Auction-based Resource Reservation in 3G Networks Serving Multicast

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***Abstract*— In this paper we extend an auction-based mechanism for bandwidth reservation in UMTS networks [2], [3] so that it can also accommodate multicast sessions. The mechanism is based on a series of Generalized Vickrey Auctions and a set of user utility functions (also used as bidding functions) expressing the user's preferences with respect to the resource allocation patterns. We extend these functions for multicast groups and assess experimentally the impact of multicast, especially under wealth asymmetry of the bidders. It appears that offering multicast improves the social welfare attained, and in many cases the provider's revenue as well.**

***Index Terms*— Auctions, resource reservation, multicast, 3G, social welfare.**

I. Introduction

AUCTIONS have recently received considerable attention as an economic mechanism for price discovery in networks. They are well-suited for allocating resources to network services with long duration. A prominent case is that of UMTS [1]: the time-scale of the duration of the users' non-voice services is of significantly higher order of magnitude than that of the time slot[1] over which resource units can be reserved. These services require Quality of Service (QoS), and thus are very demanding in resources. Accommodating such services constitutes a challenge for 3G networks due to the scarcity of the Radio Access Network (RAN) spectrum. In [2], we study this problem and propose an auction-based mechanism achieving nearly consistent reservation of the resources of a UMTS network by the users that value them the most. In [3], we adapt this mechanism so as to be applicable with HSDPA technology. Under our mechanism, competitive users receive service of very good quality and are charged according to demand, and non-competitive users are not essentially served while paying a very low or zero charge [2], [3]; also, intermediate patterns with a significant yet not satisfactory amount of resources and a non-negligible charge arise rarely. Thus, our resource reservation mechanism serves as soft CAC.

[1] For UMTS, the time slot is taken to be the 10msec UTRAN frame.

Multicast is a very promising network technology that enables the efficient transmission of only one copy of data to a group of receivers. This is very important also for 2.5/3G networks where the spectrum of the RAN is scarce. In this paper we extend the auction mechanism of [2], [3] so that it can serve multicast sessions. We also assess experimentally the impact of multicast on the provider's revenue and the social welfare attained - which equals the sum of all users' valuations for the service under *wealth asymmetry* of the bidders. That is, when the willingness to pay of the bidders is drawn from uniform distributions having different support. The impact of multicast to user-perceived QoS is also investigated. Determining whether multicast improves the network revenue and the social welfare is very important, since this gives an indication whether wireless network operators will consider the provision of multicast services.

The remainder of this paper is organized as follows: In Section II we overview the auction-based mechanism of [2]. In Section III we present its extension so as to support multicast. In Section IV, we provide an experimental assessment of our auction mechanism when multicast is enabled, while in Section V we present some concluding remarks.

II. The auction mechanism for unicast

The problem of UMTS resource allocation to sessions with QoS requirements is very complicated. Indeed, users demand sessions that span partly overlapping intervals with different durations, which in general are of much larger order of magnitude than the time scale t_a of the network frames in which resources are allocated. Our approach, as introduced in [2], is to conduct a sequence of Generalized Vickrey Auctions (GVAs), each concerning reservation of bits within one UTRAN frame. The bids submitted are atomic (i.e., either fully satisfied or rejected) of the type (p_i, q_i), where q_i is the quantity of units (bits) sought in the present frame and p_i is the price proposed for each such unit by user i. The payment rule of the GVA prescribes that each user pays for the units he is awarded the losing bids that would have become winning if all his own bids were set to zero (i.e. the social opportunity cost). Hence, winners pay less than their respective bids. Each user session has a fixed target QoS level, which for simplicity we assume that corresponds to a certain bit-rate m_i. Hence, $q_i = m_i \cdot t_a$.

In a realistic case of a UMTS network, it would not be feasible for users to bid in all these auctions. Thus, we also define in [2] utility functions pertaining to the various services that are also provided by the network operator as bidding functions for the user to choose from. They are scaled by the user's i total willingness to pay $U_{s,i}$ for the service s, which is given by the user himself as part of his service request. Then, the network runs the various auctions by bidding on *behalf* of each user. We assume that the user's i utility $u_{s,i}$ from obtaining the service s is the sum of the marginal utilities attained due to each successful allocation. Thus, $u_{s,i}(x_i^{(1)}, ..., x_i^{(K_{s,i})}) = \sum_{t=1}^{K_{s,i}} v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)})$, where $K_{s,i}$ is the number of auctions where user i participates during his service session and $x_i^{(t)}$ denotes the bit-rate that the user is allocated at slot t. Also, for every user the *bid placed by the network at each auction equals the marginal utility* to be attained if his bid is a winning one in the auction. This is justified in [2] on the basis of the well-known incentive compatibility property of the Generalized Vickrey Auction.

In particular, we introduce in [2] the following types of utility functions:

Type 1: *Indifferent to the allocation pattern.* This type pertains to volume-oriented users, such as those downloading files. The utility attained depends only on the quantity of resources allocated; hence,

$$v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)}) = \mathbf{1}(x_i^{(t)} = m_i) \cdot \frac{U_{s,i}}{K_{s,i}},$$

where $\mathbf{1}(\cdot)$ is the indicator function. This utility function is suitable for the UMTS Background Class services [1].

Type 2: *Sensitive to service continuity.* This type pertains to users receiving streaming audio or video of a certain rate that prefer the allocation pattern of Fig. 1(a) to that of Fig. 1(b) whenever perfect quality cannot be provided by the network. A marginal utility expressing this preference is

$$v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)}) = \mathbf{1}(x_i^{(t)} = m_i) \frac{U_{s,i}}{K_{s,i}} \cdot \alpha^{d_i(t)},$$

where: $\alpha \in (0, 1]$ is a discount factor expressing the user's displeasure from the existence of gaps in his resource allocation pattern; d_i is the distance between the current and the previous slots during which user i achieved reservations. *History* of previous allocations influences $v_{s,i}^{(t)}$ through the value of d_i. This utility function is suitable for the UMTS Streaming Class services [1].

Type 3: *Sensitive to the regularity of the resource allocation pattern.* Such users prefer the allocation pattern of Fig. 1(b) to that of Fig. 1(a). Hence,

$$v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)}) = \mathbf{1}(x_i^{(t)} = m_i) \frac{U_{s,i}}{K_{s,i}} \cdot \alpha^{\max\{0, \Delta d_i\}},$$

where Δd_i is the difference of $d_i^{(t)}$ (as defined above) and the length of the previous gap. This utility function is suitable for the UMTS Streaming Class services [1].

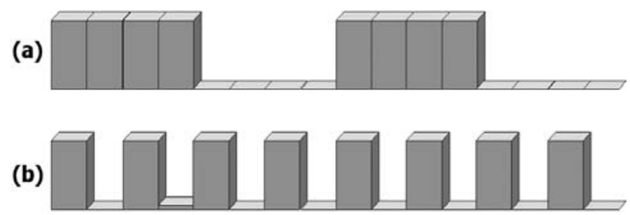

Fig. 1. Inconsistent resource allocation patterns.

III. EXTENDING THE AUCTION FOR MULTICAST

The aforementioned utility functions are suitable for unicast flows and thus only depend on the individual users' willingness to pay. In order to extend these definitions for multicast, it suffices for multicast flows to use as $U_{s,i}$ the *sum* of the total willingness to pay declared by each member g of the multicast group i, i.e. $U_{s,i} = \sum_{g \in i} U_{s,g}$.

The bid generation is performed by the network on behalf of the group, as in the unicast case. By thus aggregating the requests for multicast flows, the payment rule of the auction can be maintained. Therefore, whenever the combined bid for a multicast flow wins in the auction, the total charge must be split among the group's members. Since the total willingness to pay may be different for each user, we have opted to apportion the total charge among the users proportionally to their respective total willingness to pay. Furthermore, we consider the users to be truthful since the winning bidder generally pays a lower amount than his bid. Therefore, the charge for each member of a group will also be generally lower than his original bid. Assuming that the auction is competitive, it is expected that, in a variety of cases, users will be better off with respect to charge when joining a sizeable multicast group (see below), since the charge for e.g. a video transmission is shared among a group of users.

In practice, the group's total willingness to pay is affected by user arrivals and departures (due to users' mobility into and out of the cell) and should be updated accordingly. Indeed, a user of a group may move to a neighboring cell where he will seamlessly join the respective group that provides the service at the new cell. If such a group does not exist, then the user will compete as an individual for obtaining unicast service in the new cell. It is worth emphasizing that with the exception of handovers, we do not allow new users to join a group, after the provision of service to this group has begun. This is due to the relevant incentives: if this were indeed allowed, then it would be preferable for a user to wait and join a winning multicast group while declaring a very small willingness to pay for the service; he would thus receive service at almost a zero charge. On the contrary, departures are unconstrained, and occur due to either mobility or to the fact that a user may quit service. For simplicity, we assume in handovers that the group's d_i (for Type 2 session) or Δd_i (for Type 3 session) is common for all members and is not affected by the user arrivals. The short period chosen for the auctions is beneficial in this respect as it allows the bids for multicast flows to be constantly adapted to the actual demand for these flows in the cell.

In general, multicast flows are considerably more demanding in terms of the quantity of network resources needed than unicast flows for transmission over the air interface. This is mostly due to the inability of the network to perform power control for multicast transmissions [4]. In order to take this issue into account, we extend our approach by assuming that a multicast flow requires n times more resources than a unicast flow with the same nominal bit rate. A typical value for this overhead is $n = 6$ [4]. This also implies that the network should not allow the formation of multicast groups with size less than n; such groups are excluded from further consideration. This is justified since admitting groups having size less than n is beneficial neither for the provider, since resources would then have lower utilization, nor for the users, since they may end-up paying more than for a unicast service. Indeed, when less than n users are bidding as a group, each member should in general compensate for the social opportunity cost of more than one unicast session.

IV. Experiments

A. Methodology

In order to evaluate our auctioning scheme, we have implemented a specialized simulator and conducted a multitude of experiments according to a very detailed model specifying a) the processes of user arrivals and departures, b) the mix of unicast users and multicast groups in terms of the number of users per type of service, and c) the distribution of their total willingness to pay. The size of the multicast groups to be performed is also input to the simulator. Each user's total willingness to pay is randomly selected according to a uniform distribution having support an interval that prescribes whether the user is "low-value", "medium-value" or "high-value". The intervals used for the experiments are the $[0, 100]$, $(100, 200]$ and $(200, 300]$ respectively for the aforementioned user categories. The total quantity of resource units available at each auction fluctuates in the simulation, due to the varying allocation of resources to phone calls and SMS/MMS, and is randomly selected according to a uniform distribution whose mean is much higher than the interval width. The size (i.e. the number of multicast users per group) and the cost of each multicast session, as well as the total number of multicast sessions per experiment, are also input to the simulator. Finally, the value of the discount factor of the user utility functions is the same for all users in each experiment and is selected from the range [0.95, 0.99].

B. Experimental Results

Next, we present some typical sets of experiments that depict multicast's impact under various market conditions with respect to the level of competition and the distribution of users' wealth. A detailed presentation of the main findings of our experimental analysis, based on a multitude of experiments carried out - that cannot be presented in this subsection for brevity reasons - is provided in the following subsection.

The first set of experiments is obtained from 20 experiments where the auction was run for 1000 slots. In all these experiments, there are 25 low-value Type 2 users, 25 low-value Type 3 users and 21 high-value Type 2 users. Table I - Set A depicts the average over all experiments of the revenue and the social welfare attained, i.e. the sum of users' valuations for the services received. In the case where multicast is enabled, the high-value users form 3 multicast groups, each having 7 members. Social welfare is always higher if multicast is enabled, while that attained under unicast comes very close. This is due to the low willingness to pay of the unicast sessions; admitting more low-value sessions results in marginal increase of the social welfare attained. Interestingly enough, the revenue attained under unicast is higher than that under multicast. This can be explained as follows: Under unicast, the high-value users often compete against each other and for certain slots not all of them can reserve resources. Therefore, the social opportunity cost for these auctions is determined by high bids of high-value users, thus resulting in high provider revenue. When multicast is enabled and high-value users form groups, demand is reduced and the social opportunity cost is solely affected by the low bids of the low-value users, thus deteriorating provider's revenue.

TABLE I

TYPICAL SET OF EXPERIMENTS DEPICTING MULTICAST'S IMPACT ON AUCTION REVENUE AND SOCIAL WELFARE.

Experimental results - Set A			
Unicast		Multicast	
Revenue	Social Welfare	Revenue	Social Welfare
14563	20626	10254	22238

Experimental results - Set B			
Unicast		Multicast	
Revenue	Social Welfare	Revenue	Social Welfare
14941	21545	17291	27697

Another set of experiments is obtained from 20 experiments where the auction was run for 2000 slots. There are 25 high-value Type 2 users, 25 high-value Type 3 users and 98 low-value Type 2 users. In the case where multicast is enabled, the low-value users form 7 multicast groups, each having 14 members. Note that this is the "inverse" case of the previous set of experiments where the high-value users were supposed to form multicast groups. Table I Set B depicts the average over all experiments of the revenue and social welfare attained. It is again observed that social welfare is higher if multicast is enabled. The revenue attained under unicast is now lower than that attained under multicast. This is reasonable because under multicast the groups of low-value users have a chance to compete collectively against the high-value unicast sessions. Therefore, in this case multicast stimulates competition and improves both the revenue and the social welfare attained. This set of experiments also depicts the impact of the value of the multicast group size. In particular, the higher the multicast group size is, the higher the multicast bid is. Therefore, the more likely it becomes that this bid will be winning, that is it will be able to top the sum of $n = 6$ unicast bids in the auction.

Throughout these experiments, we have also examined the impact of the aforementioned extensions of the mechanism to the distribution and types of the resource allocation patterns attained. It was observed that these modifications have negligible impact on the distribution of the resource allocation patterns. In particular, the following still applies: competitive users and groups receive service of very good quality, non-competitive users are not essentially served, while "intermediate" allocation patterns in general arise rarely [2], [3]. However, notice that since a portion of the sessions successfully served belong to multicast groups, in general more users attain service of high quality than those served under unicast. Indeed, many users that are not served at all under unicast, are successfully served under multicast. Figure 2(I) depicts the resource allocation pattern attained by a multicast group composed of low-value Type 2 users. It is seen that QoS is perfect, since consistent reservation of resources was attained. However, when these users competed as unicast sessions, only one of them achieved to be allocated resources for approximately 80% of the service time [this pattern is depicted in Figure 2(II)], while the rest were either not served at all or reserved very limited quantity of resources.

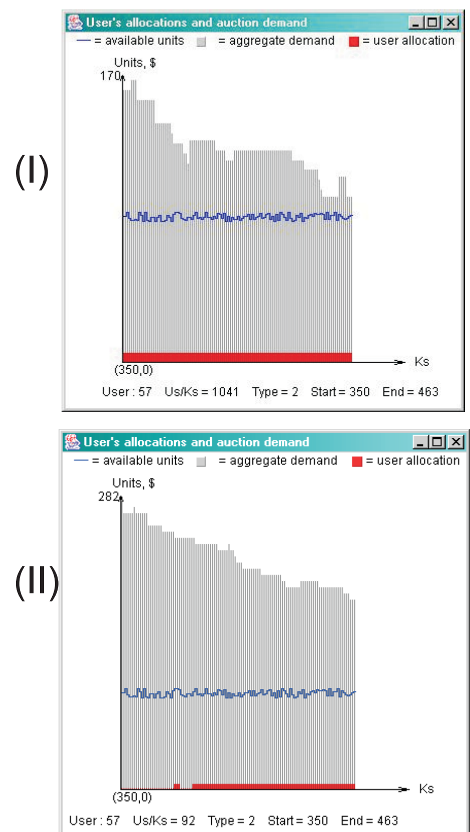

Fig. 2. Each screenshot depicts the aggregate demand for resources (topmost bars), the total available resource units (line), and the allocation pattern (lowest bars) of user sessions.

C. Discussion

Social welfare is in general improved by multicast. This is explained as follows: The quantity of resources required by a multicast group is less than the sum of resources required to serve the same users under unicast. Therefore, multicast results in a higher degree of resource utilization and more users are served by the network, thus improving the social welfare attained.

The experiments carried out indicate that multicast deteriorates provider's revenue if there is low competition in the network, i.e. the demand for resources is slightly higher than supply. In fact, the larger the percentage of users participating in multicast groups, the higher the percentage loss of provider's revenue. Indeed, if multicast is applied in such a setting, then the users no longer compete for reserving network resources but rather collaborate by forming multicast groups. This way, demand is always close to supply, leading to low revenues for the network provider. On the contrary, the experiments carried out depict that provider's revenue is essentially unaffected by multicast under medium competition and is always improved under high competition. This is sufficiently justified by the *wealth asymmetry* of the bidders. Under high competition, users with low or medium willingness to pay rarely win some auctions (or can afford to pay the market price that is determined by balancing demand and supply under other usage based pricing schemes). Hence, these users have limited actual chance of either winning anything or affecting the prices, simply because their bids are too low. Therefore, the actual competition takes place only among users having higher willingness to pay. A subset of them are declared winners, while the bids of those that lose determine the social opportunity cost. Multicast however enables low-value users to form groups (where even high-value users may join) thus submitting competitive bids in the auction. Therefore, it is likely that users that had no change of affecting the auction outcome now participate in bids that are high enough to either: a) become winning and displace some high value unicast bidders whose bids will increase the social opportunity cost that winners pay, or b) become losing just below the cut-off auction price, thus raising the charge of the winners.

Indeed, for a large number of experiments with medium competition and limited wealth asymmetry, the revenue attained when multicast is employed, though higher, is very close to that attained if no multicast sessions are allowed. However, in cases of wealth asymmetry, the gains for the provider in terms of revenue are higher. It is worth noting that a similar phenomenon has been observed in the spectrum auctions conducted by the FCC in the USA. Allowing small and medium size companies to form coalitions and participate in the auction for reserving spectrum licenses, stimulated competition and increased the government's revenue. However, in many European 3G spectrum auctions forming of coalitions served as a means of further reducing the already low auction competition, thus mitigating revenue; see [5] and references therein. These are in accordance with our findings regarding the impact of multicast in auction-based resource allocation.

Furthermore, the more low-value users form multicast groups, the easier it becomes for them to compete against high-value unicast users, since it becomes more likely that their collective bid will be high enough to top n high unicast bids. Therefore, the probability of winning in such settings under various levels of competition (i.e. demand for resources) is severely affected by the level of competition and the size of the multicast groups.

V. Conclusions

In this paper we have extended an auction-based mechanism for bandwidth allocation in UMTS networks [2], [3] so that it can also accommodate multicast sessions. The mechanism is based on a series of Generalized Vickrey Auctions and a set of user utility functions expressing the user's preferences with respect to the resource allocation patterns, which are also used as bidding functions. We have extended these functions so that they can be used for multicast groups as well and defined how multicast bids should be treated by the auctioneer. Furthermore, we have assessed experimentally the impact of allowing users to form multicast groups on the user-perceived QoS, the provider's revenue and the social welfare attained, especially under wealth asymmetry. It appears that multicast improves the social welfare attained, and in many cases the provider's revenue as well. The analysis of this paper regarding the impact of multicast, also applies to other usage-based pricing mechanisms, where the "price" is also determined by the balance of demand and supply.

VI. Acknowledgements

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References

[1] H. Holma and A. Toskala, "WCDMA for UMTS: Radio Access for Third Generation Mobile Communications", John Wiley, ISBN 0-471-72051-8.

[2] M. Dramitinos, G. D. Stamoulis, C. Courcoubetis, "Auction-based Resource Reservation in 2.5/3G Networks", Kluwer/ACM Mobile Networks and Applications Special Issue: Mobile and Pervasive Commerce, 9:6, pp. 557-566, December 2004.

[3] M. Dramitinos, G. D. Stamoulis, C. Courcoubetis, "Auction-based Resource Allocation in UMTS High Speed Downlink Packet Access", In Proc. of the First EuroNGI Conference Conference on Traffic Engineering, Rome, Italy, April 2005.

[4] FP6-IST-507607 Project B-BONE, "Broadcasting and multicasting over enhanced UMTS mobile broadband networks", URL:http://b-bone.ptinovacao.pt/.

[5] P. Cramton, "Spectrum Auctions", Handbook of Telecommunications Economics, Amsterdam: Elsevier Science B.V., Chapter 14, 605-639, 2002.