Microeconomics Inspired Mechanisms to Manage Dynamic Spectrum Allocation

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Abstract— Trying to achieve higher usage efficiency for spectrum has been on the research agenda for some time now. More efficient transmission technologies are being developed, but they alone will not solve the problem of spatially and temporally underused spectrum and radio resources. Mechanisms to optimize spectrum access over space and time are required. This paper describes schemes, based on multiple agents that collaborate to find more efficient allocation patterns in a defined coverage area. Leveraging on microeconomics inspired mechanisms, the paper describes and analyses schemes based on collaborating 'agents' (hat can be either whole operator, or BS or end user terminal) that negotiate with each other to find the most optimized allocation pattern for a given area and allocation duration.
The optimization strategies investigated include both bargaining as well as auction based mechanisms. Both allow the negotiation of spectrum and radio resources, based on market driven incentives. The auction types investigated support dynamic allocations on different timescales, ranging from short to medium and long term allocation scenarios. While auctions are discussed to be used for the longer term allocations, a MAC based rental protocol is evaluated for shorter term allocations when operated either at the BS or end user terminal level. Finally, the paper discusses how the MAC based rental protocol between BSs can be implemented.

***Index Terms* -** Anglo-Dutch Auction, Rubinstein-Stahl Bargaining, Rental Medium Access Control, Cognitive Radio

I. INTRODUCTION

SEVERAL measurement campaigns [1] on the spectrum occupancy over time, space and frequency have shown that spectrum is sporadically used and consequently offers some possibilities for an opportunistic spectrum usage between operators and/or radio access technologies (existing and incoming). This space time varying spectrum usage motivates for a more efficient spectrum usage. This improvement can be achieved with collaborative mechanisms between the different agents using the spectrum. These agents can be classified into different types such as the end user terminal, the base station (BS), or the operator itself (composed of the end user terminals + set of BSs). Therefore, dynamic spectrum allocation can be considered as a multi agent system where agents can come into communications to collaborate to share the spectrum. Based on this multi agent systems framework, any type of agent can potentially collaborate with any other type of agent. Also, since spectrum varying usage over time can occur at different timescales (per millisecond, per second, per minute, monthly, seasonal, annual), the way the different agents can collaborate can differ depending on the timescale under consideration. Anyway, since dynamic spectrum allocation can be considered as a multi agents system, it appears that the application of microeconomics inspired mechanisms is a relevant approach to manage the dynamic spectrum allocation between the agents for each of these different timescales.

This paper presents the latest research achievements of a major European research initiative (E^2R2 Project [2]) in the field of applied microeconomics based mechanisms in support of dynamic spectrum allocation.

This paper focuses on three types of collaborative agent interactions applying auctioning based mechanisms to increase the spectrum efficiency: "end user terminal – BS" for short time scale, "BS – BS" for short timescale and "operator – operator" for long term timescale.

The paper is organised as follows. Section II of the paper addresses dynamic spectrum allocation between operators for long term spectrum sharing (i.e. not real time operations). Here, each operator is considered as a whole (end user terminals + set of BSs). Purpose is to maximise jointly the network performance (number of users supported, user's QoS and spectrum efficiency)

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and the profits for the operators. In this part, two economic models are proposed. The first model is proposing an “Anglo-Dutch split award auction”. The second model proposes a bargaining based algorithm using Rubinstein-Stahl bargaining model for a distributed implementation of dynamic spectrum allocation. This latter model also discusses the good trade-off between fairness of different networks and the efficiency of network performance.

Section III of the paper addresses real time (i.e. timlescale ≤ minutes) and distributed dynamic spectrum allocation in a context of cognitive radios. Here, microeconomics is considered as an “artificial” tool (i.e. artificial money is considered) to schedule radio resources in a dynamic fashion between distributed entities (end user terminals or BSs) at the MAC level. A first scenario addresses auctioning at the end user terminal level. The second scenario addresses an over the air rental protocol between primary and secondary BSs. The rental protocol is driven by a policy based radio etiquette which can support different auction schemes to adapt to the varying environment conditions. This part focuses on the implementation of the advertisement phase of the rental protocol. Finally, Section IV concludes the paper.

II. Advanced Auctioning Schemes for long Term Spectrum Sharing between Operators

The part addresses dynamic spectrum allocation between operators for long term (i.e. not real time operations) spectrum sharing. Here, each operator is considered as a whole, i.e. a set of end user terminals and associated BSs) and real money is used in the auctioning. Driven by the pouring of diverse services supported by various Radio Access Networks (RANs) belonging to different operators, how to efficiently utilize the limited radio spectrum and guarantee the operator’s profits becomes a joint economic and technical problem. As enabling solutions, spectrum rental or trading has generated a lot of interest. In parallel with that, recent years has seen a trend of applying microeconomics inspired trading mechanisms to spectrum allocation all over the world. In the current part, we introduce two novel schemes of spectrum trading: Anglo-Dutch split award auction and distributed based bilateral bargaining (D3B) model under incomplete information for dynamic spectrum allocation.

A. Anglo-Dutch Split Award Auction

Recent years have witnessed an extensive reliance on auction mechanisms in allocating spectrums in the United States, the United Kingdom and elsewhere in Europe. On the other hand, several European countries opted for ‘beauty contests’ where licenses were allocated via *ad hoc* administrative procedures. In this paper we consider yet another auction mechanism for spectrum allocation among a small number of firms, who then compete in the delivery of communication services. While our focus is on maximizing license revenues, the spectrum allocation mechanism we are going to propose starts from a base level importance attached to consumer welfare. Simply put, this means each firm in the downstream market will have a minimum market share and a monopoly situation does not arise.

While the important theoretical contribution [3] has rightly placed auctions in the limelight in engineering spectrum allocations, not so many papers (e.g. [4]-[6]) deal with spectrum auctions[1] jointly with technical considerations . None of these papers consider the textbook style imperfect competition oligopoly model that perhaps captures better the market interaction. To fill this gap in the literature, we allow for a quantity setting oligopoly competition in the market interaction stage after spectrums have been allocated.

Our basic auction-and-market-interaction model extends the pure auction model - an *Anglo-Dutch* auction - actually used in the sale of the British 3G telecom licenses. This auction method is outlined in detail by its two main advocates [7]. Briefly, the Anglo-Dutch auction first selects n+1 bidders out of m bidders, m>n+1, using an ascending bid auction (alternatively known as *English auction*) for the right to further bid in a second-round auction for n licenses. The price thus rises until n+1 bidders remain. In the second round, each remaining bidder submits a sealed bid at or above the price at which the first-round bidding had stopped; the top n bidders in the second-round bidding win the licenses and pay either their respective bids or the n-th highest bid. When the winning bidders pay their respective bids, the procedure is known as *first-price auction*; when the bidders pay n-th highest bid, it is a simple extension of what is known *second-price auction* (or Vickrey auction).

Binmore and Klemperer [7] highlighted three aspects as the auction's principal objectives: efficiency of spectrum assignment, promotion of competition, and realization of the full economic value. Efficiency meant awarding the licenses to bidders with the best business plans, which in turn was expected to translate into relatively higher valuations for the licenses. It is well known, however, that efficiency, revenue maximization and promotion of competition often do not go hand-in-hand; some compromise is expected. Both Binmore--Klemperer recommended auction and the auction mechanism described here follows this principle of balance of objectives.

At this stage we like to note some special features of the particular auction used for the British telecom licenses, because some of these features motivate us to adapt/modify the Anglo-Dutch auction the way we do (as detailed further below). First of all, the licenses were heterogeneous and had different amounts (and types) of spectrums associated with each license, and which were chosen by the licensing authority (although in imperfect anticipation of the likely market demands that are going to prevail). This heterogeneity - both in quantity and quality - is likely to involve some inevitable inefficiency given that various bidders have diverse interests. As for volumes of spectrums per license, any ad hoc specification by the licensing authority would

1 [8] provides a comprehensive survey of how auctions have been used by various countries for spectrum allocations. The survey also offers some guidance to related papers by academic researchers. See also [7].

leave unexploited many other possible specifications that the bidders as a whole (or even the majority of the bidders) might have strictly preferred.[2] We therefore aim to disentangle the 'lumpiness' of the licenses by treating spectrums as a perfectly divisible commodity and letting the bidders themselves express their preferences for the continuum of this divisible unit. We do this simplification by dispensing with the heterogeneity of the spectrums' quality; we will assume all spectrums are identical in that they are inputs to generate the same type of service. Thus, in the product market we consider interactions between firms producing a *homogeneous good*. Finally, we model the spectrum commodity as an essential ingredient to produce the final output (or service) by assuming a Leontief-type production technology (see [11], section 2, for details).

Given the continuously divisible spectrum for allocation, rather than a discrete number of (possibly heterogeneous) licenses, we will consider the split-award auction mechanism that is often used for government procurement of a fixed volume of certain services and formally analyzed [10]. In the split-award procurement auction, bidders submit sealed bids for their respective shares in the service contract and the government (or the auctioneer) chooses the split that maximizes the sum total of bids. We adapt this split-award mechanism in one of the stages comprising the spectrum assignment problem.

In summary, our spectrum assignment game involves fours stages. The government has a fixed amount of spectrums to be allocated. In stage 1, a given number of potential firms participate in an ascending price auction to win a minimum pre-specified amount of the available spectrums and to be able to further bid for additional spectrums in a subsequent sealed-bid auction. All but two firms are eliminated in the ascending price auction and the remaining two firms pay the final dropout price, earn the pre-specified minimum spectrums and then proceed to stage 2. In stage 2, the two firms submit bids for various shares of the remaining spectrums, and in stage 3 the government chooses the split that maximizes the total bids. Finally in stage 4, the two firms compete in the service provision market and their outputs are constrained, through a Leontief production technology, by the amount of spectrums won in the ascending price and split-award auctions. We call this procedure the Anglo-Dutch, split-award auction. More formal description of this game appears in section 3 of [11].

The differences between the Anglo-Dutch auction of Binmore and Klemperer [7] and the auction mechanism we propose in this paper are several. First, the spectrum licenses in our context allow for a continuum of shares as opposed to a discrete number of licenses and this requires a different auction technique in the form of split awards. Second, the ascending bid auction of Binmore and Klemperer ensures a minimal starting bid for the eventual n+1 bidders who participate in the sealed-bid auction stage for n discrete licenses. In contrast, the ascending bid stage of our auction selects two firms for a guaranteed minimal amount of spectrums each with the possibility of additional spectrums; importantly, the option values of acquiring additional spectrums at some price do get reflected in the bidders' strategies during the ascending price auction, thus the ascending bid stage serves both for screening and surplus extractions. The minimal spectrums awarded to the two firms through the ascending bid auction also ensure that the market never degenerates into a monopoly. The basic principles behind Binmore-Klemperer method and our auction method are, however, similar - generate high overall revenues for the government and ensure some necessary competition in the downstream market for consumer welfare.

2 This, in itself, need not be a bad thing for the licensing authority. As it is commonly known, given the number of licenses to be awarded, restricting to exogenous, and possibly heterogeneous, quantity allocations in licenses (as opposed to endogenously determined allocation per license) may limit collusion among bidders; see [9] and [10].

B. *Distributed based bilateral bargaining model (D3B) under incomplete information*

Based on the architecture shown in Figure 1 and some definitions in [12], D3B scheme is elaborated in this section. Due to the decentralized properties of RANs, trader agents (TAs) can't collect all the necessary trading information, thus the negotiations between renting TA and leasing TA can be considered as a Bayesian game with incomplete information. As one of the most classic models in that game, Chatterjee and Samuelson (C&S) bargaining model in [13] is adopted for the spectrum and profit allocation in D3B. The Bayesian equilibrium and related implementation procedures are investigated in this part as well.

1) *General Description*

Chatterjee and Samuelson [13] studied a bilateral bargaining under incomplete information in 1983. Two players, a buyer and a seller, are trying to transact a good. The buyer and seller name a price; if the bid price is above the ask price, the good is sold for the average of the two prices, and if the ask price is above the bid price, the seller retains the good. Each trader knows his own valuation for the good. However, there is incomplete information on each side concerning the other side's valuation.

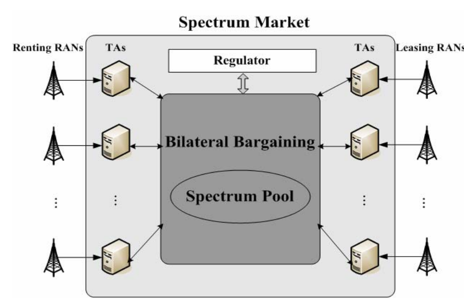

Figure 1 : Architecture of D3B for DSA in reconfigurable systems

In the case of D3B, since renting TAs' and leasing TAs' profits depend on the earning of spectrum trading, they can be also regarded as two players bargaining to transact spectrum. The bilateral bargaining between them can be abstracted into a Bayesian game model as follows:

- *Player (i)*: renting TA and leasing TA are two players $i \in N = \{1, 2\}$.
- *Valuation of the spectrum (c, v)*: c is defined as the cost valuation of the trading spectrum per STU from the aspect of the leasing TA and v stands for the value of spectrum to the renting TA.
- *Bid and ask prices* (S_{bid}, S_{ask}): Both renting TA and leasing TA hide their expected prices. They progressively change their bid or ask prices (S_{bid}, S_{ask}) so as to acquire better profits and in this way their expected prices are revealed step by step. The bargaining strategy is a means to reveal, and can also be used to determine, the expected prices of the renting TA and leasing TA.
- *Profits* $(P_{leasing}, P_{renting})$: The trade takes place at the average of the two price $(S_{bid} + S_{ask}) / 2$, if and only if renting TA's price exceeds leasing TA's price i.e. $S_{ask} \le S_{bid}$. The utility functions of the renting TA and leasing TA, respectively, are:

$$P_{leasing} = (S_{ask} + S_{bid})/2 - P_{cost}^{(lease)}$$

$$= (S_{ask} + S_{bid})/2 - c \qquad (S_{ask} \le S_{bid}) \quad (1)$$

$$P_{renting} = P_{sprov}^{(rent)} - (S_{ask} + S_{bid}) / 2$$

$$= v - (S_{ask} + S_{bid})/ 2 \qquad (S_{ask} \le S_{bid}) \quad (2)$$

2) Bargaining Strategies

Now, the key problem for both renting TA and leasing TA is how to design the optimal bids or asks to achieve maximum benefit, relying on incomplete information about the opponent. Starting with the basic concepts presented in [13], a novel approach for spectrum bargaining analysis is developed here.

Suppose the leasing TA estimates the renting TA will use a linear bargaining strategy,

$$S_{bid}^{(lease)}(v) = \alpha_{bid} + \beta_{bid}*v \quad (3)$$

where $S_{bid}^{(lease)}(v)$ is the estimation made by the leasing TA of what the renting TA's offer will be.

Correspondingly, the renting TA estimates that the leasing TA will use a linear bargaining strategy,

$$S_{ask}^{(rent)}(c) = \alpha_{ask} + \beta_{ask}*c \quad (4)$$

where $S_{ask}^{(rent)}(c)$ is the renting TA's estimate of the leasing TA's offer.

It should be noted that the leasing TA have no information about the value of v and the renting TA does not know c. Coefficient α_{bid} and β_{bid} are the estimation of leasing TA ($\alpha_{bid} \ge 0$, $\beta_{bid} \ge 0$) and coefficient α_{ask} and β_{ask} are estimated by the renting TA ($\alpha_{ask} \ge 0$, $\beta_{ask} \ge 0$). As mentioned above, leasing TA and renting TA develop their bargaining strategies to expand their own benefits.

The renting TA's optimal profit objective can be described as

$$\max_{S_{ask}} P_{leasing} = \{\frac{1}{2}(S_{ask} + E[S_{bid}^{(lease)}(v) \mid S_{bid}^{(lease)}(v) \ge S_{ask}]) - c\} * Prob[S_{bid}^{(lease)}(v) \ge S_{ask}] \quad (5)$$

where S_{ask} is the asking price of the seller to be determined, $E[S_{bid}^{(lease)}(v) \mid S_{bid}^{(lease)}(v) \ge S_{ask}]$ is the expectation (mean) of the estimated bid price of the renting TA when this estimated bid price is larger than or equal to the ask price of the leasing TA, and $Prob[S_{bid}^{(lease)}(v) \ge S_{ask}]$ is the probability that the estimated bid of the renting TA is larger than or equal to the ask of the leasing TA.

In consistent with renting TA, the leasing TA's profit maximizing objective can be illustrated as

$$\max_{S_{bid}} P_{renting} = \{v - \frac{1}{2}(S_{bid} + E[S_{ask}^{(rent)}(c) \mid S_{bid} \ge S_{ask}^{(rent)}(c)])\} * Prob[S_{bid} \ge S_{ask}^{(rent)}(c)] \quad (6)$$

We suppose Bayesian equilibrium of the game is $(S_{bid}^{*}, S_{ask}^{*})$, which represent the optimal strategies maximizing the profits of renting RAN and leasing RAN, respectively. It can be obtained from

$$\begin{cases} dP_{leasing} / dS_{ask} = 0 \\ d^2 P_{leasing} / d S_{ask}^2 < 0 \end{cases} \quad (7)$$

$$\begin{cases} dP_{renting} / dS_{bid} = 0 \\ d^2 P_{renting} / d S_{bid}^2 < 0 \end{cases} \quad (8)$$

In the effort to receive more profits, we must determine $E[S_{bid}^{(lease)}(v) \mid S_{bid}^{(lease)}(v) \ge S_{ask}]$, $Prob[S_{bid}^{(lease)}(v) \ge S_{ask}]$, $E[S_{ask}^{(rent)}(c) \mid S_{bid} \ge S_{ask}^{(rent)}(c)]$ and $Prob[S_{bid} \ge S_{ask}^{(rent)}(c)]$ to deduce the optimal strategies S_{bid}^{*} and S_{ask}^{*} from equation 7, 8. With the valuation of c and v based on load prediction, leasing TA can have an estimate of $S_{bid}^{(lease)}(v)$ and renting TA can have an estimate of $S_{ask}^{(rent)}(c)$. We embody this estimations into the functions, $E[S_{bid}^{(lease)}(v) \mid S_{bid}^{(lease)}(v) \ge S_{ask}]$, $Prob[S_{bid}^{(lease)}(v) \ge S_{ask}]$, $E[S_{ask}^{(rent)}(c) \mid S_{bid} \ge S_{ask}^{(rent)}(c)]$ and $Prob[S_{bid} \ge S_{ask}^{(rent)}(c)]$ can be calculated, and consequently the Bayesian equilibrium can be developed from equation 7, 8.

TA's valuation of c and v should be dynamically adapted in consistent with the supply demand relation of the market in near future. To be specific, spectrum will appreciate provided that demand exceeds supply in the market and prospective spectrum demand is optimistic. On the other hand, spectrum will depreciate provided that supply exceeds demand in the market and prospective spectrum demand is pessimistic. However, it is almost impossible for the individual TA to predict and assemble all the necessary information of the whole market accurately. Instead, either renting or leasing TA adapts his estimate of v or c according to his own spectrum load prediction, i.e. with current time t, if renting TA predicts that his loads increase at $t+1$, which means he is in more urgent need of the spectrum, v is supposed to be in higher price. On the contrary, if renting TA predicts his loads decrease at $t+1$, he will lower v. Correspondingly, if leasing TA predicts that his loads increase at $t+1$, which means his spare spectrum is shrinking, c will be in higher price. And if he predicts his loads decrease at $t+1$, which means he have more available spectrum to lease and he is eager to trade, his estimation of spectrum descend. Meanwhile, massive v can be statistically taken by renting TA as variable with a certain probability distribution (e.g. uniform distribution, triangular distribution) and so it does with c by the leasing TA. To be simple, in the following part, the bargaining strategies of both parties are investigated in the scenario of c and v with a uniform distribution.

3) Optimal Bilateral Bargaining Strategies under a Uniform Distribution

The renting TA assumes c to be a variable uniformly distributed in $[c_1, c_2]$, and the leasing TA assumes v to be a variable uniformly distributed in $[v_1, v_2]$. As defined in equation 6, 7, $S_{bid}^{(lease)}(v)$ and $S_{ask}^{(rent)}(c)$ are variables uniformly distributed in $[\alpha_{bid} + \beta_{bid}*v_1,\ \alpha_{bid} + \beta_{bid}*v_2]$ and $[\alpha_{ask}+ \beta_{ask}*c_1,\ \alpha_{ask}+ \beta_{ask}*c_2]$, respectively. It is obvious that the probability density for c is $1/(c_2 - c_1)$ and for v is $1/(v_2 - v_1)$. Similar probability density can also be found for $S_{bid}^{(lease)}(v)$ and $S_{ask}^{(rent)}(c)$.

With the assumption of a uniform distribution for v, $Prob[S_{bid}^{(lease)}(v) \geq S_{ask}]$ can be obtained through simple mathematical manipulation

$$Prob[S_{bid}^{(lease)}(v) \geq S_{ask}] = Prob[\alpha_{bid} + \beta_{bid}*v \geq S_{ask}]$$

$$= Prob[v \geq (S_{ask} - \alpha_{bid}) / \beta_{bid}]$$

$$= [v_2 - (S_{ask} - \alpha_{bid})/\beta_{bid}]/(v_2 - v_1) \qquad (9)$$

For $S_{bid}^{(lease)}(v)$ is uniformly distributed in $[\alpha_{bid} + \beta_{bid}*v_1,\ \alpha_{bid} + \beta_{bid}*v_2]$, $E[S_{bid}^{(lease)}(v) | S_{bid}^{(lease)}(v) \geq S_{ask}]$ can be easily

deduced as:

$$E[S_{bid}^{(lease)}(v) | S_{bid}^{(lease)}(v) \geq S_{ask}] = (S_{ask} + \alpha_{bid} + \beta_{bid}*v_2) /2 \qquad (10)$$

Correspondingly, we can establish formulations for $Prob[S_{bid} \geq S_{ask}^{(rent)}(c)]$ and $E[S_{ask}^{(rent)}(c) | S_{bid} \geq S_{ask}^{(rent)}(c)]$ under the assumption of a uniform distribution for c, i.e.

$$Prob[S_{bid} \geq S_{ask}^{(rent)}(c)] = (S_{bid} - \alpha_{ask} - \beta_{ask}*c_1)/[\beta_{ask}*(c_2 - c_1)] \qquad (11)$$

$$E[S_{ask}^{(rent)}(c) | S_{bid} \geq S_{ask}^{(rent)}(c)] = (S_{bid} + \alpha_{ask}+ \beta_{ask}*c_1)/2 \qquad (12)$$

the optimal strategy of the leasing TA can be given as:

$$S_{ask}^{*} = (\alpha_{bid} + \beta_{bid}*v_2)/3 + 2c/3 \qquad (13)$$

Therefore, when there is equilibrium, the optimal strategy for the leasing TA is to offer an asking price which is the sum of 1/3 the upper limit of his estimation of the buyer's bid and 2/3 his own lowest valuation of the trading spectrum.

Similarly, taking equation 11 and 12 into equation 6, and then from equation 8, when the game reaches the equilibrium, the optimal bidding strategy of the renting TA would be

$$S_{bid}^{*} = (\alpha_{ask}+ \beta_{ask}*c_1)/3 + 2v/3 \qquad (14)$$

Hence, the optimal strategy for the renting TA is to ask in a price which is the sum of 1/3 the lower limit of his estimation of the leasing TA's ask and 2/3 his own highest valuation.

III. AUCTIONING BASED MAC PROTOCOLS FOR COGNITIVE RADIOS MANAGEMENT

A. Auctioning between users in UMTS

Based on the increase of computational power, capacity of the systems and the investigation on cognitive radio (CR), the headstone is laid for a better adaptation of the communication systems to the individual users' needs. Parts of the responsibility to fulfil the QoS can be shifted to the mobile terminal. Furthermore, the mobile terminal is in the position to observe the current radio resource goods (RRGs) consumption based on self – cognition and environment cognition [14]. This opportunities can be used the mobile terminal to represent and act according to the users wishes and needs [15].

The demand of RRGs in a wireless communication system varies locally and dynamical, e.g., moving hotspots. If considering a cellular network, the users in different cells are not equal in their urgency to phone, willingness to pay and QoS constraint. Thus the user differs in evaluating the RRGs to set up or improve the communication. This circumstance can be used by the operator to increase its monetary gain by negotiating with the customers [16]. The negotiation will take place between agents representing the operator and the users. The agents are located in the base station and the user terminals.

In the following possible implementation of such a decentralized and dynamic pricing and allocation mechanism will described for UMTS TDD.

1) Auction model description

The UMTS TDD resource allocation mechanism will be modified in terms of the assignment of up- and downlink resources by one auction per frame. That is, each user has to pay for all RRGs carrying the data in both the up- and downlink. The pricing philosophy differs from the established tariffing of mobile calls, but it is common in data transmission. This method motivates the users to save resource and signalling effort which would be necessary because of bidding for both transmission directions. This additional signalling does not only produce additional effort, but also affects the fulfilment of the QoS based on higher transmission times. Furthermore, separate pricing of transmitter and receiver is custom in data transmission networks like Internet, WAP or GPRS.

Thus, each user terminal conveys bids of RRGs for both uplink and downlink. The RRGs will be allocated in the radio network controller (RNC) subject to maximisation of the operator's monetary gain. Afterwards, the auction result will be broadcast to all user terminals by the allocation vector, whereas the allocation as itself has to be transmitted even without the auction procedure. The price and the allocation will be determined by a modified multi-unit discriminatory auction which is adapted to the transmission frame constraints.

2) Determination of the Goods

The RRGs which will be auctioned have to be described in two dimensions: Because of using CDMA in UMTS for the multi-access, the RRGs have to be limited in the code-dimension. On the other hand, the frames are divided into 15 timeslots, which can be assigned to different users. Thus, the minimal RRG can be one timeslot and one code with spreading factor 16 resulting in 160 chips. Based on the application of QPSK, 320 bits can be ideally transmitted. After subtraction of the midamble data and guard period [17], the chips per code are reduced to 1952 chips leading to 244 bit per minimal RRG. Account for the channel coding with coding rate 1/3 and CRC, the minimal RRG can carry about 80 bits as load. The question is now if such small good does make sense. The smaller the RRGs are, the more flexible and individual the auctions can be. But the drawback is an increase of signalling effort in relation to the transmitted net data. Surely, a flexible solution also is thinkable, e.g., as long as the cell load is relatively small, small RRGs can be auctioned, and with increasing load the RRG size will increase. For limiting the complexity, a RRG will be determined to 4 minimal RRG. Figure 2 shows a load frame as an example.

3) Bid constellation

Each bid g_i consists of the number of RRGs d_i needed and the bid value p_i per RRG which are inserted in the pair (d_i, p_i). The transmission of such a pair for each RRG would tremendously increase the signalling efforts. Therefore, the bids will be limited per user terminal. Each user terminal can only submit 2 bids per QoS class, e.g., if you consider video conferencing, then the audio data should be higher prioritized than the video data. Furthermore each figure is quantized. The number of RRGs is represented by 6 bits which is enough for 60 RRGs as well as the bid value is mapped to 6 bits. For the so-called fixed signalling, a user has to send 2*2*4*6*6 = 192 bits. The user has to send a bid for a certain QoS class even if there is incentive to bid. Therefore an efficient signalling is proposed, whereas only this bids has to be submitted which are useful. The bid vector possesses in front of a header with 5 bits, in which the number of the following bids is included.

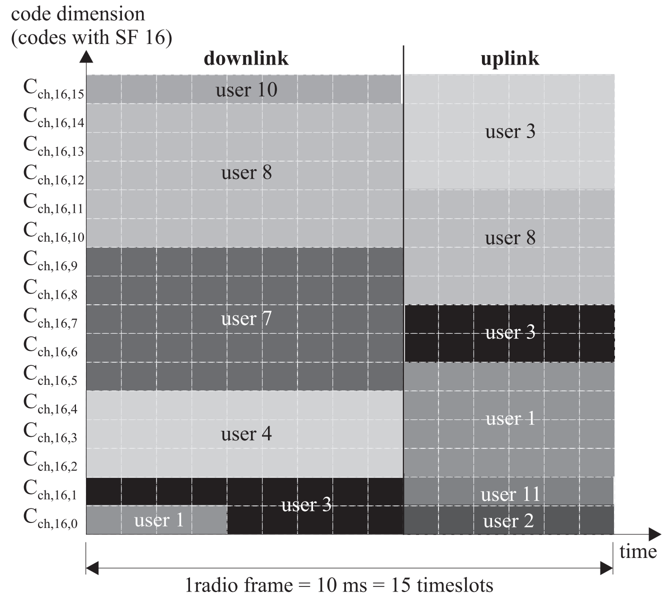

Figure 2 UMTS frame allocation by an auction

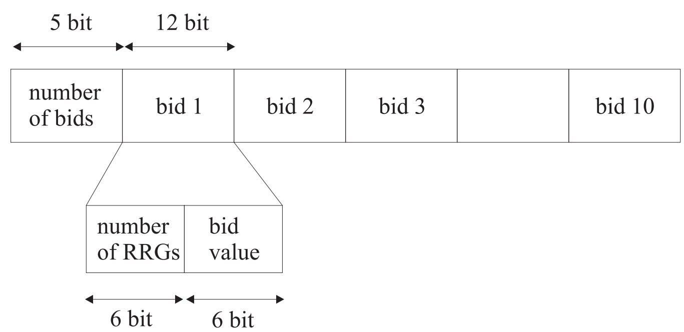

Figure 3 Efficient signaling of the bid vector

4) Auction mechanism

The auction mechanism which will be described in the following is a modified discriminatory auction adapted to the UMTS TDD frame constraints.

The set of all bids for the uplink is G_u and correspondingly the sset for the downlink is G_d . The set of the bids won for the uplink is W_u and for the downlink W_d . The allocation algorithm proceeds as following:

1. All bids, independently of uplink or downlink will be sorted in a decreasing manner, whereas bids with the same figure are randomly sorted.
2. The number of maximum available goods will be initialised by 60
3. if $r > d_i$ for the highest bid g_i in $(G_u \cup G_d) \backslash (W_u \cup W_d)$, then g_i wins, r will be reduced by d_i, and g_i will become an element of W_d or W_u , depending on whether it is a bid

for uplink or downlink. Otherwise, the bid gets only r RRGs and r will be set to zero. The bid g_i will become an element of W_d or W_u , but only with r goods, i.e., (r, p_i).

4. Repeat 3. until $r = 0$.

After step four, all RRGs has been assigned, but the following side constraint has not been fulfilled:

- The number of RRGs, which are assigned for both uplink and downlink, have to be a multiple of four, because one time slot can only be used for either uplink or downlink.
- The number of RRGs, which are assigned for both uplink and downlink, have to be at least four, because one time slot has to be allocated for both links.

The next steps will assure to fulfil these side conditions.

5. Add bids from $G_{u,d} \backslash W_{u,d}$ to $W_{u,d}$ as long as the following conditions holds:
   a. $S_{u,d} = \sum_{g_i \in W_{u,d}} d_i$
   b. $S_{u,d} \equiv 0 (\bmod 4)$
   c. $S_{u,d} \geq 4$
6. If $S_u + S_d > 60$, then go to a) else to 7.
   a. If the gain of the $(S_u + S_d - 60)$ goods with the smallest prices, for which $g_i \in W_u$ holds, is smaller than the same number of goods with the smallest prices, for which $g_i \in W_u$ holds, then go to b. else c.
   b. If $S_u > 4$, then remove the $(S_u + S_d - 60)$ with the smallest prices from W_u. Respectively, for bids (d_i, p_i) with $d_i > S_u + S_d - 60$, change g_i to $(d_i - S_u - S_d + 60, p_i)$. Afterwards continue with 7, otherwise if $S_u \leq 4$, goto c.
   c. If $S_d > 4$, then remove the $(S_u + S_d - 60)$ with the smallest prices from W_d. Respectively, for bids (d_i, p_i) with $d_i > S_u + S_d - 60$, change g_i to $(d_i - S_u - S_d + 60, p_i)$. Afterwards continue with 7, otherwise if $S_d \leq 4$, goto b.

7. Finish allocation mechanism

In the next step the good location in the frame has to be considered. Because of the higher distortion resistance of longer codes, it is more convenient to stretch the allocation in time than in code dimension. Moreover, for the uplink the multi-code usage per mobile terminal is limited to 2. That is, the RRGs have to be bundle by using spreading factor 2, 4, 8 and 16. The drawback is that not all numbers, e.g., 7 RRGs, cannot be allocated, therefore, the RRGs preliminarily assigned to the users will be reduced and allocated to another user.

5) *Simulation*

A node B allocates the RRGs to bidders. The incoming data of the four QoS buffers underly a Poisson process with arrival rate λ. For $\lambda < 0.2$ the load increases linearly in the channel and for $\lambda \geq 0.2$ the cell capacity is reached. Each bidder is risk-neutral and bids equal for each RRG according to the transmission priority.

In Figure 4 the relative signalling effort of frame-based auctioning is considered. The relative signalling effort is defined as the signalling data needed per auction divided by the net data sent. This parameter is depicted in dependence on the averaged data rate per buffer and user. All relations decrease up to $\lambda = 0.2$, because the more data sent, the smaller is the relation. If the cell capacity is reached and moreover the demand is higher than the supplied capacity ($\lambda > 0.2$), every frame is full loaded. Thus, the relation for the fixed signalling remains constant at about 20 % which is relatively high. The efficient signalling reaches a minimum of 6% at $\lambda = 0.2$. This is an acceptable signalling effort, keeping in mind that this already includes the allocation vector which has to convey for every allocation mechanism. For $\lambda > 0.2$, the signalling effort increases, because the higher the averaged load is, the higher is the probability that a bid has to be sent for the buffer. Therefore, the efficient signalling effort approximates the fixed signalling effort by increasing the capacity needed to the cell capacity.

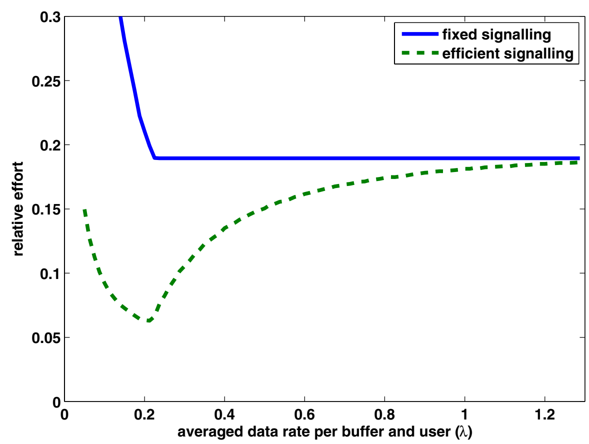

Figure 4: Signaling effort in relation to the amount of load data

Figure 5 shows the comparison of the operator's revenue using either the uniform-price auction or the discriminatory auction. The averaged revenue per auction is measured in the sum of the quantized prices which can take the values 1,…, 64. The discriminatory auction clearly has a higher revenue than the uniform-price auction because a user has to pay the bid. In contrast, in the uniform-price auction the user has to pay at most the bid. The revenue increase for both with higher load needed, because the higher the probability is that higher bids will be submitted in the auction. Thus, an operator would prefer the discriminatory auction.

6) *Rental protocol*

This section addresses real time (i.e., timescale ≤ minutes) and distributed secondary spectrum usage where auctioning is considered as an "artificial" tool (i.e. virtual money is considered) to schedule radio resources at the MAC level in a dynamic fashion between BSs operated by different operators.

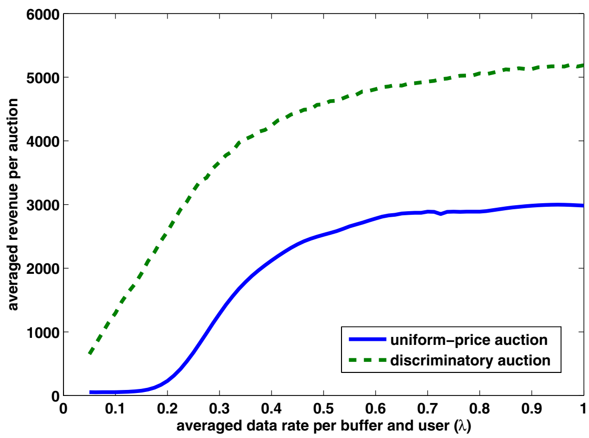

Figure 5 Comparison of two different auctions

B. *Secondary Spectrum Rental protocol between Base Stations*

Secondary spectrum usage between different operators can be achieved with distributed dynamic channel allocation (DCA) [19] in which spectrum is pooled between cells and can be accessed by any of the systems in a geographical area where cells of the different systems overlap or are neighbours. The force of distributed DCA is that it uses local information about the current available channels in each cell offering more suitable conditions to reuse frequency as often as possible. With this approach, the spectrum availability knowledge can be performed on peer to peer basis between neighbouring or overlapping cells.

In this multi cell and operators environment enabling secondary spectrum usage with DCA, one main challenge is to schedule primary cell's radio resources (time + frequency) between several secondary cells competing for the access and usage of these resources while ensuring access fairness. One way to achieve this is to facilitate "real time automated negotiation of leased use rights" [18] for spectrum sharing between primary and secondary cells in a distributed and real time fashion.

This scheduling can be approached with a real time credit token based rental protocol [20] enabling a distributed and dynamic auctioning between each primary cell and secondary cells participating to DCA. In such a local multi cell environment market place, the primary cell acts as the resource offeror, and the secondary cells acts as the resource renter. The primary cell opens for renting its resources for a temporally use for the secondary cells belonging to different operators**.** Negotiation relies on auctioning based mechanisms.

The radio etiquette [20] rules the inter BS rental protocol. This radio etiquette can be specified by the policies applied on credit token "units" during the negotiation transactions. These policies, among other things, can specify the type of auctioning method [21] that has to be used by the rental protocol as a function of the context (e.g. e number of secondary cells participating to auctioning, renting time duration, etc). The application of an ascending bid auctioning for the rental protocol is illustrated in [20]. The overall negotiation and transaction process between one primary BS and several secondary BS is preferably applicable to multi-carrier based systems like orthogonal frequency division multiple access (OFDMA) which provides sufficient flexibility in time and frequency to allocate dynamically the radio resources. In the rental protocol, the primary BS advertises about this auction. Provided this auction, the interested secondary BSs can bid during a predefined period of negotiation to be granted and allocated with the resources. A dynamic and iterative process is then launched. This approach provides the means for an adaptive policy based dynamic resource sharing management.

The implementation of the rental protocol requires some primary BS to secondary BS communications or vis versa. This can be enabled [20] with the introduction of the appropriate signaling either over the backhaul (i.e., wired based), or with over the air communications between BSs. The remaining part of this section III.B focuses on the over the air BS to BS communications mechanisms related to the advertisement phase of the rental protocol. Some secondary spectrum advertisement discovery procedures are described in the case the over the air BS to BS communications use end user terminals as RF bridges between primary and secondary cells (Figure 6).

1) *Over the air advertisement discovery procedures*

The discovery consists in defining appropriate signalling procedures (Advertisement Time Intervals) at the MAC level (over the air) enabling the secondary spectrum reuse opportunities discovery as follows:

- Primary cells can advertise periodically to the neighbouring secondary cells about their offers for secondary radio resource renting.
- Secondary cells can inform periodically the surrounding cells about their search for secondary radio resources opportunities for renting.

Additionally, the procedures also consist in:

- Using policy based management of secondary terminals when these terminals act as bridges between the primary and secondary BSs.
- Managing the ranking of the Advertisement Time Intervals to speed up the discovery in case of urgent radio resources need to rent.

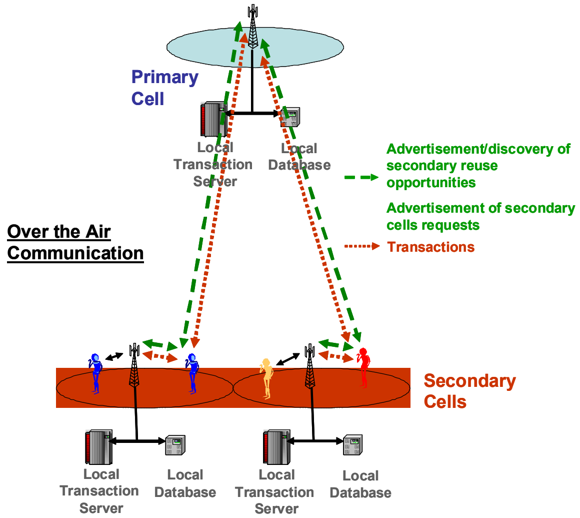

Figure 6: Over the air communications between BSs using terminals acting as bridges

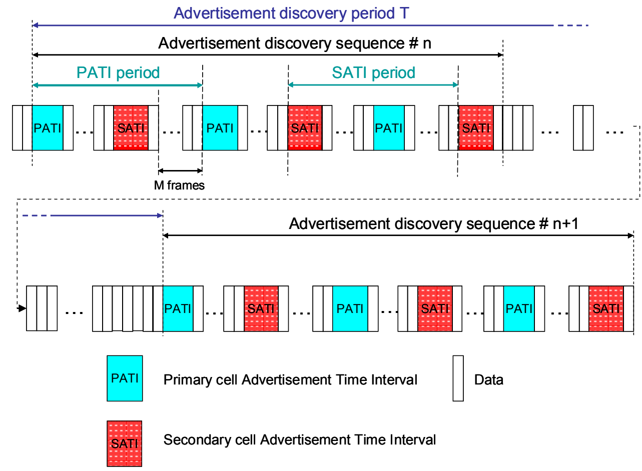

Figure 7: Advertisement MAC frame structure for secondary spectrum usage opportunities discovery

<u>MAC frame structure for advertisement discovery</u>

On a given frequency channel, Figure 7 describes the proposition of MAC frame structure enabling the support of the discovery of the secondary spectrum reuse opportunities between the primary and secondary cells. This MAC frame is structured as follows:

- An *Advertisement discovery sequence* is periodically inserted in the data frame to support the discovery for two cases:
  - Discovery of the primary cells' offers by the secondary cells,
  - Discovery of the secondary cells' requests by the primary cells.
- The Discovery of the primary cells' offers is enabled by the usage of the Primary Advertisement Time Interval (PATI).
- The Discovery of the secondary cells' requests is enabled by the usage of the Secondary Advertisement Time Interval (SATI).
- The number of PATI and SATI within the *Advertisement discovery sequence* can be tuned a function of the context (e.g. number of primary and secondary cells) to avoid to waste capacity. For example (in Figure 7), the number of PATI and SATI is the same within the sequence #n. However, there can be different numbers of PATI and SATI in a sequence.
- The *Advertisement discovery sequence* periodically occurs every *Advertisement discovery period T.* This period T can also be tuned as a function of the context (e.g. number of primary and secondary cells).

<u>Advertisement discovery MAC frame structure usage</u>

The usage of PATI and SATI is such as:

- The PATIs are dedicated to primary BS transmissions in downlink.
- Each PATI is used by a primary BS in downlink for broadcasting.
- The information included in each PATI is related to the parameters of the rental protocol [20]. :
- The PATIs are ranked in each *Advertisement discovery sequence* in such a way that the first PATI is assigned to the primary BS whose renting period will occur first, the second PATI is assigned to the primary BS whose renting period will occur in second, and so on. Re-ranking is updated dynamically each time a new primary BS is arriving. This mechanism avoids the terminals of the secondary cells (see paragraph "*Advertisement discovery from primary cell by secondary cell* " below) to scan all PATIs when the secondary cells have to find very shortly some available resources to rent. In this manner; they have directly knowledge of the next available resources they can bid for.
- Each primary cell releases the PATI it is using when its auctioning period starting time has elapsed. This enables new arriving primary cells to use this PATI (eventually after the re-ranking) to advertise future secondary spectrum usage opportunities.
- The SATIs are dedicated to secondary BS transmissions in downlink.
- Each SATI is used by a secondary BS in downlink for broadcasting.

- The information included in each SATI is related to the starting time from which the secondary BS would be interested to rent period opened for renting, and the ending time of the period opened for renting.
- The PATI and SATI positions in the frame are referenced by universal time, and these positions are known by the "primary" and "secondary" terminals. A "primary" terminal is a terminal belonging to a primary cell. A "secondary" terminal is a terminal belonging to a secondary cell.
- There are no direct communications between the primary and secondary BSs (Figure 6). The primary-secondary BS communications are performed via primary and secondary terminals which act as bridges as follows:
    - A "secondary" terminal performs the bridge between its secondary BS and the primary BS (provided the coverage of the primary cell overlaps with the secondary cell area, and this secondary terminal is located in the overlapping area).
    - A "primary" terminal performs the bridge between its primary BS and the secondary BS (provided the coverage of the secondary cell overlaps with the primary cell area, and this primary terminal is located in the overlapping area).
- Secondary terminals in the overlapped (primary/secondary) cell area listen to the PATIs.
- Primary terminals in the overlapped (primary/secondary) cell area listen to the SATIs.

IV. CONCLUSION

Depending on the spectrum allocation problem that has to be solved, be it short medium or long term allocation, always the best possible or most suitable optimization approach has to be used. There is no single approach that will lead to an optimum solution for all cases. This paper discussed a heterogeneous access networks system view where collaborating agents are jointly trying to optimize the short medium and long term spectrum allocation problems. A basic auction-and-market- interaction model based on the Anglo-Dutch split award auction, and a bargaining approach based on Rubinstein-Stahl bargaining, have shown being very suitable for revenue driven spectrum resource optimization in medium and long term allocation scenarios involving different operators.

Tackling the optimization problem from the end user side, short term/real time allocations could be based on microeconomic principles. Hereby the spectrum, or codes, is considered as an economic good, and the allocation again can be based on auctions, or on a rental model. An implementation scheme enabling the over the air advertisement phase of the rental protocol applied between primary and secondary base stations has been proposed.

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REFERENCES

[1] New York City Spectrum Occupancy Measurements September 2004, December 15, 2004, Shared Spectrum Company.
[2] FP6 End-to-End Reconfigurability (E2R2) Integrated Project (IP), www.e2r2.motlabs.com.
[3] Milgrom, P.R., 2000. Putting auction theory to work: the simultaneous ascending auction. Journal of Political Economy 108, 245-272.
[4] Janssen, M.C.W., 2006. Auctions as coordination devices. European Economic Review, 50, 517-532.
[5] Janssen, M.C.W. and Karamychev, V.A., 2006. Selection effects in auctions for monopoly rights. Forthcoming, Journal of Economic Theory.
[6] Jehiel, P. and Moldovanu, B., 2001. Auctions with downstream interaction among buyers. Rand Journal of Economics 31, 768-791.
[7] Binmore, K. and Klemperer, P., 2002. The biggest auction ever: The sale of the British 3G telecom licenses. Economic Journal 112, C74-C96.
[8] Jehiel, P. and Moldovanu, B., 2003. An economic perspective on auctions. Economic Policy, April issue, 269-308.
[9] Klemperer, P., 2002. How not to run auctions: The European 3G mobile telecom auctions. European Economic Review, 46, 829-845.
[10] Anton, J. and Yao, D.A., 1989. Split awards, procurement and innovation. Rand Journal of Economics 20, 538-552.
[11] Bag, P., Levine, P. and Rickman, N., 2006, Anglo-Dutch, Split-Award Spectrum Auctions with a Downstream Market, mimeo, University of Surrey.
[12] M. Pan et al, "A Novel Bargaining Based Dynamic Spectrum Management Scheme in Reconfigurable Systems", ICSNC 06, Oct. 29 – Nov. 3, 2006, Tahiti, French Polynesia, to appear.
[13] K. Chatterjee and W. Samuelson, "Bargaining Under Incomplete Information," Operations Research 31: 835-851, 1983
[14] Joseph Mitola III, "Cognitive radio for flexible mobile multimedia communications", Sixth International Workshop on Mobile Multimedia Communications (MoMuC'99), San Diego, CA, 1999.
[15] C. Kloeck, H. Jaekel, F. Jondral, "Auction Sequence as a New Resource Allocation Mechanism", Proceedings of the IEEE VTC 2005, Dallas, USA, September 2005
[16] C. Kloeck, H. Jaekel, F. Jondral, "Dynamic and Local Combined Pricing, Allocation and Billing System with Cognitive Radios", Proceedings of the IEEE DySPAN 2005, Baltimore, USA, September 2005
[17] UMTS/3GPP: TS 25.221 V6.1.0, Universal Mobile Telecommunication System(UMTS); Physical channels and mapping of transport channels onto physical channels (TDD). Technical report, 2004.
[18] ET Docket No. 03-108, Notice of Proposed Rule Making And Order, FCC, December 2003.
[19] D. Grandblaise, K. Moessner, G. Vivier, R. Tafazolli, "Credit token based scheduling for inter BS Spectrum Sharing",4th Karlsruhe Workshop on Software Radios (WSR'06), Karlsruhe, Germany, 22-23 March 2006.
[20] D. Grandblaise et al, "Credit Token based Rental Protocol for Dynamic Channel Allocation", CROWNCOM 2006, Mykonos Island, Greece, June 8-10, 2006
[21] V. Krishna; "Auction Theory", Academic Press 2002