One-Shot Multi-Bid Auction Method in Dynamic Spectrum Allocation Networks

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***Abstract*— The radio spectrum is a scarce, valuable and thus expensive resource. Creating a "spectrum market" is a possible solution to distribute spectrum efficiently. In this paper we propose an auction method with a pricing scheme developed in a Dynamic Spectrum Allocation (DSA) framework that handles interference issues in a flexible way. We take interference into account as a source of spectrum utilization degradation, captured by the so-called geographical coupling and technology coupling parameters. We propose a one-shot multi-bid pricing scheme that takes the special properties of DSA into account. For an efficient spectrum brokering, there should be a strong incentive for users to accommodate each other. The idea behind the proposed pricing method is to charge providers that do not tolerate others and cause large interference to other regions. A simulation example is also given to highlight the achievable gains using our proposed solution.**

I. Introduction

Radio spectrum is a valuable resource but usable frequencies are scarce. Spectrum should be distributed to the uses and users that generate the greatest value but existing management systems fail to do this. When designing usage rights, the focus tends to be on avoiding interference between users and uses and not so much on maximizing the economic benefits derived from the spectrum. As a result, valuable spectrum is left unused at any given time. This is the motivation for a more spectrum efficient technique, called Dynamic Spectrum Allocation (DSA), where the assigned spectrum blocks may vary in time and space.

The IST-DRiVE project [1] dealt with the coordinated DSA problem. The goal was to develop methods for dynamic frequency allocation and for co-existence of different radio technologies in one frequency band in order to increase the total spectrum efficiency. They investigated only the co-existence of UMTS and DVB-T technologies [2] [3].

The IST-OverDRiVE project [4] dealt with the problem in more details. They defined 'DSA areas' in which the traffic demands of different RANs are rather constant in space (yet they may be time variant).

A more detailed overview of Dynamic Spectrum Allocation can be found in [5] [6] [7].

Allocating the spectrum dynamically initiates a market-based spectrum allocation method, as well.

a) Trading and liberalization: Creating a "market for frequencies" is a possible solution to distribute spectrum efficiently. There are two distinct policies that could be introduced separately or in combination: *trading* – the transfer of spectrum usage rights between parties in a secondary market, and *liberalization* – the relaxation of restrictions on services and technologies associated with spectrum usage rights. While trading alone allows the market to determine *who* has access to spectrum, liberalization lets the users decide *how* spectrum is used. Without liberalization, secondary market activity will be limited to transfers of existing usage rights. Without trading, liberalization will only enable existing users to switch services and technologies; alternative users would not be able to access spectrum. Introduction of both trading and liberalization could lead to more efficient use of spectrum [8].

Note, however, that trading and/or liberalization is not necessarily appropriate in all cases. For the foreseeable future, spectrum trading will co-exist alongside other spectrum management approaches.

b) Rights and obligations: Spectrum usage rights are associated with a set of *rights* (which enable the user to use spectrum in certain ways) and *obligations* (which specify conditions that users must fulfil in order to maintain their rights). Usage rights can be defined in relation to four basic parameters [8]: *geographical area* (e.g., a country, a region or a defined area around a base station), *duration and time of access* (e.g., unlimited or defined length, access to spectrum throughout the entire day, or at a specific time of day only), *spectrum block* (i.e., the frequency range to which access is granted), and *protection from interference* (i.e., the right to receive signals without harmful interference from other spectrum users and the obligation not to cause such interference).

Holders of spectrum usage rights should be free to supply any type of electronic communication service (*service neutrality*) while ensuring that interference is appropriately dealt with, and to use any technology, abiding by common conditions (*technology neutrality*) [8].

c) Interference: Spectrum users in the liberalized environment will need to be confident that neighboring users will meet their obligations, especially in regard to interference, and that their own rights will be upheld. This requirement puts the additional burden on regulators and spectrum users of coordinating new and less predictable interference relationships. As a result, more flexible approaches to interference management would be necessary. Where possible, new, technology-neutral parameters for interference management will be required for adjacent frequencies and geographical areas.

d) Targeted spectrum blocks: In order to achieve the objective, tradability would have to cover a substantial part of the spectrum. A step-by-step approach focusing on a few "test-bands" cannot provide increased competition and innovation. Offering only a limited tradable spectrum would entail the risk of anti-competitive hoarding behavior [9].

The EC proposes the introduction of markets for frequencies currently used for [9]: terrestrial mobile communication services, including public mobile services (e.g., GSM, 3G) and special user groups (e.g., PMR, PAMR); fixed wireless communication services (WLL, BWA, and microwave links); TV and radio broadcast services (local, regional and national broadcasting) and satellite (fixed and mobile).

Spectrum trades are already taking place in a number of countries worldwide (e.g., in Canada, USA, Australia, New Zealand). In recent years, many European countries (e.g., Austria, Sweden, UK) have sanctioned *de facto* transfers of usage rights between companies, even though trading was theoretically prohibited. Following the implementation of the new EU Framework Directive, all European countries now have the option to introduce secondary trading of spectrum usage rights.

The rest of the paper is organized as follows. Section II overviews the related solutions for market driven spectrum distribution proposed so far. Section III defines a spatio-temporal DSA framework that forms the basis of our proposed allocation and pricing scheme given in Section IV. Section V gives an illustrative example on the achievable gains using our proposed solution. Finally, Section VI concludes the paper.

II. Related work

The authors of [10] introduced a DSA scheme in which a spectrum manager periodically auctions short-term spectrum licenses. The spectrum manager sells spectrum at a unit price, which may be plausible in certain scenarios, e.g., when there is a large number of spectrum buyers and none has enough power to influence the market clearing price. To overcome the situation when these assumptions are violated, in [11] the spectrum manager uses second price (or Vickrey) auctions instead. While earlier works only concentrated on CDMA providers, in [12] the situation is further extended with the presence of a DVB-T network provider. The focus was on the simplest non-trivial model capturing the following issue: a 'two island' geography, in which each CDMA network has one cell per island but a single DVB-T cell covers both adjacent cells. This implies inter-cell interference issues and inter related auctions, where license to use a spectrum band over one island has no value to the DVB-T operator unless it comes with a license to use the same band over the adjacent island.

Somewhat similar questions arise in wired communication networking environment as well. Lazar and Semret introduce the Progressive Second Price (PSP) Mechanism, an iterative auction scheme that allocates bandwidth on a single communication link among users [13] (see also the extensions in [14], [15]). The allocations and prices to pay are computed based on the bids submitted by all the players. Users can modify their bids by knowing the bids submitted by the others, until an equilibrium is reached. The main drawback of this scheme is that the convergence phase can be quite long. The mechanism was modified by Delenda, who proposed in [16] a one-shot scheme: players are asked to submit their demand functions, and the auctioneer directly computes the allocations and prices to pay without any convergence phase. In [17] they suggested an intermediate mechanism, which is still one-shot, but which does not suppose any knowledge about the demand functions. They considered quasi-linear utility functions, just like in [18], but here they allowed players to submit several bids like in [19], and used an allocation and pricing scheme that is close to the one described in [16]. Unlike in the PSP mechanism, they did not suppose that players know the bids submitted by the others before bidding.

The authors of [20] proposed a distributed competition-based architecture of spectrum management based on multi-agent model, called Market Competition Dynamic Spectrum Management (MCDSM). They introduced two new concepts, namely 'spectrum trading unit' (i.e., the spectrum block is divided into small tradable slices) and 'spectrum occupied state', to propel and simplify the operation of spectrum market. To fulfill the spectrum transactions each RAN is supposed to have an intelligent Trading Proxy Agent. In the spectrum market, if some RAN can deal with its own service requirements and have some spare spectrum it can sell the extra spectrum.

Compared to the above solutions, our solution differs from the previous DSA-pricing proposals, since those solutions used 'islands geography' and did not deal with interference whereas our solution takes the interference between regions into consideration. Well elaborated proposals can be found for bandwidth-sharing in wired networks. However, these could not be used to give the optimal allocation in our case due to the specialities of dynamic spectrum allocation, but the idea of determining the cost of the allocation is based on the exclusion-compensation principle, that lies behind all second-price mechanisms.

III. Spatio-temporal DSA model

In a previous paper [21] we defined a model for Dynamic Spectrum Allocation that handles interference issues in a flexible way. A brief summary of the model is presented here as the base for our pricing mechanism proposed in Section IV.

In the proposed model we consider regions within which we assume that the spatial distribution of the spectrum demand is homogeneous, only temporal changes are allowed. (For example, assume that the spectrum demand in the business quarter of a city, in the suburban region, or on a highway changes with time only.)

Assume that the spectrum block to be distributed among all service providers, also called as Coordinated Access Band (CAB) [6], is the frequency range $(\check{s}, \hat{s})$. The whole area is divided into K non-overlapping regions (R_k). Within the given region, M network service providers (NSPs) compete for the spectrum. The spectrum block allocated to the m^{th} NSP within the k^{th} region at time t is:

$$S_{m,k}(t) = (\check{s}_{m,k}(t), \hat{s}_{m,k}(t)). \tag{1}$$

The notations emphasize that the spectrum allocation is highly dynamic, each provider can be given different spectrum blocks at different regions and different time instants. (To ease the notations, the dependence on time t is not written explicitly in the followings.) Furthermore, let $|S_{m,k}|$ denote the size of the allocated spectrum block, i.e., $|S_{m,k}| = \hat{s}_{m,k} - \check{s}_{m,k}$.

A. Interference and spectrum efficiency

In our model we take interference into account as a source for spectrum utilization degradation. "Noisy" spectrum cannot be fully utilized. First of all, spectrum utilization is decreased if the same frequency is used by different NSPs in nearby regions. The level of interference depends on the geographic location and size of the regions, as well as on the radio access technique used, the transmission power, and the positions and types of radio transmitters. This level of interference can be expressed by the *geographic coupling* parameter ε. Let $0 \leq \varepsilon_{l,k}^{(m)} \leq 1$ denote the "noise level" caused by provider m operating in region R_k that can be "heard" within region R_l. It is zero if there is no overhearing at all, and the value of one would mean that the radio transmission is heard undamped. The smaller the geometrical coupling the better from the interferences point of view.

From the NSPs point of view, the level of interference is the measure of how much their radio technology is affected by competing technologies. The level of disturbance (or jamming) between different NSP radio technologies is captured by the *radio technology coupling* parameter η. Let $0 \leq \eta_{m,n} \leq 1$ denote the coupling between the radio technologies used by the m^{th} and n^{th} NSPs. Looking at the two extremes, if the two NSPs have the same spectrum slice within the same region and $\eta_{m,n}$ is zero, NSP_n does not affect NSP_m at all, while when $\eta_{m,n}$ equals one means that the spectrum is ruined for NSP_m.

The cumulative effect of the geographic and radio technology couplings on NSP_m operating in region R_k from NSP_n in region R_l having the same spectrum is simply the product of the two factors, namely, $\varepsilon_{l,k}^{(n)} \cdot \eta_{m,n}$.

Having the appropriate model parameters to capture interference, let $\xi(S_{m,k})$ denote the *efficiency* of spectrum block $S_{m,k}$ that can be calculated as

$$\xi(S_{m,k}) = \frac{1}{|S_{m,k}|} \int_{S_{m,k}} \xi_{m,k}(\lambda)\, d\lambda, \tag{2}$$

where $\xi_{m,k}(\lambda)$ is the efficiency of frequency λ from NSP_ms point of view in region R_k, that is

$$\xi_{m,k}(\lambda) = \prod_{i=1}^{M} \prod_{j=1}^{K} \left(1 - \varepsilon_{j,k}^{(i)} \cdot \eta_{m,i} \cdot I_{\{\lambda \in S_{i,j}\}}\right). \tag{3}$$

Here $I_{\{\lambda \in S_{i,j}\}}$ indicates whether frequency λ is allocated to NSP_i in region R_j or not. The efficiency is one if no interference occurs, and less than one if there is interference with neighboring regions.

B. Feasible allocation

In our DSA scenario providers can have different capacity demands in different regions. Assume that the m^{th} provider in the k^{th} region has the capacity request $c_{m,k}$. We call an *allocation* $\mathbf{S} = (\mathbf{S}_1, \ldots, \mathbf{S}_M)$ with $\mathbf{S}_m = (S_{m,1}, \ldots, S_{m,K})$ *feasible*, if the spectrum blocks $\{S_{m,k}\}$ used by the NSPs satisfy the following conditions:

$$|S_{m,k}| \geq c_{m,k}, \quad \forall m, k\,, \tag{4}$$

$$\xi(S_{m,k}) \geq \beta_m, \quad \forall m, k, \tag{5}$$

$$\min_{\lambda \in S_{m,k}} \xi_{m,k}(\lambda) \geq \alpha_m, \quad \forall m, k. \tag{6}$$

In words, (4) makes sure that each allocated spectrum block is big enough to satisfy the NSPs capacity request. However, the real question is how the service of the NSP degrades if the allocated spectrum block for the service is "noisy", i.e., its efficiency is less than one. Thas is why conditions (5) and (6) assure that the spectrum "quality" is good enough for the given service. It can happen that robust techniques with error-prone encoding, or wideband solutions are more tolerant to noisy spectrum than others. In our model, parameters α and β try to answer this question. These two parameters can be seen as tolerance levels, i.e., to what extent the interference is tolerated by the provided service. We assume that—from the operators point of view—when the spectrum efficiency is above the tolerable limit, the service can be provided adequately. Parameter β_m gives the minimum spectrum quality that must be met *on the average* (see (5)), while parameter α_m prescribes the minimal efficiency that must be available *at all frequencies* in the allocated block (see (6)).

C. Interference tolerance

Knowing the real tolerance levels of an NSP would be a great help in the DSA framework. However, from the operators point of view, it would be much easier to say that interference is not welcome at all, "clear" spectrum block is needed to provide the service ensuring maximal user satisfaction. If all providers were intolerant to interference, then strictly disjoint spectrum blocks were needed even in neighboring (or coupled) regions everywhere. This would greatly reduce the effectiveness of DSA, and the result would look like nearly the same as the rigid spectrum allocation methodology used today. This would cause the spectrum to be more scarce, and thus *more expensive* at the end. In a DSA scenario where tolerance is much rewarded by increasing spectral efficiency, certain mechanisms need to be implemented to make it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible. A proper *pricing scheme* that charges providers who do not tolerate others and interfere to larger extent than necessary with other regions would be of great importance.

IV. Pricing scheme in the proposed DSA model

Our goal here is to propose a one-shot multi-bid pricing scheme that takes the special properties of the dynamic spectrum sharing into account. Although the progressive second price auction mechanism gives a suitable allocation for infinitely divisible resources, in case of dynamic spectrum allocation the size of the distributable spectrum cannot be explicitly determined, due to interference. It may happen that inside one region there will be carriers that cannot be distributed because of the interference arising from the neighboring regions, while other carriers can be allocated to more than one providers that do not disturb each other. This was the reason to suggest a proper pricing mechanism that satisfies the special needs of dynamic spectrum allocation and that charges providers that do not tolerate others and cause large interference to other regions.

A. Allocation and pricing rules

According to the proposed allocation scheme the spectrum is redistributed at given time intervals. Before the beginning of each time-period the providers send their multi-bids to a centralized spectrum broker entity. This entity calculates the optimal feasible allocation -based on the DSA model- that maximizes social welfare, and also calculates the costs for the providers.

Let $\mathcal{I} = \{1, \ldots, i, \ldots, I\}$ denote the set of providers. Since the demands in different regions can be different, we have to handle the providers in each region separately, i.e., $I = M \cdot K$, where M is the number of network service providers (NSPs) and K is the number of non-overlapping regions.

Provider i submits a set of $N^{(i)}$ two-dimensional bids

$$B_i = \{b_{i,1}, \ldots, b_{i,N^{(i)}}\}, \tag{7}$$

where

$$b_{i,n} = (q_{i,n}, \Theta_i(q_{i,n})), \quad n = 1, \ldots, N^{(i)}, \tag{8}$$

where q represents the quantity of the demanded resource and Θ is the total value that the provider is willing to pay for the desired quantity.

The auctioneer collects all multi-bids to form the multi-bid profile

$$B = \{B_1, \ldots, B_I\}. \tag{9}$$

This profile will be used to compute the allocation a_i and the total price charged c_i for each player $i \in \mathcal{I}$. The multi-bid profile obtained by deleting the bid of provider i is defined as

$$B^{(-i)} = \{B_1, \ldots, B_{i-1}, \emptyset, B_{i+1}, \ldots, B_I\}. \tag{10}$$

The objective of the pricing problem is to maximize the efficiency $\sum_{i \in \mathcal{I}} \Theta_i(q_{i,n})$. We note, that the measure we use for efficiency corresponds to the usual social welfare criterion (see [18]). Thus, the optimal, feasible allocation is defined as

$$\tilde{A}^f(B) = \{a_1, \ldots, a_I\}, \text{ where } a_i = q_{i,\tilde{n}_i} \tag{11}$$

and

$$(\tilde{n}_1, \ldots, \tilde{n}_I) = \arg \max_{\substack{n_1, \ldots, n_I \\ (q_{1,n_1}, \ldots, q_{I,n_I}) \in Q^f}} \{\sum_i \Theta_i(q_{i,n_i})\}, \tag{12}$$

where Q^f is the set of feasible allocations (for the feasibility conditions refer to equations (4), (5) and (6)). The feasibility conditions are checked using a Simulated Annealing process.

Similarly, we can calculate the optimal feasible allocation for the $B^{(-i)}$ profile:

$$\tilde{A}^f(B^{(-i)}) = \{a_1^{(-i)}, \ldots, a_{i-1}^{(-i)}, \emptyset, a_{i+1}^{(-i)}, \ldots, a_I^{(-i)}\}. \tag{13}$$

Each player $i \in \mathcal{I}$ is charged a total price of $c_i(B)$, where

$$c_i(B) = \sum_{\substack{j=1,\ldots,I \\ j \neq i}} \Theta_j(a_j^{(-i)}) - \Theta_j(a_j). \tag{14}$$

The intuition behind this pricing rule is an exclusion-compensation principle which lies behind all second-price mechanisms: player i pays so as to cover the "social opportunity cost", that is to say the loss of utility he imposes on all other users by his presence.

By calculating the cost based on the principle of the second-price mechanism we can ensure that a provider which does not cause much interference, and this way his presence does not impose a significant loss of utility on the other providers, will pay a lower price, whereas an "intolerant" provider which causes much interference and results a significant loss of utility for other providers will pay a considerably higher price for the spectrum.

V. Example

Consider a simple scenario with two regions as shown on figure 1. Two NSPs operate in both regions within the CAB. In region *A* there is also a DVB-T provider that covers region B, too. Furthermore, in region *B* a UWB provider is also present.

The DSA model is characterized by matrices η, ε^1, ε^2, ε^3, and ε^4 (see Table I and II). In words, matrix η shows the radio technology coupling parameters between the NSPs. Recall, that $\eta_{m,n}$ denotes the coupling between the radio technologies used by the m^{th} and n^{th} NSPs. The smaller this value, the better it is from the interferences point of view. By looking at the elements of matrix η in Table I we can see that the

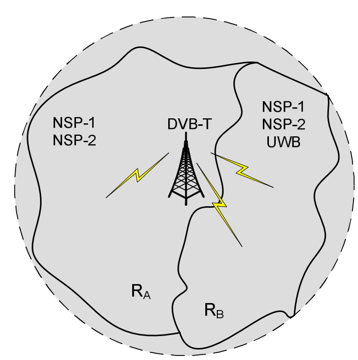

Fig. 1. Example scenario.

η	NSP-1	NSP-2	DVB-T	UWB
NSP-1	0	0.5	0.6	0.05
NSP-2	0.4	0	0.7	0.1
DVB-T	0.5	0.6	0	0.05
UWB	0.05	0.05	0.05	0

TABLE I

RADIO TECHNOLOGY COUPLING PARAMETERS $\eta_{m,n}$.

$\varepsilon^{(1)}$	R_A	R_B
R_A	1	0.2
R_B	0.2	1

$\varepsilon^{(2)}$	R_A	R_B
R_A	1	0.3
R_B	0.3	1

$\varepsilon^{(3)}$	R_A	R_B
R_A	1	1
R_B	1	1

$\varepsilon^{(4)}$	R_A	R_B
R_A	1	0
R_B	0	1

TABLE II

GEOGRAPHIC COUPLING PARAMETERS $\varepsilon^{(m)}$.

radio technology used by the UWB provider does not affect, and is not affected significantly by other providers ($\eta << 1$). Therefore we expect it to pay a low amount according to the pricing rules.

Table II shows the geographic coupling parameters between the regions. Recall, that $\varepsilon_{l,k}^{(m)}$ denotes the "noise level" caused by provider m operating in region R_k that can be "heard" within region R_l. By looking at the elements of matrix ε^4 we can see a strong coupling ($\varepsilon \approx 1$) between the regions ensuring the DVB-T provider to cover both regions. It has also a low tolerance level (see Table III for the interference tolerance parameters; $\alpha \approx 1$ and $\beta \approx 1$) so we expect it to pay a high amount for the exclusive use of the allocated spectrum block.

Table IV lists the multi-bids of the providers.

The optimal allocation and the total costs of the providers was calculated based on the allocation and pricing rules described in section IV. A simulation tool was developed using Matlab to calculate the optimal values. The feasibility check of the solution is based on a Simulated Annealing process. Table V shows the optimal feasible allocation and the costs of the providers.

The third column of the table shows the average cost of one spectrum unit for each provider.

Just as we have expected, the DVB-T provider pays far the most from among the providers, since it covers both regions and its level of tolerance is low.

Similarly, we can see that the cost assigned to the UWB provider in Table V is zero, since it does not interfere with the other providers. The zero cost can mean for example, that this provider does not have to pay any additional cost over the base spectrum unit price.

We also note, that the geographical coupling of NSP-1 is less than that of NSP-2, meaning that it causes less interference than the other, henceforth the unit price is also smaller than for NSP-2.

	NSP-1	NSP-2	DVB-T	UWB
α	0.5	0.7	0.95	0.5
β	0.9	0.95	0.975	0.8

TABLE III

AVERAGE (β_m) AND MAXIMUM (α_m) INTERFERENCE TOLERANCE PARAMETERS.

B_1 : NSP-1 (R_A)

q	0	25	30
Θ	0	75	85

B_2 : NSP-2 (R_A)

q	0	10	25
Θ	0	30	45

B_3 : DVB-T (R_A)

q	0	5	10
Θ	0	25	35

B_4 : NSP-1 (R_B)

q	0	20	30
Θ	0	40	50

B_5 : NSP-2 (R_B)

q	0	15	20
Θ	0	45	55

B_6 : UWB (R_B)

q	0	20
Θ	0	20

TABLE IV

MULTI-BIDS

	q	c	c/q
NSP-1 (R_A)	25	15	0.6
NSP-2 (R_A)	10	10	1
DVB-T (R_A)	5	20	4
NSP-1 (R_B)	20	10	0.5
NSP-2 (R_B)	15	10	0.6
UWB (R_B)	20	0	0

TABLE V

OPTIMAL ALLOCATION AND THE COSTS OF THE PROVIDERS.

VI. CONCLUSION

A market-driven Dynamic Spectrum Allocation (DSA) framework is a promising new approach to increase the usage efficiency of radio spectrum. In this paper we proposed an auction and pricing method that can be used to distribute spectrum usage rights among competing radio network service providers (NSPs). The outlined solution is a one-shot multi-bid auction method, based on our spatio-temporal DSA framework [21] that takes into account interference issues in a flexible way. The suggested pricing mechanism satisfies the special needs of DSA, and charges providers that do not tolerate others, and cause heavy interference to other regions. The intuition behind this rule is that a particular user pays so as to cover the loss of utility he imposes on others by his presence.

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