General distributed economic framework for dynamic spectrum allocation

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We present our novel dynamic spectrum sharing management scheme in which the allocation and the pricing of radio frequency bands are performed in a distributed manner. We focus on a non-cooperative setting where the frequency leasers act for their own benefit, and we design the system policies in order to assure that the resulted allocation yields high spectrum utilization. We provide scalable and incentive-compatible allocation and pricing mechanisms on our physical radio interference model. Our evaluations prove that our distributed dynamic spectrum allocation scheme imposes high charges on frequency leasers that exclude others by their presence in terms of interference; therefore it is a suitable approach to reach efficient and flexible spectrum utilization.

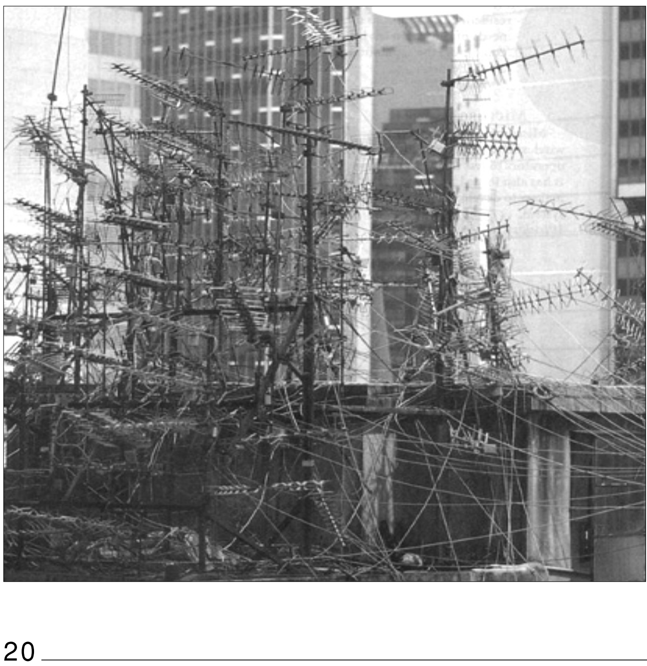
1. Introduction

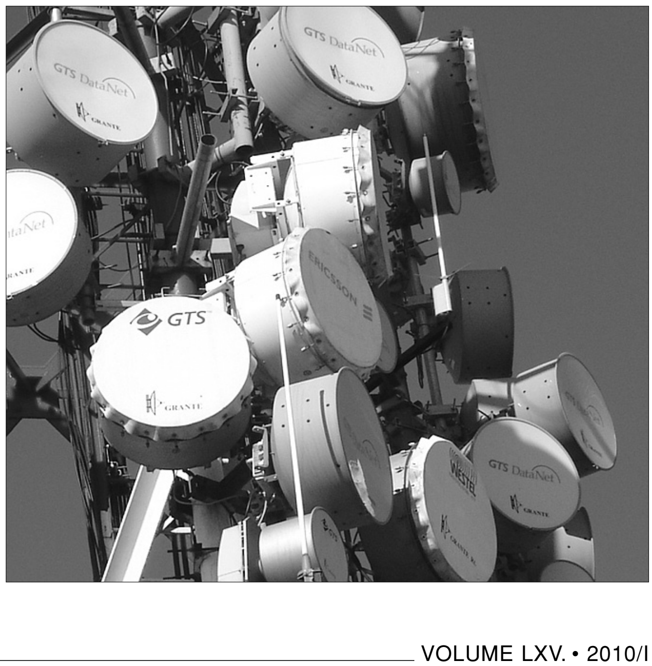
Actual radio spectrum allocation is not efficient due to rigid regulation: it is access-limited (i.e., big player syndrome), and peak traffic planning and spectral re-usage restrictions cause temporal and spatial under-utilization since spectrum demands vary in time and space. Therefore the current radio spectrum allocation regulation results in sub-optimal spectrum utilization, and excludes many potential frequency exploitation opportunities. While new generation radio interfaces support flexible transmission frequencies and the convergence of telecommunications services makes actual restrictions seem out of date, recently presented dynamic spectrum allocation (DSA) solutions also lack the consideration of some key issues.

Bounding interactions among frequency leasers (e.g., noise, interference) must be taken into account with the required emphasis reflecting realistic relations, and the management framework must fulfill the basic requirements of general distribution of limited resources. We propose a distributed spectrum management framework to allocate frequencies for Wireless Service Providers (WSPs) dynamically with the goal of improving the efficiency of frequency utilization: we make the case of spatio-temporal DSA.

We build a self-organizing scheme in which the participants manage the allocation and pricing of spectrum, and the central authority only enforces our policies. The result is efficient frequency utilization while inciting the deployment of interference-tolerant technologies. Our framework takes into account the selfishness of WSPs (in the game theoretic sense) and provides a scalable allocation method.

We apply game-theoretic modeling to reflect WSP selfishness, and we build the mechanism design with





the goal of assuring desirable properties of allocating limited resources among participants. Our basic principles are the following: the overall spectrum utilization should be maximal, and in case of “conflict of interest” the frequency bands are allocated to those who “value” it the most.

2. Related work

In this section we direct the focus on papers that study the allocation and pricing aspects of DSA from the important body of research considering the management of DSA systems.

The seminal paper of Buddhikot [1] initiated a sequence of papers focusing on allocation and pricing. Their models assume a central spectrum broker that allocates spectrum licenses for short leasing times, and introduce the notion of interference *conflict graph*. The authors provide linear programming formulation of the spectrum allocation with feasibility constraints: maximal service vs. minimal interference, maximal broker revenue vs. max-min fairness. In [9] fast heuristic algorithms are proposed to perform the broker’s central allocation by optimizing these metrics. The same authors give a general bidding framework in [8], where the broker strives to maximize its revenue.

Zheng’s [2] introduces distributed algorithms to allocate spectrum by local coordination and collaborative sharing among users: selfishness is not taken into account. In [4] they switch to an auction-based allocation scheme in which the objective is maximizing the revenue. Their work in [12] highlights the weaknesses of the widely-employed interference modeling by pairwise conflict graph, and they show how to derive the latter from physical interference models. Zheng et al. return to auction-theory by proposing to implement the Vickrey-Clarke-Groves (VCG) mechanism [11,3,5] for spectrum allocation in [13].

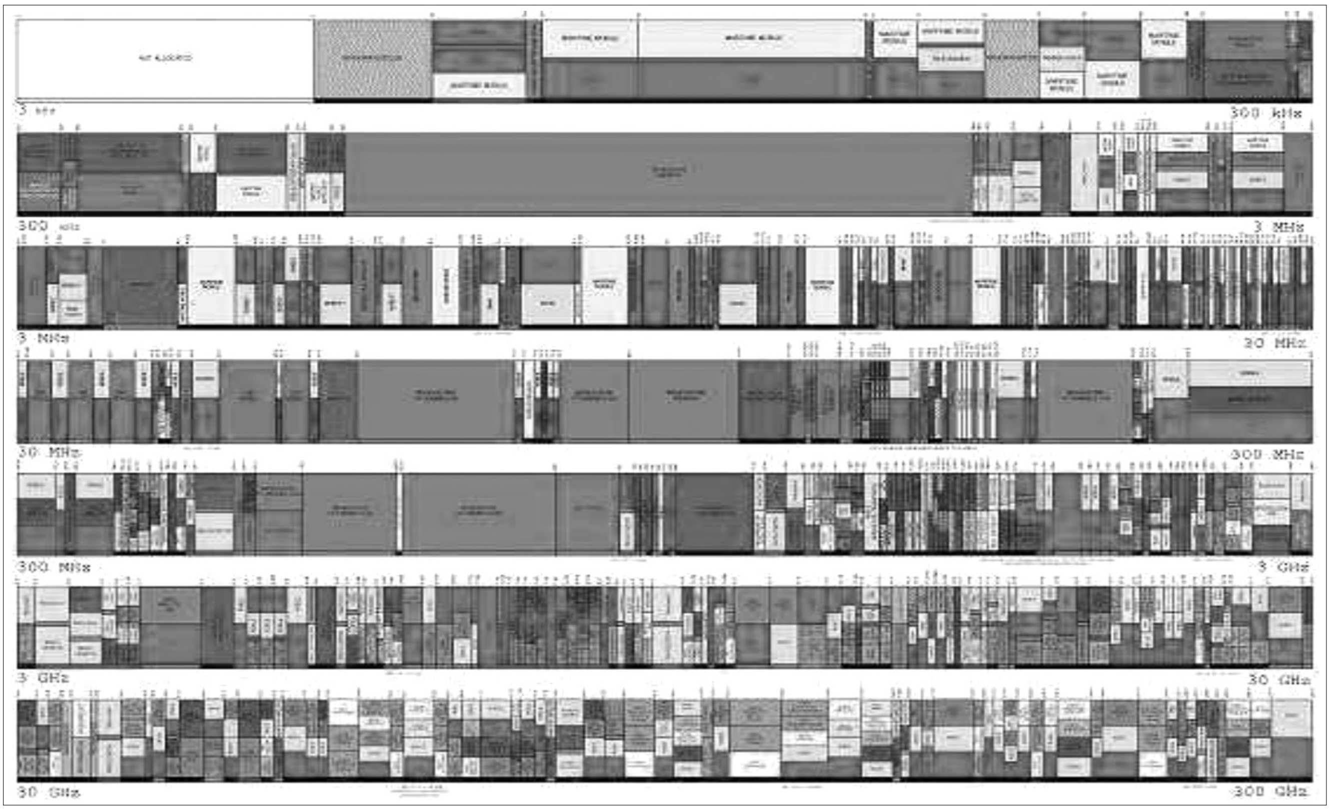
The DSA system presented in [6] also performs allocation and pricing by VCG mechanism. The authors propose a general spatio-temporal model with physical interference modeling. Frequency leasers participate in one-shot multi-bid auctions and obtain frequency usage rights for prices that maximize broker revenue or social welfare.

3. Spectrum allocation model

In our allocation framework the fairness receives new connotation, i.e., unlike the max-min fairness presented in [1,2] that assures a bit of the spectrum for every participant, in our model the one who can pay more gets the frequency band. This approach yields fairness towards the spectrum band itself because this latter is going to be exploited by the highest added utility-providing leaser. In this section we review our model’s details: first, we present a simple way to describe participants’ economic perception linked to spectrum usage, second, we argue on a general interference model, and at last our allocation and pricing schemes are introduced.

3.1 Node description

Our model’s system participants are the possible frequency leasers that exploit radio bands within delimit-



able geographic zones, practically base stations of WSPs, called nodes. We model each node by its frequency band demand and its utility that describes its willingness to pay for acquired frequency shares. The utility is based on discount estimated incomes from the node's services. In order to model interference tolerance, we also define the "bearable" interference level for each node, i.e., the maximum cumulative interference level that the node can tolerate. Interference may occur if the same frequency is also used by other nodes, and it is defined as the maximal measured interference on the node's operating area. Details on interference are discussed in the next section.

3.2 Interference model

As the majority of related work, we assume that the radio spectrum can be divided into small, non-overlapping, homogeneous spectrum bands with pre-defined sizes. Our general physical model considers point-to-point signal attenuation formulas to take spatial and transmitting power parameters into account in order to establish the interference values among nodes (i.e., measured signal-to-interference-and-noise ratio). The central authority controls the applied radio technologies (e.g., coding), the types of radio transmitters and transmitting power levels of nodes. We refer the reader to [6] for more details on the physical interpretation of interference aspects.

Many prior works model inter-node coupling by conflict graph where nodes represent the frequency leaser base stations, and an edge exists between two given nodes if they cannot utilize the same frequency band without facing serious performance diminution due to high interference. This approach has been shown to have important drawbacks: as [12] argues, it is unable to model aggregated (cumulative) interference, moreover [6] reasons on the asymmetric nature of interference. With physical interference model, however, significant complexity is reached when optimizing spectrum allocation, which calls for scalable distributed DSA.

3.3 Distributed spectrum allocation and pricing

Distributing spectrum is harder than dividing other goods, mainly because of interference and tolerance. We introduce the notion of one-way buy-outs among nodes: if necessary because of inter-node jamming, disturbing leaser nodes can be excluded by disturbed nodes. The buy-outs are performed via auctions: nodes place bids for required frequency bands, and can bid against any actual license holder if inter-node interference overgrows their bearable limits. If multiple bidders are present for the same frequency band, a second-price (or Vickrey) auction is carried out, i.e., the highest bidder wins and pays the second bid. After nodes have made their bids to acquire necessary licenses, the winner's "second price" is divided between the former leaser and the authority.

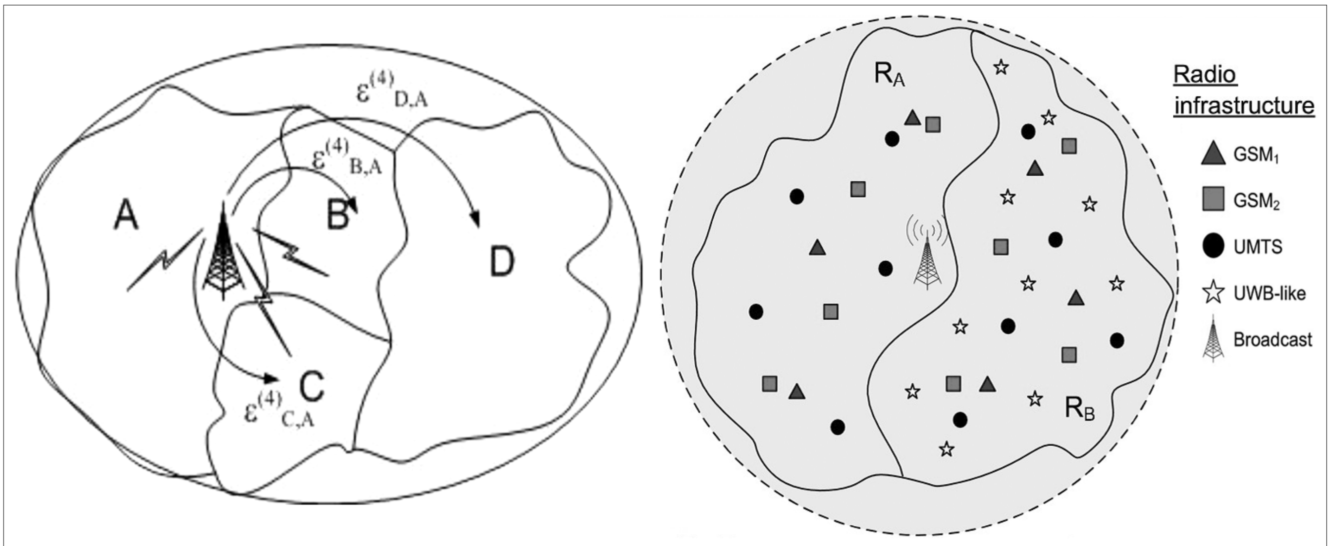
Two different types of spectrum allocation might occur:

Seamless: if a new node demands the use of a given frequency band on which its perceived interference is low, and it would not cause too much interference to other nodes. In this case, the node acquires the right to exploit the frequency, and does not have to pay anything in order to use the frequency.

Exclusive: at any allocation, if the interference experienced by any node is/becomes too high, then the disturbed node may buy out the node that causes (a part of) the interference. Exclusion happens in the form of a second-price auction: the buyer pays the second highest bid, the positive difference between the winner bid and the excluded node's prior payment, if any, is paid to the authority and the rest compensates the excluded node. Any node may voluntarily leave the spectrum by auctioning its actually leased spectrum band: the price of the frequency band is set among the bidders.

3.4 Distributed algorithm

We assume that nodes are autonomous and selfish, thus they try to maximize their payoffs. The payoff is, by definition, the *realized* valuation of the spectrum (the



difference of incomes and expenses), therefore selfish nodes strive to allocate the required size and quality frequency bands for the minimal occurring cost. The cost one might need to cover is due to the price of exclusion of other, interfering nodes. As the number of other nodes, that need to be excluded, grows, the cost increases as well.

In our algorithm, nodes perform two optimization steps *iteratively* until stable allocation is reached. At first, each node checks its allocated frequency band's size and the incurred interference against its demand and tolerance levels respectively. If no inconvenience is found, the current allocation is held. Otherwise, it positions its frequency band on the spectrum, so that, first, re-buying frequencies at which it has been previously excluded would cost the least possible, and second, the cost of exclusion of other nodes to assure that interference is kept below the required level would be minimal. Therefore the selfish strategy of each node is to buy out the cheapest interfering player set possible to assure own service quality at the cheapest frequency band.

Finding the optimal allocation of spectrum centrally is an NP hard problem in general. The main reason for this complexity is interference, therefore many approaches introduce simplifying models and apply heuristics. In our framework the allocation is optimized in a distributed way. For a brute-force exhaustive search, the algorithm requires a node to evaluate $|F|^* \exp(|G|)$ values, where F stands for the number of frequency unit bands in the spectrum, and $|G|$ denotes the cardinality of the group consisting such nodes that cause interference to it. Restricting the focus only to those nodes that cause significant interference, the algorithm complexity drops, however, we applied heuristics (greedy, simulated annealing, etc. optimization to find the cheapest band, conform to demand, with the cheapest necessary buyouts) in our simulations in order to further accelerate the algorithm.

4. Evaluation of distributed DSA

In this section we discuss the advantageous properties of the DDSA framework.

Our pricing rules incite truthful bidding of selfish nodes, i.e., nodes report their true utilities when bidding for spectrum in DDSA [10]. The well-known truthfulness property of Vickrey auctions makes bidding true utilities to be bidders' dominant strategies. A more detailed proof of incentive compatibility and truthful bidding in second-price auctions is shown in [7].

The DDSA framework supports the fairness idea behind VCG mechanisms in terms of efficient pricing. An interference-friendly node, that has high interference tolerance level and causes little interference to others, pays relatively less for the spectrum [10]. The implication of our valuation based allocation and pricing framework is that the iteration of re-allocations assures fairness despite the fact that exclusions are only unidirectional. Those nodes that cause important interference must hold high valuation because interfered nodes try to buy them out by engaging in auctions for the disturbing nodes' spectrum bands: service providers that cause high interference are punished with high costs. Also, this approach leads to an efficient spectrum allocation, where frequency bands are allocated to the most valuable leasers at the highest possible price.

Our distributed design makes the system more flexible in terms of possible re-allocation of spectrum at any time without a centrally announced or periodical auction. Furthermore, no central intelligence is needed for computing allocation and prices.

Generally, when selfish nodes' decisions drive the system, the outcome is suboptimal compared to the result of a central allocation based on full information. Since in numeric evaluations we arrived at similar outcomes (for simple simulations) to those of applying central DSA, but much faster, the distributed optimization seems efficient and scalable.

5. Conclusions

We proposed a general distributed DSA framework that offers a distributed mechanism design, well suited to practical employment issues. The applied model handles interference effects without any restricting assumptions. Through game theoretic modeling and mechanism design, we put the emphasis on the economic perspective.

We proposed distributed allocation and pricing schemes, and heuristic algorithms that provide scalable, efficient and incentive-compatible spectrum allocation.

Authors

LÁSZLÓ TOKA graduated in 2007 at Budapest University of Technology and Economics and received his MSc degree in Telecommunications on the Faculty of Electrical Engineering and Informatics. He also obtained the engineer diploma of Telecom Bretagne and Eurecom in France. He participated in the pre-doctoral education courses of the Networks and Distributed Systems Department at the University of Nice Sophia-Antipolis and received a research master degree. After graduating he enrolled as a PhD candidate at Telecom Paris and at Budapest University of Technology and Economics. His research domain is around economic modeling of distributed IT systems and networks.

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References

[1] M.M. Buddhikot, K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks", In Proc. of First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 8-11 November 2005, Baltimore, MD, USA, pp.299–307.

[2] L. Cao, H. Zheng, "Distributed spectrum allocation via local bargaining", In Proc. of Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON), 26-29 September 2005, Santa Clara, CA, USA, pp.475–486.

[3] E.H. Clarke, Multipart pricing of public goods. Public Choice, 11(1), September 1971.

[4] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, S. Suri, "A general framework for wireless spectrum auctions" In DySPAN, 17-20 April 2007, Dublin, Ireland, pp.22–33.

[5] T. Groves, Incentives in teams. Econometrica, 41(4):617–631, 1973.

[6] L. Kovács, A. Vidács, B. Héder, Spectrum auction and pricing in dynamic spectrum allocation networks. The Mediterranean Journal of Computers and Networks, Special issue on Recent Advances in Heterogeneous Cognitive Wireless Networks, 4(3):125–138, 2008.

[7] S. Sengupta, M. Chatterjee, S. Ganguly, An economic framework for spectrum allocation and service pricing with competitive wireless service providers. In DySPAN, 2007.

[8] A.P. Subramanian, M. Al-Ayyoub, H. Gupta, S.R. Das, M.M. Buddhikot, Near-optimal dynamic spectrum allocation in cellular networks. In DySPAN, 2008.

[9] A.P. Subramanian, H. Gupta, S.R. Das, M.M. Buddhikot, Fast spectrum allocation in coordinated dynamic spectrum access based cellular networks. In DySPAN, 2007.

[10] L. Toka, A. Vidács, Distributed Dynamic Spectrum Management, In 32nd International Conference of Telecommunications and Signal Processing, 2009.

[11] W. Vickrey, Counterspeculation, auctions, and competitive sealed tenders. The Journal of Finance, 16(1):8–37, 1961.

[12] L. Yang, L. Cao, H. Zheng, Physical interference driven dynamic spectrum management. In DySPAN, 2008.

[13] X. Zhou, S. Gandhi, S. Suri, H. Zheng, eBay in the sky: Strategy-proof wireless spectrum auctions. In ACM MobiCom, 2008.