A Bandwidth Allocation Mechanism for 4G

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***Abstract*— The current trend in wireless systems is evolving towards Fourth Generation (4G). 4G prescribes that users can enjoy mobility, seamless access and high quality of service in an all-IP network on an "Anytime, Anywhere" basis. The 4G network access comprises of multiple heterogeneous geographically coexisting wireless networks. In this paper we propose a mechanism for the allocation of the downlink bandwidth of such an "integrated" network. In particular, we propose an incentive-compatible, efficient, auction-based mechanism of low computational complexity. Subsequently, we extend this mechanism so that it can also accommodate multicast sessions, while retaining its nice properties regarding incentives and computational complexity. We also define a repeated game to highlight interesting issues that arise regarding the value of the users utilities and user incentives in such a setting. We then transform this mechanism to a cooperative bandwidth allocation mechanism capable of prioritizing certain classes of services and emulating DiffServ and time-of-day pricing schemes. Finally, we assess the proposed mechanism and provide some concluding remarks and topics of future work.**

I. Introduction

The current trend in wireless systems is evolving towards Fourth Generation (4G). 4G prescribes that users can enjoy mobility, seamless access and high quality of service in an all-IP network on an "Anytime, Anywhere" basis. The 4G network access comprises of multiple heterogeneous geographically coexisting wireless networks [1]. This integrated network access approach has been also motivated by the 3G cellular mobile networks and their potential enhancement with WLAN radio access, and also WiMax, which can utilize the analog TV bands (700 MHz) that will be made available with the upcoming roll out of digital TV. Thus, integrated wireless network access can comprise the means of information gathering and service provision in the information cities of the near future.

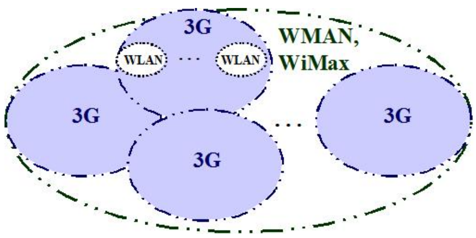

Fig. 1. Co-existing wireless access networks.

In this paper we propose a mechanism for allocating the downlink bandwidth of such a 4G network whose access architecture is hierarchical in terms of radius and thus geographical coverage. In particular, we address the problem of deciding on which user flows to admit and how the downlink bandwidth of the "integrated" access of a 4G network should be allocated to the competing user services so that efficiency is attained, i.e. social welfare is maximized.

We propose an auction mechanism, applicable in 4G hierarchical networks, comprising of multiple layers (tiers) of wide, middle and local area access networks owned by one operator. Due to the hierarchical structure of the network, depicted as Fig. 1, each user can be served by means of either a higher tier network of that area, or by some lower tier network (e.g. a WLAN). The standard 4G assumption that user terminals are capable of accessing multiple network interfaces is made. Our model is motivated by the 4G integrated access model and the fact that wireless operators invest in WLANs as a cheaper means of providing high speed download services compared to other technologies such as HSDPA [2]. Finally, terminals capable of connecting to multiple network interfaces are available in the market [3].

We then extend the proposed mechanism so as to support multicast. Multicast is a very promising technology that enables the efficient transmission of only one copy of data to a group of receivers. This is very useful for the 4G networks where due to the exponentially increasing demand for high-speed data services and the scarcity of the wireless spectrum, it is imperative to utilize the network efficiently.

The remainder of this paper is organized as follows: Section II contains an overview of related work. In Section III we present the proposed auction mechanism and its properties.We extend our mechanism in Section IV so as to support multicast. Section V discusses utility definition and user incentives issues in a repeated game comprising of consecutive auctions. In Section VI we transform the auction mechanism to a cooperative mechanism capable of prioritizing services and emulating DiffServ and time-of-day pricing schemes. Section VII assesses our mechanism's computational complexity. Finally, in Section VIII we provide some concluding remarks and interesting directions for future research.

II. Related Work

A plethora of architectures, protocols, resource management and handoff schemes for 4G have been proposed in the literature (see [1], [4], [5], [6], [7], [8] and references therein). Those proposals generally lack economic merit, since they do not prioritize users in terms of their utility for the service, as opposed to our approach. In fact, most of them are complements to our scheme, since they provide the technological solutions by means of which our scheme can be applied.

Hierarchical bandwidth allocation has been studied in [9], where in the top level a unique seller allocates bandwidth to intermediate providers (e.g. Internet Service Providers), who in turn resale it to their own customers in the lowest level. This model involves resale among the 3 tiers pertaining to different actors, as opposed to our case where a single actor owns *multiple* tiers and aims to efficiently allocate their bandwidth.

A utility-based load balancing scheme in WLAN/UMTS networks is proposed in [10]. For each network, a utility reflecting the current load is computed. The values of the network utilities, i.e. loads, are communicated to the clients who can switch to the less loaded network. Thus, this scheme cannot prioritize users in terms of their utilities.

Closest related to our work is the scheme of [11], where *fixed rate pipes* over *two* alternative paths are auctioned among synchronized users having different utilities for the two paths and thus submitting different bids. The latter contradicts the seamless access concept of 4G, as opposed to our work. Also, the scheme of [11] cannot be generalized for multiple services, rates and networks, as opposed to our scheme.

III. The Proposed Auction

Users compete for downlink data services, such as ftp, video and audio streaming over a 4G access network depicted as Fig. 1. Each service flow is shaped by the network operator in a similar way with the 3G networks, i.e. by means of token buckets [12]. Therefore, in our model different services $s_i, s_j \in \mathcal{S}$ may differ only in terms of their respective mean rates $m_i \neq m_j$.

We propose a sealed-bid auction, run periodically for allocating bandwidth over a given period of time, i.e. users are synchronized. Dynamic user arrivals and departures may occur at the various auctions; this is discussed in Section V.

Each user $i \in \mathcal{I}$ has a certain utility u_i and declares a willingness to pay w_i for a service of rate m_i, by submitting w_i as part of his service request. Let p_i denote the per unit of bandwidth willingness to pay of user i, i.e. $p_i = w_i/m_i$. For an $L-$tier network architecture, let $C_k^{(l)}$ denote the capacity of the l-tier access network k, with $l = 1, .., L$; i.e. $l = 1$ corresponds to the network technology having the greatest geographical coverage. k is the index of the l-tier network accessible by the user, e.g. the index/ESSID of a WLAN inside the coverage of which the user is located. Users are both unaware of and indifferent to the internal routing of their traffic.

Upon a service request is received, the operator[1] creates the bids $b_i^{(l)} = (p_i, m_i)\ \forall i \in \mathcal{I}$, $l = 1, .., L$ and updates the respective active bids sets $\mathcal{B}_k^{(l)}$ for all networks k accessible by the user, one per tier. The basic idea is that winner determination is performed starting from the highest coverage network, where competition is most fierce. The users bids are sorted by p_i and given the capacity constraint, the highest of them are declared as winning. The auction winners are propagated to the lower tier network auctions, from which their bids are deleted. Winner determination is then performed for the next layer, until the lowest tier is reached; this is done simultaneously, in a distributed fashion for same-tier networks. A sample auction execution for a two-tier network comprising of a 3G network and three WLANs is provided as Fig. 2; in order to keep the presentation of the auction simple, there is no top-tier WiMax or LTE interface in this simplified example.

[1]The terms network and operator are used to refer to the auctioneer.

The proposed auction is defined as follows:

Step 0: Set $l = 1$. Sort($\mathcal{B}_k^{(l)}$) $\forall k, l$ // sort bids per p_i.

Step 1: Determine winning bids $\mathcal{W}_k^{(l)}$ of the l-tier network k to be the *largest* set of the *highest* bids of $\mathcal{B}_k^{(l)}$ that do not violate the capacity constraint $C_k^{(l)}$.

Step 2: For every user i having bid $b_i \in \mathcal{W}_k^{(i)}$ delete user i's bids from $\mathcal{B}_k^{(j)}$, $\forall j > l$. Set $l = l + 1$.

Step 3: If $(l < L)$ goto *Step 1*.

Step 4: Compute payments.

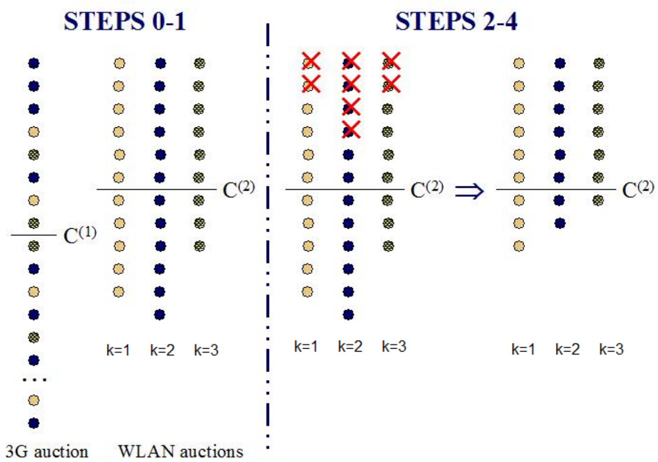

Fig. 2. Sample algorithm execution for a UMTS/WLAN network. Different colors denote the different WLANs that users can utilize.

A. Incentive compatibility and efficiency

The payment rule of the auction (Step 4) should enforce truthful bidding, i.e. $w_i = u_i\ \forall i \in \mathcal{I}$, so that social welfare can be maximized. This mandates applying the VCG payment rule [13], which defines each user's charge to be the social opportunity cost that his presence entails. Formally, user i is charged $SW_{-i}(0, \theta_{-i}) - SW_{-i}(\theta)$, where SW_{-i} is the social welfare of bidders other than i, θ is the set of the users' reported valuations and $(0, \theta_{-i})$ is the efficient outcome if i's reported value were 0 and the other users' reports remain unchanged. Thus, each user pays the losing bids that would be winning if his own bid were set to 0. This amount is both unaffected by and less than the user's own bid. In general, this rule requires the auction to be rerun by removing each of the winners to compute his charge, resulting in NP complexity.

However, our mechanism takes advantage of its hierarchical structure: Note that all user bids are propagated to the upper layers so that winner determination is performed and then the winners are propagated downstream so that the auction proceeds at the lower tiers. A similar upstream update can be made for the users that will win in the lower tiers. That is, the winning bids of the $l+1$,..,L-tier auctions are deleted from the local losing bids index of a l-tier auction. Thus, the information required to determine the "global" social opportunity cost is available *locally* per auction. Hence, each winner's i charge is computed as the sum of the highest (locally stored) losing bids whose sum of rates equals m_i and there is no need to rerun the auction.

Prop. 1: The proposed auction is efficient.

Proof: By construction, our auction examines all the bids at the top layer and admits the highest. This is repeated for all tiers, making impossible not to admit a bid that is higher than those admitted. Since the highest - truthful - bids are admitted, social welfare is maximized, i.e. efficiency is attained. ■

B. Revenue

Since our mechanism is essentially a VCG auction, it attains the highest revenue among *all* efficient mechanisms [13].

IV. Supporting Multicast

In this section, we extend the auction of Section III to support multicast. In particular, our auction is complemented with the operator's decision on whether a user is served by means of unicast or multicast. Hence, this is decided by the operator as a network optimization decision, opaque to the users. Thus, it is not part of the user's strategy space to choose between a unicast or a multicast service session. From a technological point of view, a multicast group is beneficial for the network, provided that it has at least $n^{(l)}$ members. This is due to the signaling overhead of the multicast, which depends on the underlying network technology.

The operator constructs the multicast bids $\mathcal{M}_k^{(l)}$ that complement the unicast bids $\mathcal{B}_k^{(l)}$ in the auction by grouping together at least $n^{(l)}$ users requesting the same service, e.g. watching a video at a certain quality. Let $g \in \mathcal{G}$ be a multicast group. The multicast bid is straightforwardly defined as (p_g, m_g), where $p_g = \sum_{i \in g} p_i$ and $m_g = m_i$.

Prop. 2: It is beneficial for the network and harmless for the users of a multicast group to have their unicast bids deleted.

Proof: Since $n^{(l)} > 1$, and $p_g = \sum_{i \in g} p_i > p_i,\ \forall i \in g$, a multicast bid always tops its members' unicast bids, thus having *strictly* higher probability of winning. Also, since $m_g = m_i < \sum_{i \in g} m_i,\ \forall i \in g$, it is always socially efficient to serve users by means of multicast when the $n^{(l)}$ constraint is met, since more users can be served by the network. ■

Due to Prop. 2, auction winner determination is performed as follows: The operator deletes the "redundant" unicast bids of the users belonging to some multicast group. He then mergesorts the unicast and multicast bids and declares the *largest* set of the *highest* bids that do not violate the capacity constraint as winning. Therefore, the same algorithm of Section III is applied to declare the winning unicast and multicast group bids, denoted as $\mathcal{W}_k^{(l)}$ and $\mathcal{WM}_k^{(l)}$ respectively.

Prop. 3: Social welfare is maximized.

Proof: Efficiency is attained, since users bid truthfully, i.e. $w_i = u_i$, and after the algorithm terminates it is impossible for a winning bid to be lower than any kind of losing bid:

$$b_w > b_i \quad \forall b_w \in \mathcal{W}_k^{(l)}, \quad \forall b_i \notin \mathcal{W}_k^{(l)} \tag{1}$$

$$b_g > b_i \quad \forall b_g \in \mathcal{WM}_k^{(l)}, \quad \forall b_i \notin \mathcal{WM}_k^{(l)} \tag{2}$$

$$b_w > b_g \quad \forall b_w \in \mathcal{W}_k^{(l)}, \quad \forall b_g \notin \mathcal{WM}_k^{(l)} \tag{3}$$

$$b_g > b_i \quad \forall b_g \in \mathcal{WM}_k^{(l)}, \quad \forall b_i \notin \mathcal{W}_k^{(l)} \tag{4}$$

■

V. Time, User Utility and Incentives

Defining the user utility for receiving service in a certain time interval is non-trivial, especially for long-lived services where the consistent reservation of resources in subsequent auctions is highly beneficial. Hence, user utility may depend on the history of resource allocations. History-dependent utility functions capable of expressing such preferences have been introduced in [14]. These could complement our scheme by using them to compute the value of w_i to be submitted at time t, as a function of the user's utility for the long-lived service and the history of user's allocations so far.

A small value for the length of time for which the auction allocations apply, allows our scheme to quickly adapt to the varying demand. However, it also implies that the auction is run more often. Thus, this value should be large enough for the auction to run between two consecutive allocation intervals. This obviously depends on the complexity of the auction, which is derived in the penultimate section of this paper.

We now briefly address the issue of user incentives for this repeated game, depicted as Fig. 3, where users bid in a sequence of auctions. Node START denotes user's i start of bidding and in general each node (*state*) corresponds to the bidding phase of each auction he participates. At each node user i selects an *action*, i.e. to bid truthfully $b_e = w_i$, or shade his bid $b_l < w_i$, or bid aggressively $b_m > w_i$.

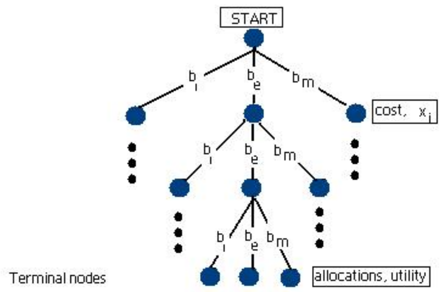

Fig. 3. The sequential form of the repeated game for 3 auctions.

Incentive compatibility still holds if user bids for independent services at the various auctions. We then address the most interesting case where *complementarities* exist among the user allocations in subsequent auctions: Placing a bid b_l at any node is not beneficial, since b_l only increases the probability of losing without affecting the payment. It could be argued however that a bid b_m can be beneficial, due to the extra value that a present allocation (which becomes more likely by over-bidding) can bring to the overall service. However, this would *not* be the case for extremely "uncertainty averse" (conservative) users, who - by definition - in cases of choice/behavior under uncertainty always opt to play the safest strategy. Therefore, for this type of users truthful bidding comprises a subgame perfect equilibrium strategy. This "maximin" behavior was proposed by Wald [15] for situations of severe uncertainty, which is also encountered by our auction bidders.

VI. A Cooperative Scheme

In this section we show how the proposed mechanism can be transformed to a cooperative bandwidth allocation mechanism for operators who prefer flat rate pricing to usage based pricing schemes. In this context, the user utility for the service $w_i \forall i$ is replaced by a predefined weight w_s that the operator assigns to each *type* of service s. This modification suffices to modify the auction to a cooperative bandwidth allocation scheme. Note that under this modification, determining the payments of the winners is performed instantly, i.e. in $O(1)$.

Due to the different weights assigned per service type, this scheme prioritizes the services having greater weights. These services will enjoy statistically higher quality than others and this scheme serves essentially as a DiffServ mechanism. Also, the operator can assign different weights per time of day in the various services. This way, in peak hours he may discourage demanding services by assigning a low weight, thus emulating time-of-day pricing. Finally, weights can be by dynamically computed from weighting functions per flow, so that each weight takes into account the flow's overall service time to prioritize older flows, emulating schemes like CHiPS [16].

VII. Assessment

Having assessed our mechanism in economic terms, we proceed to assess its computational complexity.

1) Auction Complexity: Sorting the bids of each link auction is done in $O(N \cdot logN)$, with N denoting the total number of bids. Winner determination is then done in $O(N)$, so that the point where the capacity constraint is violated is found. Computing winners' charge exploits the fact that user rates are not arbitrary but pertain to discrete service rates: First, we compute the charge for all service rates by adding the highest losing bids whose sum of rates equals this rate. Then each winner is charged his respective service charge. This is bounded by $O(s \cdot N)$, with s denoting the number of different service rates. Deletion of bids can be done in $O(N \cdot logN)$ since finding each bid can be done in $O(logN)$ using binary search and this must be performed for at most N bids. Since same-tier auctions run in parallel, while different tier auctions sequentially, the mechanism's overall complexity is bounded by $O(L \cdot (N + s \cdot N + N \cdot logN))$.

2) Multicast Extension Complexity: Creation of multicast bids can be done by parsing *once* the sorted list of bids and classify the users to separate groups, based on their selection of service, for which the total numbers of users and willingness to pay are updated as the list is constructed. This is done in $O(N)$, with N denoting the total number of bids. Subsequently, each redundant unicast bid must be deleted. Finding each bid can be done in $O(logN)$ using binary search. Since at most N bids must be deleted, the complexity bound of multicast is $O(N + N \cdot logN)$.

VIII. Conclusions

In this paper we have presented a mechanism for the allocation of the downlink bandwidth of a 4G network which could serve as the infrastructure over which information gathering and service provision are performed in the information cities of the near future. In particular, we have designed an incentive-compatible auction mechanism of low computational complexity. We have extended the mechanism so that multicast is supported, defined a repeated game to study utility and incentives issues and transformed our auction to a cooperative scheme for services prioritization. We have assessed the proposed mechanism in economic, game-theoretic and complexity terms and argued it is attractive, efficient and fast. Defining weighting functions for emulating DiffServ and CHiPS with our cooperative mechanism comprises a topic of future work.

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