A simulation model for the dynamic allocation of network resources in a competitive wireless scenario

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Abstract. Next-generation wireless networks will enable the usage of different network technologies fully transparent to the user. Applications will be able to dynamically adapt to the conditions and technical constraints of the network. This vision requires a dynamic allocation of scarce network resources to different users. This paper presents simulation results from a model of admission control and dynamic resource allocation in wireless networks, in a two-provider, multiple-user scenario. The access allocation and connection procedure is implemented using an efficient (welfare maximizing) incentive mechanism for capacity allocation at both providers.

1 Introduction

The term Next-Generation Wireless Network (NGWN) describes a vision of a truly seamless, multi-technology, multi-provider network, serving mobile and fixed users with a variety of multi-media services. The major factors in achieving integration, flexibility and efficiency in NGWN are: the seamless integration of different access technologies, a high-performance physical layer, the adaptability of services and applications, and access to the core network, which must be flexible and adaptive [1]. Berezdivin et al. [1] state that the adaptation of application and services is the central element and is equated to the need that each element best uses its resources.

Application and service adaptation will pose many challenges to network operators. One of the prevailing questions is the dynamic allocation of scarce network resources in such a heterogeneous system. Wireless networks will introduce the possibility of having simultaneous access to competing networks, allowing users to seamlessly switch between network providers, even during ongoing service sessions. While in most mobile voice and data networks users are authorized by a subscriber identity module (SIM card), user authorisation in all IP-based networks can be designed much more flexible. Virtual mobile network providers, for example, purchase access capacities from different mobile networks and offer them to end customers. The aspect of multiple access has not yet been modeled in a dynamic allocation scheme.

The goal of this paper is to describe a model of access competition in a wireless multi-provider setting, while presenting its implementation in a simulated environment. Furthermore, the paper highlights the main conclusions arising from the results provided by simulation runs.

The simulation scenario is comprised of mobile agents – the users in the system – competing for access to two rival network providers. The mobile agents are allowed to adjust some resources to the agent's best use. Given the assumption of a competitive access framework, users' decisions on access will be bounded by their own resource-consumption levels and the contract conditions offered by the providers.

The rest of the paper is organised as follows: Section 2 briefly surveys the recent literature on the dynamic pricing of resource allocation in wireless networks. Section 3 introduces a two-provider multiple-user model in which users roam seeking connection to one of the two networks. The focus of the model is on the design of an incentive-compatible mechanism that assures the achievement of a measure of benefit once the allocation of a network resource such as bandwidth is granted. Section 4 presents the architecture and design of the simulation enviroment. Section 5 discusses the simulation results and provides an interpretation of the results derived. Section 6 draws a conclusion from the first results and depicts the next steps planned.

2 Dynamic pricing for resource allocation in wireless networks

Dynamic resource allocation mechanisms have been applied in a variety of situations in wireless networks. Because the wireless transmission channel inherits additional complexity, such as varying channel quality and interference between networks and users, concepts from fixed networks cannot be transferred without careful consideration.

In order to organise the existing approaches to dynamic pricing in wireless networks we propose a simple layer model, distinguishing six abstraction levels of resource allocation (Figure 1). The horizontal layers representing the network model are mapped across the columns depicting the specifics of different wireless technologies up to the packet layer. The IP layer is seen as the first unifying layer, which provides full transparency to the above layers. On the lowest level of the layer model we find approaches dealing directly with the physical properties of the wireless channel. The emergence of Code-Division-Multiple-Access (CDMA) networks has pushed the need for sophisticated power management schemes that distribute the transmission power between active users in the network cell. Advanced mechanisms for allocating the power to different users can significantly increase the channel capacity allocation per user [2].

In [3], the authors design an allocation model for the uplink of a wireless mixed voice-and-data network in a two cell scenario. Voice users' demands are seen as inelastic while data users are "elastic users" who can assign a value to different data rates allocated to them. The optimisation problem is reduced to

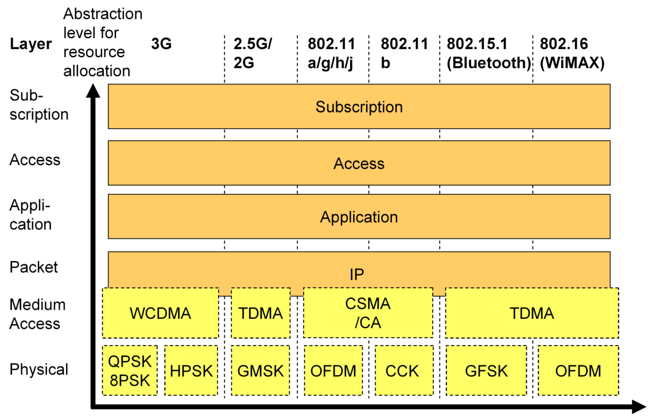

Fig. 1. The layer model to structure existing approaches for resource allocation and dynamic pricing in wireless networks

finding the maximal acceptance radius for voice users, depending on the signal attenuation, and the power allocation for data users.

A characteristic of wireless networks is the varying quality of the transmission channel. Many parameters, such as the structure of buildings or the speed of user movement influence the error rate and the transmission speed of the wireless connection. [4] study the use of pricing for downlink communication from a single wired network access point, focusing on the maximisation of the providers' revenue subject to the varying quality of the channel. In the extreme case, network providers would always provide all capacity to the users with the best channel quality to maximise throughput and, therefore, revenue. [4] introduces a first-price auction to allocate bandwidth among users, who are able to receive data, even with a bad channel, when they are willing to pay a higher price. This also means, that users may be charged different prices per time slot depending on their situation and location.

A different approach is chosen by [5]. An all-pay auction mechanism is proposed to distribute the available channel time. To illustrate the properties of the scheme they use a one cell, two user scenario with no interference between the users but different channel states which determine the throughput. For each time slot an auction is held. They show that the allocation leads to a Nash equilibrium which is no worse than 3/4 the maximum possible throughput when fairness constraints are not imposed and all slots are allocated to users with the best channel quality.

On the upper levels of the layer model only a few market-based allocation approaches can be identified (see e.g., [6] and [7]). These approaches focus at least in some aspects on user transparency and price predictability. While this aspect has already been discussed for broadband networks [8], comprehensive models for next-generation wireless networks are still missing.

3 A model of resource allocation in a wireless multi-provider setting

We introduce a model for the dynamic allocation of resources in a competitive wireless framework consisting of two wireless providers and a mixture of users. We assume all demand functions are quasi-linear. The allocation is dynamic in the sense that users can enter and leave the service areas at any time. Both providers use the Progressive Second-Price auction [9] as a mechanism to allocate bandwidth. The dynamics of connection and disconnection have an impact on the relative prices that providers charge for admission to and resource allocation in their networks.

3.1 Three problems arising from a wireless multi-provider setting

The framework proposed here raises three problems. One is faced by any user who has to decide which provider to purchase capacity from. This decision comes after learning the results of a competitive bidding process that involves all users.

A second problem is the provider problem. Each of the two providers must realize that users may learn some information from their networks before making their decision about connection. Thus, a network making an announcement may expect users to accept the announced price or not.

In our model, users get a reply from each provider and then make a decision; providers receive bids and then communicate results to the users; a provider is also able to infer that he is losing a customer to the competing network when users who bid for access decide not to connect. Making sure users learn in a timely fashion such information is the challenge posed by the coordination problem.

3.2 The Progressive Second-Price auction

Semret [9] proposes a game theoretic approach to the objective of a more efficient and fair utilization of shared resources; such an approach, called network games, results in mechanisms where intelligence and decision making is distributed. In a network the interacting agents acquire resources from the network on behalf of applications which need bandwidth and buffer space. Outcomes as efficient as those of a central controller may be collectively achieved if appropriate rules of interaction are introduced. Semret proposes that pricing can be resolved within the engineering of the network, overcoming the ex-post price structure generally imposed on most networks; his mechanism is called the Progressive Second-Price (PSP) auction.

The PSP auction is based on two aspects of mechanism design: realization and Nash implementation. Realization means the design of a message process (exchange of information between agents and the centre) that enables the achievement of a certain objective. Nash implementation means that allocation rules are designed with incentives, driving the players to an equilibrium where the desired allocation is achieved. This means that no agent can improve her situation by submitting a new bid without worsening the situation for another agent.

The PSP auction is an application of the Generalised Vickerey (GV) auction to allocate divisible objects (in this case, network resources) among bidders. PSP adopts this concept by letting all users submit information consisting of two values: the desired share of the total resource and the price they are willing to pay for it. The auction consists of players submitting bids (player i declares his desired shared q_i of the total resource and a price p_i he is willing to pay for it) and the auctioneer allocating a share a_i of the resource to player i at the cost c_i. The PSP auction allocation rule assigns player i a bandwidth a_i which is equal to the minimum value between his capacity bid, q_i, and the remaining capacity after all those capacity bids, q_k, whose prices beat (or are equal to) $i's$ bid ($p_k \geq p_i$) are subtracted from the total capacity to be allocated Q. In other words, the allocation rule is:

$$a_i(s) = q_i \wedge \left[Q - \sum_{p_k \geq p_i, k \neq i} q_k \right]$$

and s represents the set of bids by i, denoted as s_i and by the rest of the players, denoted as s_{-i}. The payment by any agent i is a weighted average of the (unit) prices offered by the other agents; each weight is the incremental capacity from including j in the auction. The pricing rule can be written as:

$$c_i(s) = \sum_{j \neq i} p_j \left[a_j(s_{-i}) - a_j(s_i; s_{-i}) \right]$$

The auction gets active when a new user attempts to join the network or another active user leaves. Both such events trigger the search for a new equilibrium and prompt users to start the submission of new bids. In order to guarantee the convergence of the algorithm a bidding fee ϵ has been introduced to let bidders change their bids only when the gain in net benefit is large enough. This is expressed in [9] as a modified concept of equilibrium known as ϵ-Nash equilibrium. From a technical perspective, the algorithm produces a minimum of signalling overhead since only two values have to be submitted.

4 Description of the simulation architecture

The simulation environment has been developed in the JADE framework. JADE provides a middleware concept to set up multiple, independently acting agents. Each market participant, user or provider, has been modelled as an agent with a specific behaviour profile defined at the beginning of the simulation. The JADE communication protocol enables communication between all agents as well as provides a discovery service to dynamically identify other market participants offering or requesting services.

A GUI-enabled agent processes all user input about agent types and agent profiles at auction startup and provides a status monitor at auction runtime to display results and performance parameters. Once the simulation has been started, two intermediary management agents manage the creation of agents and document simulation results in a central SQL database. At the beginning of the simulation all agents marked as resource providers (auctioneers), which offer network resources on the market, disclose their service parameters in a directory service. Bidding agents can then identify suitable network services from this directory and can subscribe at the respective auctioneers to participate in the bidding process.

4.1 The bidding process

At the start of the simulation bidders are able to discover all auctioneer agents in their range. As soon as they get registered at the auction they receive feedback about ongoing auctions and the bids submitted by other participants. Bidder agents can submit a bid to an arbitrary auctioneer agent. After submitting one or more bids a bidder agent "sleeps" for a pre-defined time period before it again observes the auction results. Whenever the bidder receives a new auction result from one of the auctioneers, a process is started to analyse the result and to calculate a new truthful reply for the next auction round. The truthful reply is based on the information received from the last auction round, namely, the bids from all other agents participating in the auction. In a first step, the bidder determines the quantity, at which it is able to compete against other bidders at its given demand profile. In a second step, the unit price is determined, which is the bidders marginal value.

4.2 The auctioning process

Since auctioneers act independently and do not cooperate with other network providers the auctioning process is conducted in a similar way as for the single provider scenario. As soon as an auctioneer agent receives a new bid it conducts a PSP auction and sends the results back to all participating bidder agents. The information sent back contains the individual resource quantity allocated to the bidder together with the total costs. Additionally, each bidder receives information of the bids submitted by each bidder.

4.3 Description of the simulation setup

The basic auction setup consists of five bidders requesting network resources from two auctioneers (table 1). Bidders' demands do not depend on the type of service requested. Table 1 shows the maximum quantity and maximum (unit) price for each user demand function. All users are in range of two available wireless networks represented by two independently acting auctioneers. In the simulation the overall network resource Q is kept stable at $Q = 100$ but the distribution between the two auctioneers is varied from $Q_1 = 50, Q_2 = 50$ and $Q_1 = 100, Q_2 = 0$. It is assumed that there is no interaction or cooperation

Name	User1	User2	User3	User4	User5
Maximum quantity	90	85	80	70	65
Maximum Unit Price	10	12	15	20	22

Table 1. Parameters for the first simulation experiment

between the network providers. Network providers act independently and do not communicate either to maximize overall revenue or to provide shared capacity.

The order of bids submitted in each round does not play any role in the final allocation result but can determine the number of auction rounds up to the final equilibrium at both auctions.[1]

4.4 The simulation sets

Two different sets of simulation runs were conducted, each with different bidding strategies applied. The first set of experiments assumes that users bid with their demand at both auctions without any coordination between the outcomes (called *BidAll*). It is also assumed that bidder agents can consume resources from several providers at the same time. When the two auctions have reached equilibrium users stay with the resulting quantities even if they have won resources from both auctions. This inhibits the risk of overbidding because, in equilibrium, resources were assigned from both auctioneers and bidders did not "coordinate" their demand accordingly. In extreme cases, this behaviour could lead to the winner's curse. However, with high congestion as in this case and the particular bidder profiles chosen, the winner's curse is unlikely to happen.

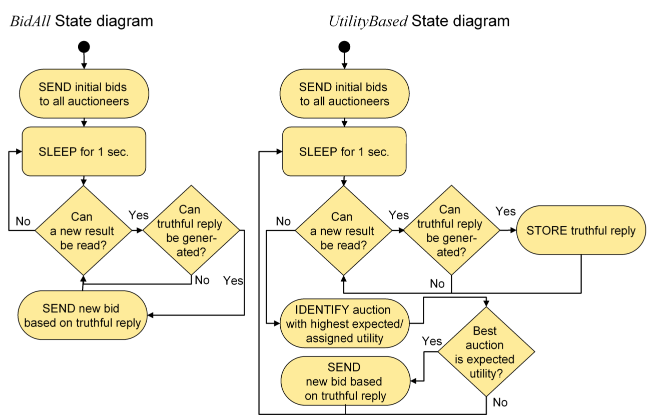

Fig. 2. The simplified state representation of the bidder agent

The second set assumes that bidders coordinate their behaviour between both auctions (called *UtilityBased*). Instead of sending out a truthful reply only based on the signals received from this particular auction, bidders compare the net benefit of both auctions. The bid with the highest net benefit is selected and sent to the respective auctioneer. If no new truthful reply can be generated but the bidder decides to stay with the existing bid from one of the last rounds, no message is sent to any of the auctioneers. Sending a new bid only to the one auction with the highest net benefit does not mean that the bidder resigns from other auctions since, once submitted, bids stay valid for future auction rounds.

[1] Since we conduct our simulations in an agent-based environment, certain external conditions can influence the timing of bids submitted in each simulation run

Even if no new bid is submitted the bidder is always informed about new results to be able to generate a new truthful reply.

Figure 2 depicts the bidding strategies of both simulation sets as a simplified state diagram.

For both scenarios 50 simulation runs were conducted. In each run the distribution of resources between the two providers was changed from $Q_1 = 51, Q_2 = 49$ to $Q_1 = 100, Q_2 = 0$. When the equilibrium at both auctions was reached, the values for revenue and consumer surplus were recorded by each bidding agent. Social welfare is defined as the sum of the revenue and the consumer surplus for each simulation run and is measured in a monetary unit.

5 Discussion of the simulation results

A linear optimisation model was used to calculate the maximum revenue at 1,456.2. Figure 3 displays the allocation of benefits between providers and consumers as the share of resources between the two providers changes from 50 - 50 to 100 - 0.

A prominent result is that the total welfare generated by different combinations of proportions in which providers supply the access market comes closer to the maximum as one seller's share gets relatively larger than the other's. There is some loss in efficiency when the market is equally supplied in comparison to the (monopolistic) one-provider situation. In the worst case such loss does not exceed 5% of the maximum revenue.

A second observation is that large differences in the providers' revenues can be observed between the two sets of simulation results. (See Figure 4) Joint revenues in both simulations decrease and get closer as the relative difference in shares of the supplied resource gets larger. As a consequence consumers' surplus exhibits a tendecy to improve, with some exceptional cases when UtilityBased strategy is used by the bidders.

Since agents seem to bid more carefully when using the *UtilityBased* strategy, in the sense that they only submit a new bid when it provides a higher utility than the current bid does, we would expect such strategy to improve consumers' surplus over the *BidAll* strategy. However, when providers equally supply the access market, *UtilityBased* yields more revenue to them than *BidAll* does, and as the difference in the relative shares of supply become larger revenue differences become smaller.

The latter can be explained by noticing that since under *UtilityBased* an agent switches between auctions, bids submitted to an auction in earlier rounds stay active and influence the price level in the auction. The pricing rule of the PSP auction works on the basis of an exclusion-compensation principle, which determines prices while attempting to cover the "social opportunity cost" created by a bidder's presence. Because a bid remains active in the auction that did not report the highest utility to the bidder, the compensation still takes place at such auction. Consequently, as the auction rounds progress, prices do not decrease as fast as in the single-auctioneer PSP auction.

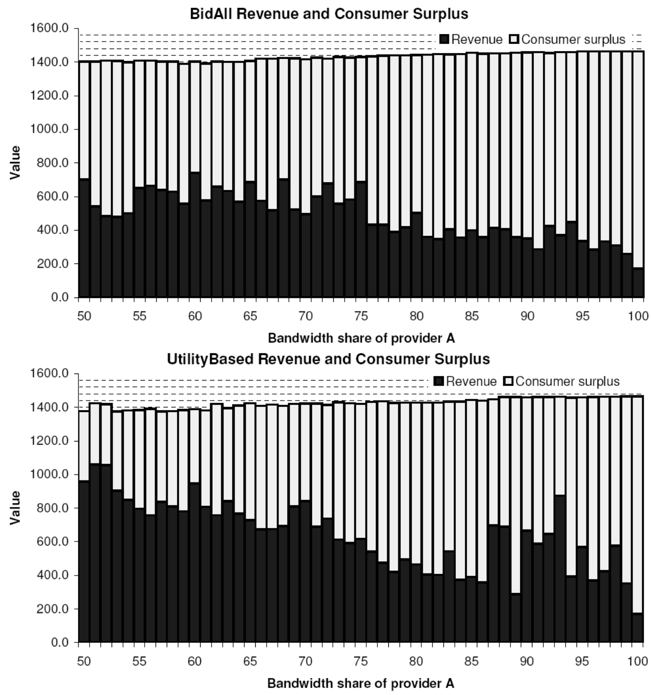

Fig. 3. Results of simulation set 1 and set 2 (consumer surplus, supplier revenue, and overall social welfare) for the *BidAll* bidding strategy and *UtilityBased* bidding strategy

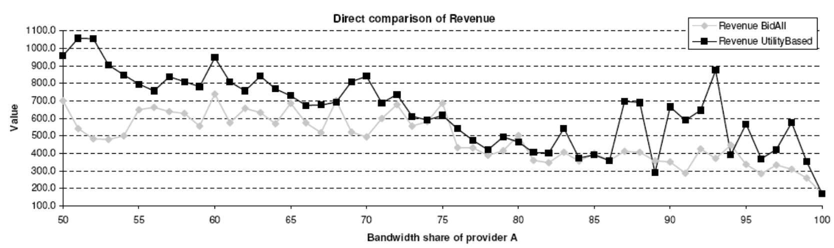

Fig. 4. Comparison between supplier revenue achieved with experiments of set 1 and set 2

6 Conclusion and next steps

Our framework presents a proposal as to how to organise dynamic resource allocation in competing wireless networks based on an existing, social welfare maximising mechanism. Many challenges are ahead to transform this first approach into a comprehensive framework for dynamic resource allocation in competing wireless networks. An immediate next step is the improvement of the bidding mechanism using multibidding [10]. This has been shown to eliminate the convergence-time problem in a single PSP auction.

An unresolved issue is still how to model the bidding behaviour of agents bidding accross several auctions. Some promising proposals have been made for single objects in [11]. We intend to transform the framework of the problem space of this research to one in which bidding for divisible objects at different auctions is possible, avoiding overbidding (see also [12] for details).

As described, the PSP auction is efficient as it maximises the total social benefit. A rich source of problems opens if revenue maximisation, instead of social welfare maximisation is considered. Exploring the research problem from this perspective will also attract the attention of wireless network operators to explore future pricing models of next-generation wireless networks.

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