts of energy, thus contributing to reduce CO_2 emissions caused by the ICT industry.

As any marketplace, the misbehavior of even few agents (either residential users or private companies) playing strategically might seriously affect the efficiency of the allocation mechanism used by the mobile operator, thus discouraging honest agents from participating to the market. This, in turn, reduces the maximum amount of traffic that can be offloaded and the potential energy saving. To address this issue, we present a *reverse truthful auction* targeted for the scenario described above, which forces each Access Point (AP) owner to bid truthfully.

Our work makes the following contributions:

- We propose and analyze a reverse auction to implement an innovative marketplace both for selecting the cheapest Access Points and offloading the maximum amount of data traffic from the RAN.
- We present an innovative payment rule, which extends the classical Vickrey-Clarke-Groves (VCG) scheme, and demonstrate that it guarantees both *individual rationality* and *incentive compatibility* (i.e., *truthfulness*). To the best of our knowledge this is the first payment rule that considers explicitly the trade-off between the total cost and the gain of offloading data connections.
- Since the optimal reverse auction is NP-hard, we further propose a greedy algorithm that solves in polynomial time the allocation problem for large network instances.
- We perform a numerical analysis and comparative evaluation of the proposed optimal and greedy algorithms, considering real-size network scenarios.

The paper is structured as follows: Section II discusses related work. Section III presents the system model considered in our work. Section IV formulates the combinatorial reverse auction as an optimization problem, and presents our new payment rule that makes the auction individually rational and truthful. Section V describes the greedy algorithm to solve efficiently the problem, while Section VI illustrates and analyzes numerical results. Finally, concluding remarks are discussed in Section VII.

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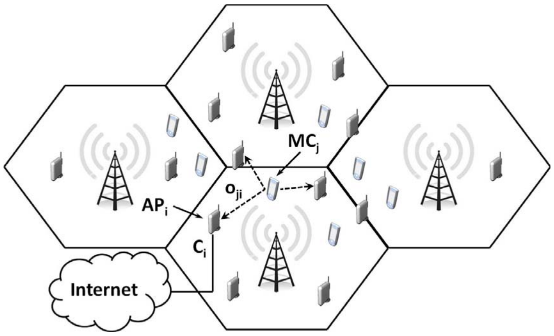


Fig. 1: Network scenario considered in this work. The MN is managed by a single operator that provides access to its customers (e.g., MC_j), while the unused capacity of wireless access devices (e.g., AP_i) is leased to the operator for data traffic offloading.

II. RELATED WORK

In recent years, several research groups have investigated the benefit of opportunistically exploiting WiFi access networks to improve the QoS experienced by mobile devices [2], [3], proposing similar architectures to integrate third-generation wireless networks with local-area wireless technologies. These works show the benefits of using multiple wireless connections to increase the throughput and reduce the latency experienced by data connections. However, they miss opportunities for optimizing communications, since they design user-centric approaches without exploiting the global vision of Heterogeneous Mobile Networks.

With the upcoming generation of cognitive radio networks, market-based auctions have been extensively studied as an efficient mechanism to dynamically sublease the unexploited licensed spectrum to secondary users and increase the revenue of the spectrum owner [4], [5], [6].

Auction theory has also been exploited to design innovative traffic engineering techniques and routing protocols, to force the collaboration of intermediate relaying nodes [7], [8], [9].

Finally, recent research has analyzed virtual network scenarios where several service providers compete among each other for using the resources owned and managed by a network operator [10], [11].

Unlike recent literature, our work envisions a new marketplace based on reverse auctions, where WiFi APs are exploited by mobile network operators to offload the traffic of their customers. Furthermore, we explicitly consider the more general partial covering problem of data connections, proposing a new payment rule to address the limits of the VCG scheme.

III. SYSTEM MODEL

This section presents the economic definitions and assumptions, as well as the network model we adopt in the design of our auction mechanisms.

Let us refer to the Heterogeneous Mobile Network (HMN) sample scenario illustrated in Figure 1, which is composed of a Mobile Cellular Network formed by four Base Stations and a set of wireless Access Points (APs) connected to the Internet. The mobile network is managed by a single operator that provides ubiquitous access to its mobile customers (MCs), while each participant to the trading marketplace (either a residential user or a private company) is the owner of a wireless AP.

Each AP owner i has an unexploited capacity C_i of its Internet connection that he is willing to lease for a given price v_i, unknown to the operator. To this end, he submits to the operator the bid $[b_i,\ C_i]$, representing the price that i asks for leasing the capacity C_i of his AP to the operator.

Through the mechanisms proposed in this work, the operator selects both the access points (APs) and the subset of its mobile customers (MCs), whose data traffic is offloaded from the mobile network to the selected APs. To prevent market distortion, the proposed mechanisms force AP owners to provide the true information about the private valuation of their APs ($b_i = v_i$).

Let us denote by $p_i \geq 0$ the price paid by the operator to AP owner i to exploit its available capacity C_i. Then, assuming a quasi-linear utility function for AP owner i, we can define the utility of i, u_i, as the difference between the price paid by the operator, p_i, and the private valuation v_i, according to Equation (1):

$$u_i = \begin{cases} p_i - v_i & \text{if AP } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The utility represents therefore the residual gain of owner i obtained from the leased capacity of its AP.

We observe that the transmission rate and the channel utilization required to satisfy the data traffic demand depend on the distance between the smart-phone of the mobile customer and the access point to which it can be connected.

Given the amount of traffic d_j of its mobile customer MC_j, the operator computes the vector of channel utilizations, $\overrightarrow{o_j} = \begin{bmatrix} o_{j1} & o_{j2} & \dots & o_{ji} & \dots & o_{jn} \end{bmatrix}$, where each pair (j, i) refers to a possible allocation of MC j to AP i, whereas n represents the number of APs in the network. Channel utilizations are computed as $o_{ji} = {}^{d_j}/_{r_{ji}}$, where the element o_{ji} represents the channel utilization of AP i when it is used to offload the data traffic of MC j, and it is computed as the ratio between the traffic demand d_j and the maximum achievable transmission rate of the wireless link that might connect MC j and AP i, r_{ji}. Note that this latter value can be easily obtained from the MAC layer through a scanning of the wireless channels, which is performed periodically by all network devices.

IV. OPTIMAL AUCTION FOR MOBILE DATA OFFLOADING

This section presents the combinatorial auction we propose to jointly select the wireless APs and the MCs data connections that can be offloaded from the cellular network. Indeed, in several network scenarios, mechanisms like those proposed in [12], [13], [14] fail to find a feasible solution, since they require the assignment of *all* mobile data connections.

Hereafter, we formalize the Integer Linear Programming model which provides the optimal allocation for the auction, namely the APs to be purchased and the mobile data traffic that can be offloaded.

Let $\mathcal{M}$ denote the set of mobile customer devices (MCs), and $\mathcal{A}$ the set of wireless access points (APs) whose owners participate to the reverse auction of the mobile operator. Let us define $\mathcal{M}_i \subseteq \mathcal{M}, i \in \mathcal{A}$ as the set of MCs that are covered by AP i (i.e., the MCs that are in the radio range of AP i).

We can now introduce the decision variables used in our ILP model. Binary variables x_i, $i \in \mathcal{A}$, indicate which residential users win the auction, i.e., the APs whose available capacity is exploited by the mobile operator to serve the extra-traffic of its MCs ($x_i = 1$ if the available capacity of AP i is used, 0 otherwise). Binary variables y_{ji}, $i \in \mathcal{A}, j \in \mathcal{M}$, provide the assignment of MCs to APs ($y_{ji} = 1$ if MC j is assigned to AP i, 0 otherwise).

Given the above definitions and notation, the reverse combinatorial auction problem with partial covering of mobile customers can be stated as follows:

$$\min \quad f(x,y) = \sum_{i \in \mathcal{A}} b_i \cdot x_i - \sum_{i \in \mathcal{A}} \sum_{j \in \mathcal{M}_i} c \cdot y_{ji} \tag{2}$$

s.t.

$$y_{ji} \leq x_i \qquad \forall i \in \mathcal{A}, \forall j \in \mathcal{M}_i \tag{3}$$

$$\sum_{i \in \mathcal{A}} y_{ji} \leq 1 \qquad \forall j \in \mathcal{M} \tag{4}$$

$$\sum_{j \in \mathcal{M}_i} y_{ji} o_{ji} \leq x_i \qquad \forall i \in \mathcal{A} \tag{5}$$

$$\sum_{j \in \mathcal{M}_i} y_{ji} d_j \leq x_i C_i \qquad \forall i \in \mathcal{A} \tag{6}$$

$$y_{ji} = 0 \qquad \forall i \in \mathcal{A}, \forall j \notin \mathcal{M}_i \tag{7}$$

$$x_i, y_{ji} \in \{0,1\} \qquad \forall i \in \mathcal{A}, \forall j \in \mathcal{M}. \tag{8}$$

The first term of the objective function (2), $\sum_{i \in \mathcal{A}} b_i \cdot x_i$, represents the total cost paid by the operator to lease the APs used for the data offloading of its mobile network. The second term, $\sum_{i \in \mathcal{A}} \sum_{j \in \mathcal{M}_i} c \cdot y_{ji}$, aims at maximizing the offloading of data connections from the cellular to the rented WiFi networks. The parameter $c > 0$ is a trade-off value between these two opposing objectives, representing the gain of the operator by offloading the traffic of MC j to AP i.

Constraints (3) are coherence constraints ensuring that only the access points that win the auction can be used to serve mobile customer connections.

The set of constraints (4) ensures that mobile data connections are served using *at most* one leased access point.

Constraints (5) and (6) prevent the allocation of an overall traffic demand that cannot be satisfied by an access point, due to the maximum achievable transmission rate of the wireless channel and the limited capacity of the Internet connection made available by the residential user, while constraints (7) prevent the assignment of MCs to APs that are not in the reciprocal radio range. Note that the channel assignment of access points can be optimized in order to reduce interference effects among nearby devices by using classical coloring algorithms coupled with the IEEE 802.11k standard.

Finally, constraints (8) ensure the integrality of the binary decision variables.

Since the operator aims at offloading its mobile network as much as possible, the parameter c should be set as pointed out by the following proposition.

Proposition IV.1. *In order to offload the maximum amount of traffic of Mobile Clients, the value of the parameter c must be greater than the maximum bid, namely* $c > \max\{b_i\}$.

In fact, it is easy to prove that when parameter $c > \max\{b_i\}$, we always get an improvement in terms of minimization for the objective function by selecting an additional AP h, since $b_h \leq \max\{b_i\} < c \cdot \sum_{j \in \mathcal{M}_h} y_{jh}$.

Having defined the ILP model representing the optimal auction, we now illustrate the payment rules and the conditions that force AP owners to ask their real valuation for the utilization of the capacity that they make available through their access points.

In order to guarantee individual rationality and make the payment acting as an incentive for the participation, we propose to modify the VCG rule adding a new term to the price paid to the winner that depends on the number of connections that its presence permits to offload, according to the following expression:

$$p_i = f(x^{-i}, y^{-i}) - f^{-i}(x,y) + c \cdot \sum_{j \in \mathcal{M}_i} y_{ji}. \tag{9}$$

Theorem IV.2 (Individual Rationality of (9))**.** *The payment rule defined in Equation (9) satisfies the individual rationality property, i.e.,* $\forall i \in \mathcal{A} : x_i = 1, p_i = f(x^{-i}, y^{-i}) - f^{-i}(x,y) + c \cdot \sum_{j \in \mathcal{M}_i} y_{ji} \geq v_i$.

With our payment rule, the operator pays to the winners of the auction their contribution to the social welfare (i.e., the money that their presence permits to save) plus an additional incentive that depends on the connections that without their presence cannot be offloaded from the RAN, thus forcing to keep the Base Stations turned on.

Theorem IV.3 (Truthfulness of (9))**.** *The payment rule defined in Equation (9) satisfies the truthfulness property (incentive compatibility).*

PROOF: Let (x,y) and (x',y') be the solutions to the problem (2)-(8), when the AP owner i declares v_i and v'_i, respectively. Furthermore, let (x^{-i}, y^{-i}) denote the solution to the same problem without considering the AP i (i.e., forcing $x_i = 0$ as additional constraint to the original problem). Note that $x_i^{-i} = x_i'^{-i}$.

The utility of i when it declares v_i, $u(v_i)$, is equal to:

$$\begin{aligned} u(v_i) &= p_i(v_i, x, y) - v_i = \\ &= \sum_{k \in \mathcal{A} \setminus \{i\}} v_k \cdot x_k^{-i} - \sum_{k \in \mathcal{A} \setminus \{i\}} \sum_{j \in \mathcal{M}} c \cdot y_{jk}^{-i} + \\ &- \left(\sum_{k \in \mathcal{A}} v_k \cdot x_k - \sum_{k \in \mathcal{A}} \sum_{j \in \mathcal{M}} c \cdot y_{jk} \right), \end{aligned}$$

whereas, when it declares v'_i, the utility is equal to:

$$\begin{aligned} u(v'_i) &= p_i(v'_i, x', y') - v_i = \\ &= \sum_{k \in \mathcal{A} \setminus \{i\}} v_k \cdot x_k^{-i} - \sum_{k \in \mathcal{A} \setminus \{i\}} \sum_{j \in \mathcal{M}} c \cdot y_{jk}^{-i} + \\ &- \left(\sum_{k \in \mathcal{A} \setminus \{i\}} v_k \cdot x'_k + v_i - \sum_{k \in \mathcal{A} \setminus \{i\}} \sum_{j \in \mathcal{M}} c \cdot y'_{jk} - \sum_{j \in \mathcal{M}_i} c \cdot y'_{ji} \right). \end{aligned}$$

Since (x,y) is the solution that minimizes the objective function (2), $(x,y) = \underset{x \in X, y \in Y}{\arg\min} \sum_{i \in \mathcal{A}} b_i \cdot x_i - \sum_{i \in \mathcal{A}} \sum_{j \in \mathcal{M}_i} c \cdot y_{ji}$, we have:

$$\sum_{k \in \mathcal{A}} v_k \cdot x_k - \sum_{k \in \mathcal{A}} \sum_{j \in \mathcal{M}} c \cdot y_{jk} \leq$$
$$\sum_{k \in \mathcal{A} \setminus \{i\}} v_k \cdot x'_k + v_i - \sum_{k \in \mathcal{A} \setminus \{i\}} \sum_{j \in \mathcal{M}} c \cdot y'_{jk} - \sum_{j \in \mathcal{M}_i} c \cdot y'_{ji},$$

therefore $u(v_i) \geq u(v'_i)$, and the AP owner i cannot increase its utility by bidding unilaterally untruthfully. ■

V. GREEDY AUCTION FOR MOBILE DATA OFFLOADING

The optimal reverse auction problem described in the previous section is NP-hard. Indeed, it can be shown that the knapsack problem can be polynomially reduced to the problem (2)-(8). Therefore, an operator can hardly find a solution to reconfigure its mobile network on-the-fly, since the computation time necessary to solve large and real-life network instances increases very sharply. To this end, in the following, we design an efficient algorithm to solve in polynomial time the allocation problem.

The greedy auction is summarized in Algorithm 1, and it is composed of two main phases: (1) the *allocation* phase, which selects the APs in ascending order of their bids divided by the total channel utilization of those MCs which they may serve (i.e., $b_i / \sum_{j \in \mathcal{M}_i} o_{ji}$), until the maximum amount of data traffic generated by mobile customers can be offloaded, and (2) the *payment* phase, which establishes the price paid to each winner as a function of the first unused AP in the sorted list (the first looser). This latter is also referred to as *critical access point* for i (denoted by s), and the price asked by its owner as *critical value* for i, which will be denoted as p_s.

Algorithm 1: Greedy Reverse Auction

```
   Input  :  $\mathcal{M}, \mathcal{A}, b_i, C_i, d_{ji}, o_{ji}$
   Output:  $x_i, p_i, y_{ji}$
1  $(x_i, y_{ji}, s) \Leftarrow$ Greedy_Allocation_Phase($\mathcal{M}, \mathcal{A}, b_i, C_i, d_{ji}, o_{ji}$) ;
2  foreach $i \in \mathcal{A} : x_i = 1$ do
       $p_i \Leftarrow \frac{b_s}{\sum_{j \in \mathcal{M}_s} o_{js}} \sum_{j \in \mathcal{M}_i} o_{ji}$ ;
   end
```

The greedy allocation phase, which is detailed in Algorithm 2, sorts the set of APs in non-decreasing order of their submitted bids per channel utilization of the MCs which they may serve, $b_i / \sum_{j \in \mathcal{M}_i} o_{ji}$. Then, each element of the sorted list is selected until all MCs are assigned to an AP. The assignment procedure assigns to each AP $i \in \mathcal{A}$ selected as winner the maximum number of unsatisfied MCs in its radio range such that either the wireless channel is not saturated (i.e., its utilization is lower than 1) or the overall traffic demand does not exceed the capacity of the wired connection.

In addition to selecting the APs used by the operator and provide the allocation of the mobile customers to such APs, Algorithm 2 computes also the *critical access point* $s \in \mathcal{A}$, which is the first unselected AP or the last selected AP of the sorted list. When all APs are selected by the allocation phase, the last AP is removed from the set of winners in order to guarantee the truthfulness (step 3 of Algorithm 2).

We observe that Algorithm 1 implements a truthful auction. In fact, the allocation phase satisfies the monotonicity property (recall that the APs are sorted in non-decreasing order of their bid per number of covered mobile customers), and there exists a critical value which determines if the AP owners bid is satisfied or not.

Algorithm 2: Greedy_Allocation_Phase (Step 1 of Alg. 1)

```
   Input  :  $\mathcal{M}, \mathcal{A}, b_i, C_i, d_{ji}, o_{ji}$
   Output:  $x_i, y_{ji}, s$
1  $L \Leftarrow Sort\left(i \in \mathcal{A}, \frac{b_i}{\sum_{j \in \mathcal{M}_i} o_{ji}}, \text{“}non - decreasing\text{“}\right)$ ; $U \Leftarrow \mathcal{M}$;
2  while $L \neq \emptyset \wedge U \neq \emptyset$ do
       $l \Leftarrow i$; $i \Leftarrow Next(L)$; $x_i \Leftarrow 1$;
       while $\sum_{j \in \mathcal{M}_i} y_{ji} o_{ji} \leq 1 \wedge \sum_{j \in \mathcal{M}_i} y_{ji} d_j \leq x_i C_i$ do
           $\mathcal{V}_i \Leftarrow Sort(j \in \mathcal{M}_i, o_{ji}, \text{“}non - decreasing\text{“})$;
           $j = Next(\mathcal{V}_i)$;
           if $\sum_{h \in \mathcal{A}} y_{jh} = 0$ then
               $y_{ji} \Leftarrow 1$; $U = U \setminus \{j\}$;
           end
       end
   end
3  if $L = \emptyset$ then
       $s \Leftarrow l$;
   else
       $s \Leftarrow Next(L)$;
   end
```

VI. NUMERICAL RESULTS

This section presents the numerical results that illustrate the validity of the proposed approaches to implement the bandwidth trading marketplace for fostering mobile data offloading.

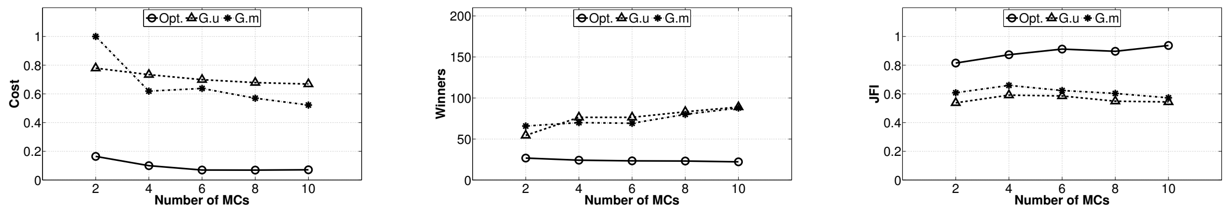
For our simulations, we refer to the scenarios designed within the FP7 European Project EARTH and described in [15]. More specifically, we extend the baseline reference deployment scenario composed of 7 cell sites, whose Inter-Site Distance (ISD) is fixed to 500 meters. Each Macro Base Station (BS) installed around a central site serves 3 sectors, resulting in 21 sectors in total.

We consider 10 APs randomly placed within each sector, and vary the number of MCs in the $[2, 10]$ range.

To evaluate the number of APs necessary to offload the maximum amount of data traffic and switch off the BSs, we evenly divide the maximum bandwidth of a BS sector (20 Mbps using 16 QAM dual-stream MIMO as suggested in [15]) among all MCs inside that sector.

The bids submitted by any AP owner i, b_i, are drawn from a uniform distribution with mean value equal to 10 monetary units (e.g., USD) and interval size twice the average, to evaluate the payments fairness in the worst case scenario.

The maximum achievable transmission rate of the access links that can be established between MC j and any of its surrounding APs i, r_{ji}, is defined according to the reception sensitivity of the Wistron CM9 commercial wireless cards based on Atheros chipset. The path loss, which is necessary to evaluate the sensitivity of the receiving node, is computed according to the Friis propagation model.



(a) $Cost = \sum_{i \in \mathcal{A}} p_i x_i$ (b) $w = \sum_{i \in \mathcal{A}} x_i$ (c) $JFI = {(\sum_{i=1}^{w} \rho_i)^2}/{w \cdot \sum_{i=1}^{w} {\rho_i}^2}$

Fig. 2: Performance metrics measured in the heterogeneous scenario with 10 APs in each of the 21 sectors.

Figure 2 shows the performance of our three mechanisms as a function of the number of MCs inside a BS sector. The curves identified by labels "Opt.", "G.u" and "G.m" illustrate the performance metrics computed using the Optimal and the two Greedy algorithms which sort the list of APs according to their *bids per channel utilization* (${b_i}/{\sum_{j \in \mathcal{M}_i} o_{ji}}$) and their *bids per number of MCs* (${b_i}/{|\mathcal{M}_i|}$), respectively.

Figure 2(a) shows the *overall cost* paid by the operator to offload the data traffic of its MCs with the proposed mechanisms ($\sum_{i \in \mathcal{A}} p_i x_i$). For the sake of clarity, the cost has been normalized with respect to the maximum value, which is equal to 1500$ (i.e., 18$ per selected AP). Even if the Optimal Algorithm (the "Opt." curve) outperforms the Greedy Algorithms, the high computation time necessary to solve the auction might discourage operators to exploit the proposed marketplace in the presence of high mobility of their MCs. On the contrary, the two Greedy Algorithms (the "G.u" and "G.m" curves) find a solution in polynomial time, thus representing an efficient alternative to select the APs for offloading the data traffic and compute their payments. Furthermore, it can be observed that the offloading cost decreases as the number of MCs increases, since the fixed bandwidth of a BS sector is spread among more MCs devices, thus resulting in lower demands and channel utilizations of the wireless links established with the assigned APs. Conversely, as illustrated in Figure 2(b), the higher is the number of MCs, the higher is the number of APs selected by the Greedy mechanism (i.e., the number of winners $w = \sum_{i \in \mathcal{A}} x_i$), due to the suboptimal assignment computed by the *allocation* phase. Nevertheless, both Greedy approaches select a percentage of APs always inferior to 50% of the overall number of available APs (210 in our scenario).

Figure 2(c) shows the Jain's Fairness Index of the ratio between the paid price and the number of MCs assigned to AP i, $\rho_i = {p_i}/{\sum_{j \in \mathcal{M}_i} y_{ji}}$, as a function of the number of MCs within a sector. Even though auctions usually perform very poorly in terms of fairness of the allocation, our mechanisms pay approximately the same price per number of assigned MCs to more than 60% of the owners of the APs selected as winners. Furthermore, all algorithms achieve an average bandwidth utilization of the selected APs higher than 75%.

VII. CONCLUSION

This paper proposed a new trading marketplace where mobile operators can rent the bandwidth of Internet connections made available by third party WiFi Access Points. The offloading problem was formulated as a combinatorial auction and an innovative payment rule was designed to guarantee both individual rationality and truthfulness for those realistic scenarios in which only part of the data traffic can be offloaded.

In order to solve efficiently the offloading problem for large-scale network scenarios, we also proposed a greedy algorithm that preserves the *truthfulness* property.

Numerical results demonstrate that the proposed schemes well capture the economical and networking essence of the problem, thus representing a promising solution to implement a trading marketplace for next-generation access networks.

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