Dynamic valuation function based definition of the primary spectrum user in collocated cellular networks

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***Abstract*—We propose to use generalization of a second price VCG auction to dynamically allocate shared radio resources among collocated, equally prioritized mobile network operators in multi carrier HSDPA cellular network. The spectrum usage priority will be dynamically decided based on the comparison of individual valuation functions, used as an input for the spectrum auctioning game. After theoretical introduction to the game theory, we demonstrate that short term auction based spectrum sharing provides spectrum utilization gains for coalition of MNO's having un-equall cell specific traffic loads, allowing network operators to secure their business and at the same time, open new market possibilities with additional revenue opportunities.**

Keywords: Auctions, valuation function, spectrum broker, spectrum trading, spectrum sharing, primary user, game theory, VCG, HSDPA

I. INTRODUCTION

Spectrum resources sharing, as well as its flexible realization of dynamic spectrum access, has become very popular research topic, not only due to its research potential, but also due to the increasing market interest in larger revenues for Mobile Network Operators (MNO), as well as from regulatory and policy makers point of view, where the main interest is in increasing end-user satisfaction and in improving the spectrum utilization [1], [2], [3]. With the rapid growth in the number of mobile terminals, constantly increasing demands for the mobile services generated data rates, the limitation of spectrum allocation is becoming bottleneck for many cellular network operators. Therefore, physical radio resources sharing has been widely considered for the future of wireless communications, both to overcome the scarcity of spectrum as well as to decrease Operational Expenses (OPEX) of cellular networks.

Spectrum sharing permits the network operators to tune their radio resources allocation dynamically, according to varying traffic demand. In addition, sharing network elements reduces the cost of acquisition and maintenance of the network per operator [4], [6]. Based on these principles, we are making an attempt to model cellular network radio access, considering *conditional and opportunistic access* to the shared radio resources, where the condition is formulated based on the game theory driven principles of valuation functions. This approach is seen as one of solutions, to avoid channel sensing complications of the cognitive radio and an attempt to allow more flexible spectrum usage in cellular networks, allowing dynamic declaration of the primary and secondary spectrum usage based on the subscribers demands.

In this context, different resource sharing solutions, utilizing auctioning concepts have been proposed in the literature. In [17] two auction mechanisms for allocating the received power were proposed. The first was an auction in which users were charged for the received SINR, which, when combined with logarithmic utilities, lead to a weighted max-min fair SINR allocation. The second was an auction in which users were charged for power, which maximized the total utility when the bandwidth was large enough and the receivers were co-located. Both cases were motivated by the scenario in which users wish to purchase a local, short-term data service. In our approach we provide a solution, which requires much less information exchange between auction players, than the concepts mentioned above. We propose to use Vikrey, Clarke and Groves (VCG) mechanism (generalized from the *second price auction* concept) for equal value, multi-unit auctions in the context of radio resource allocation for cellular networks. VCG mechanism is a standard concept in Algorithmic Game Theory and its main advantage is the combination of two properties: maximization of *social value* and *incentive compatibility*. Incentive compatibility ensures that participants do not gain by bidding different than their true valuations, and hence we will refer to bids as valuations of resources submitted to the auctioneer. Our auction-based mechanism can be seen as a compromise between two approaches:

- to jointly schedule the total traffic from all service providers involved in auctions (maximizing radio resources utilization), or
- to have orthogonal radio resources dedicated to each operator for his exclusive usage (no information exchange required).

For that, we introduce a third party virtual *Auctioning Unit* (AU), responsible for regulating the usage/pricing of the radio resources based on received operators valuations.

The paper is organized as follows. First we describe standard features of the VCG mechanisms which were used as the engine for the spectrum resources distribution, in Section II. Section III is dedicated to the utility functions, which were

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used as the decision criteria for the primary user definition, among participating, concurrent parties. Finally, system level simulation results are presented in Section VI, based on the model described in Section IV and V.

II. VCG MECHANISMS

Vikrey, Clarke and Groves, proposed in a series of papers a class of mechanisms for distributing goods to users. The common feature of these mechanisms is that they produce socially optimal distributions, at the same time remaining incentive compatible [12], [13], [14], [8].

Intuitively, the way to obtain incentive compatibility is to charge each user i the amount by which the other users suffer from i being in the system. In this construction, the payment of i does not directly depend on his submitted valuation (for the goods to be distributed), but on the valuations of other users and the distribution itself.

Consider a game played by m players interested in n identical goods. Each single player i has his utility from obtaining a certain amount of these goods. Let $[n]$ be a shorthand for $\{1, 2, \ldots, n\}$. Each player submits a function $V_i : [n] \rightarrow R$ called valuation to the auctioneer, which assigns goods to players based on their valuations and computes payments. We will assume the utilities and therefore also the submitted functions are submodular, that is the profit from having one more good decreases with the number of goods already obtained.

The main objective of the auctioneer is to maximize the utilization of the goods (social value maximization) and therefore he attempts to assign goods so that the total utility is maximized. The following simple VCG mechanism is known for having this property.

For each player $p_i \in P$ define $P^{-p_i} = P \setminus \{p_i\}$ to be the set of all players except p_i.

For any subset of players $S \subset P$, we define an assignment of n goods to S to be a function $f : S- > [n]$ such that $\sum_{p \in S} f(p) \leq n$, i.e., such that the total number of assigned goods is at most the number of available goods n. Given an assignment f we define its *social value* to be the total value the players get from the goods assigned to them in the assignment f. More formally, the social value of an assignment f is denoted by $Val(f, S) = \sum_{o_i \in S} U_i(f(o_i))$, i.e. the total utility of players given assignment f.

Observe, that given the utilities of the players it is trivial to calculate $Val(f, S)$, moreover given the utility functions one may find the social value optimizing allocation by running a simple greedy algorithm. This algorithm looks at the marginal profits of obtaining one more good, and considering goods one by one, allocates the next good to the player whose marginal utility is the highest. The crux of the VCG method lies in revealing the utilities to the auctioneer. One argues that if the prices charged to the players are carefully chosen, players will have no incentive in submitting bids, different then their valuations. Intuitively the users have to pay for the damage they make to the others. We will now specify the payments in more details.

Consider the total profit a group of players $S \subset P$ may make from using n goods. We call this maximal total profit the n-goods value of the set S, and we denote it by $Val_n(S) = max_{n\text{-goods assignment } f} Val(f, S)$.

The mechanism is defined as follows:

- Distribute goods according to an assignment f^* of n goods that maximizes $Val(f, P)$,
- Charge each player p_i the amount of money equal $Val_n(P^{-p_i}) - Val_{n-f^*(p_i)}(P^{-p_i})$, i.e. the amount by which the total value for the other players gets worse because of p_i using his $f^*(p_i)$ goods.

The charge may simply be computed by repeatedly applying the greedy algorithm to the setting with one player removed. Such computation would require $2m$ runs of the greedy procedure and would then require roughly quadratic time. Note however, that one may compute the valuations all together by considering a sorted sequence of merged marginal valuations of the different players.

Assuming the submitted valuations of the players are truthful, the computed assignment of goods is by definition the one that maximizes the total profit of the players. It remains to argue that no player has any incentive to declare valuation different from his true valuation, associated with his utility. This property of the mechanism called incentive compatibility is the focus of game theory. It is known that VCG mechanism are essentially the only possibility for truthful auctions [8].

Application of a VCG mechanism is only possible if the underlying (social value) optimization problem is computationally easy. We may obtain this by assuming that the distributed goods are of the same value and that the players' valuation functions are submodular. Not only it is an acceptable restriction from the application perspective, it is also vital for the construction of the mechanism.

By allowing valuations that are not submodular the optimization problem becomes NP-hard, which may be shown by a reduction from the Knapsack problem. For auctions with heterogeneous goods, still assuming submodular valuations, the joint utility optimization can only be approximated with $(1 + 1/e)$ factor [9] without the incentive compatibility property, and with a logarithmic factor by an incentive compatible mechanism [10]. In case of heterogeneous goods and non-submodular valuations the problem becomes $\sqrt{n}$ hard to approximate [11] even without incentive compatibility.

III. APPLICATION TO SPECTRUM DISTRIBUTION AND UTILITY FUNCTIONS

The main requirement for the players to participate in the described mechanism is to estimate their demand for goods and to quantify this demand in terms of money they are willing to pay for each granted good's unit. As we believe, only the player himself can estimate the utility of goods, his utility is not directly known to the mechanism. The only information the mechanism has is the valuation reported by the player. The calculation of utility functions may consider different factors and it's completely subjected to the players' judgment. For the operators to participate in the auction they have to decide, depending on their policies for traffic and user prioritization, QoS and environmental conditions, how important it is for them to succeed in transferring a certain portion of data.

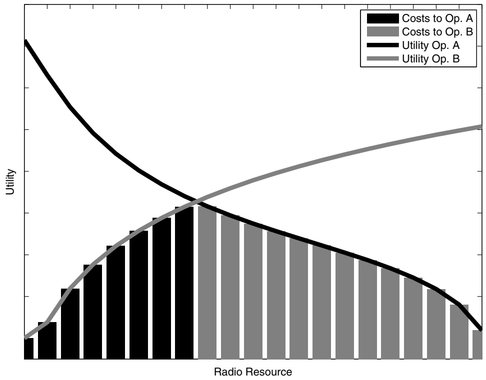

Figure 1. Example realization of cell specific resource distribution based on the valuation functions for 2 operators. The split of resources is on the intersection of the valuation curves.

We believe that a fairly accurate estimation can be computed for short time horizons (within range of seconds) where the number of active connections is not expected to vary too much and the traffic profiles can be recognized.

A. Realization of example valuation

One of the determining factors in the calculation of the valuation function is the amount of data to be transmitted in the next period of time Δ. Therefore, an easy way of determining the valuation would be a ratio between the amount of buffered data and the number of resources. Assuming Q_k to be the pending cell specific data to be transmitted by operator k its valuation for getting x resources could be given by:

$$U_k(x) = \alpha \sum_{i=1}^{x} \frac{Q_k}{i} = \alpha Q_k \cdot H_x \approx \alpha Q_k \cdot ln(x), \qquad (1)$$

where α represents a scaling constant to convert the values into realistic price, and H_i is the i-th harmonic number. NOTE: This function is closely related to proportional fairness scheduling rules.

If all players calculate their valuations this way, the resources will be distributed proportionally to the current Q_k values. Moreover, each operator o_k has the guaranty that the total paid fee will be at most αQ_k, even if the other players decide to use different valuation methodologies.

IV. ANALYTICAL MODEL

Consider two network operators who are interested in providing mobile services, using a particular Radio Access Technology (RAT), over the same geographical area which is typical in case of highly populated locations. We assume these operators have collocated Base Stations (BS), which is a reasonable assumption since this approach is already widely applied in the market for the network cost reductions[7]. Such model is not typical cognitive radio model, as both network operators are considered as primary users at the initial phase - we rather investigate, whether each of them is utilizing its own spectrum resources in the optimal way. Furthermore, this does not mean that the modeled concept is to punish the less loaded or under-utilized network operator, as the described carriers auctioning is, or can be, based on the money flows being a compensation for the potentially non-served load in the donor's network.

The described spectrum auctions do not introduce any limitations to the players set. However, from the practical consideration as well as for the simplification purposes, two co-siting operators are considered as sufficient for the presented performance analysis.

The spectrum available for the auctioning game will be merged into a single pool of HSPA carriers, which will be available at each cell, and can be used by any operator in TDMA mode, depending on the auction outcomes in each cell. In case of non-shared carriers, frequency reuse 1 was considered.

The decision of which of the pooled and shared resources are to be used by each operator for particular time period Δ is taken by the AU and its decision will be valid for a time period of duration Δ, after which the *Auctioning Process* (AP) must be repeated and new resources allocation scheme shall be provided. At each time interval, operators calculate their valuations for resources in the next interval. Valuation information is forwarded to the cell specific AU unit. The AU's decisions will be made based on submitted valuations.

A valuation is a function that encodes the amount of profit a particular operator expects from using a certain number of resources in the next time period. How to optimally calculate such function is not obvious and may differ from operator to operator. However, we show that already the simple valuations from Section III A lead to substantial spectrum utilization gains.

NOTE: Proposed auction-based spectrum sharing can be seen as a RAT independent solution, as far as regulators and the specification allow certain frequency band to be used by other RAT's. For the purpose of this analysis, single RAT was selected for performance evaluation. Inter-RAT evaluation is out of scope of this paper.

V. SYSTEM LEVEL NETWORK MODEL

System model consists of 19 3-sectorized, homogeneous cells in wrap around configuration. We assume, that two MNO operators who are willing to participate in the auction based spectrum sharing, are co-sited, providing coverage over the same geographical area and serve their own subscribers only (i.e. national roaming disabled). UE locations were generated randomly.

Assumed co-located BS' enforcement might be seen as a limitation from the network planning perspective, but on the

Parameter	Value and comment
Network layout	Hexagonal grid, 19 sites/57 sectors
Wrap around	Yes
Network operators	Two operators, co-sited
Spectrum auctions setup	Auctions running in all cells
Inter site distance	500 m
Terminal distribution	Random UE locations in all cells
Cell Isolation	0 dB
Carrier frequency	2 GHz
RAT	MC-HSDPA
Number of bands	1
BS antenna configuration	3 sector
Antenna beamwidth	70 deg
Antenna Front To Back ratio	20 dB
NodeB antenna gain	14 dBi
NodeB Tx power	43 dBm
Minimum UE to BS distance	35 m
Propagation model	128.1 + 37.6log10(R); R [km]
Shadow fading	8 dB
Shadowing correlation	1 between sectors, 0.5 between sites
Penetration loss	0 dB – indoor scenario not considered
Thermal noise level	-102.9 dBm
Channel model	PedA 3 km/h
Fading across carriers	Uncorrelated
Simulation duration	10 sec.
Traffic	Bursty traffic
Scheduler	Proportional Fair

Table I
SELECTED SYSTEM LEVEL PARAMETERS

other hand, it opens the possibility to re-use the RF components from the other auction player's infrastructure, which might be a serious advantage in many cases. Moreover, there will be need to exchange certain amount of auctioning-related control information - BS co-location might ease practical realization of such information flow. Detailed solution, as well as standardization related analysis, is out of scope of this paper. In the Table I, more details on the system level model were provided.

A. Spectrum resources consideration

Spectrum resources allowed to be used by the AU in auctions were proposed to be pooled in one set, as it was described in Section IV. The most straight forward use-case, would be to have (at least) two collocated operators, who are willing to allow certain percentage of their spectrum (expressed in the number of HSPA carriers in this case) for auctioning purposes. It shall be kept in mind, that auctioned carriers (AUC) can be accessed by any of the auction participants, under the TDMA sharing principles. This kind of the spectrum sharing scheme is also called orthogonal spectrum sharing [15]. Furthermore, we assume that licensed bands are considered for described scenarios and all auction players have equal (or, proportional to the amount of shared radio resources) priorities in accessing AUC carriers. For sake of simplicity, we have assumed that each of the operators have deployed Multi Carrier HSDPA network and each of them agreed to assign number of owned HSPA carrier for the auctioning pool. As we assume that the available channels are of identical value, the decision to be made is the number of channels to be allocated to each of the operators. NOTE: The radio resources to be pooled for the auctioning purposes might be also provided by third party player, e.g. broadband wireless provider.

Parameter	Value
Number of packets per burst	10
Packet arrival rate	0.1 sec.
Burst size	Variable
Packet size within burst	Fixed
UE's per cell	10

Table II
TRAFFIC MODEL PARAMETERS

B. Traffic Model

It is important to note that the resources sharing scenario is meaningful only in case of highly loaded networks, or in other words, in case of capacity limited networks. From practical point of view: no MNO is expected to ask for additional spectrum resources, in case when the currently owned spectrum resources are sufficient for smooth operation of particular network. For that reason, traffic model is seen as crucial aspect in the presented analysis due to the fact, that the used valuation function was simply modeled as the cell specific data buffer size for each of operators (i.e. bids for the multi-unit auctioning purposes were modeled by the variable cell load and proportional fairness). Therefore, it was expected, that the operator with highly loaded network is going to use the shared resources more frequent than the other operator.

Aspects of the equal traffic model among auction participants were investigated in [18], also considering various spectrum exchange algorithms in HSPA and LTE network. Orthogonally modeled traffic arrival was proposed in [16]. In this paper, we evaluate HSPA system performance by considering a more realistic, partially correlated load balance among two operators, introducing tolerance on top of the reference offered cell load in order to generate operator specific load. For that purpose, tolerance of ±10 and ±50 were selected to be used in the simulations. The smaller value was selected to simulate the sharing performance among two comparable operators. The second case was defined for less uniform market situation, e.g. MNO's focusing on certain subscriber's classes. Traffic model was based on the operator's specific demands, being defined based on the packet burst size. Number of the active subscribers using data services was fixed and constant for both operators in all sectors.

VI. SIMULATION RESULTS

In this section we present and analyze simulation results based on the system model as described above, focusing on the total goodput (application level throughput, not accounting the retransmissions and overheads) figures for both evaluated MNO's, i.e. not considering individual operator's gains and pains coming from the discussed solution, which were described in [18]. In the first step, we look at the throughput 50%-tile comparison for three scenarios, where only one carrier was released by each auction player to be pooled for

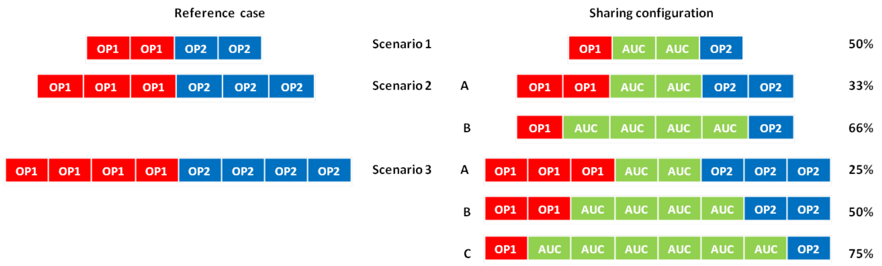

Figure 2. Carrier allocation scheme and shared carriers percentage; OP1: Operator1 only, OP2: Operator2 only, AUC: Auctioned carriers – Operator1 or Operator2

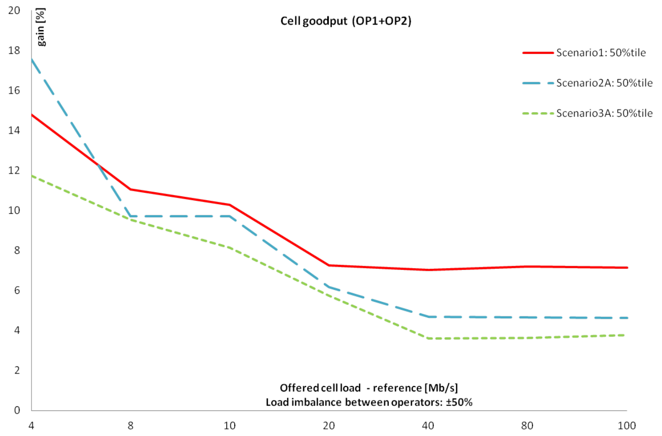

Figure 3. Single HSPA carrier sharing comparison, for various scenarios

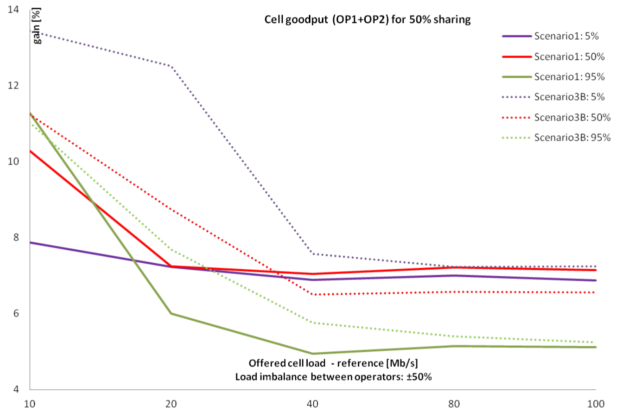

Figure 4. Total goodput for 50% sharing scenarios: 5, 50 and 95%tile comparison

sharing purposes (i.e. Scenario 1, 2A and 3A). As depicted on Figure 3, consideration of only one carrier per MNO being pooled for sharing purposes allowed generation of visible gains in terms of the total goodput, which can be easily translated into the increased spectrum utilization. Achieved sharing gain varies depending on the cell load and saturates for highly loaded network scenarios.

In the next step, we investigate the HSPA carrier's configuration impact on the sharing gain over the respective reference cases, as a function of the cell load. As depicted on Figure 2, we have defined two scenarios, where 50% of the owned carriers were shared by both network operators: these are Scenario 1 and 3B - these configurations were selected for comparison in order to keep fixed sharing ratio as parameter.

Based on the results presented on Figure 4, it was observed that despite of evident sharing gains achieved in both scenarios in terms of total spectrum utilization, in can be additionally concluded, that for particular sharing percentage (i.e. 50% in this case), the cooperation results for each of the depicted throughput percentiles are reaching the saturation levels for the increasing cell load values. Furthermore, the introduced saturation levels can be considered as constant and stable. Based on this observation, the next step in the results analysis was the evaluation of sharing percentage impact on the total cell goodput.

On Figure 5, we can observe, that in the evaluated scenarios, the higher spectrum resources sharing factor was, the higher gains were achieved in terms of total cell goodput. In general, this conclusion holds for all analyzed throughput percentiles. In most cases, the highest gains were observed for 5%-tiles of the cell goodput's, what can be translated into the cell edge users improvements.

Based on this observation, it would be interesting to look at larger carrier's configurations, but due to the HSPA carriers spectrum requirements, higher spectrum configurations were seen as not too realistic. Therefore, further study will be continued based on the LTE network, what is out of scope of this work.

The curves depicted on Figure 6 (±50 load imbalance) have non-increasing trends, which might give an impression, that there might be even higher gains opportunities for cell load values lower that those presented on the enclosed figures. However, a limit to these gains comes from the fact that sharing brings benefits only in case of capacity limited scenarios. Once we have cell specific offered load low enough, we do not need to participate in the described auctioning game (the exclusively owned spectrum resources are sufficient to serve the offered load) - therefore the sharing gain is no longer visible. Moreover, comparing simulation results for various load imbalance ratios between operators (i.e. ±10 and ±50, as depicted on Figure 5 and 6, respectively), one can notice, that the higher sharing gains were achieved in case of larger

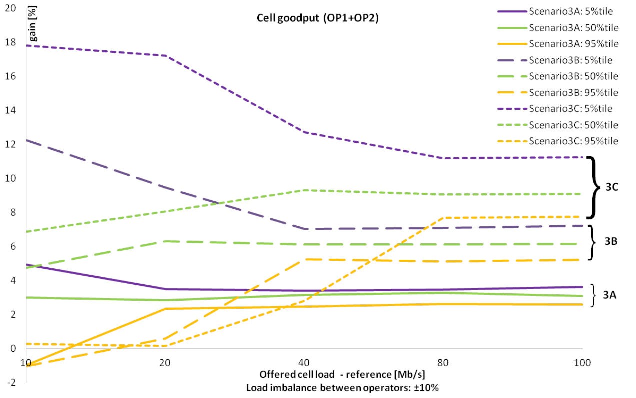

Figure 5. Total goodput for Scenario 3A, B, C for 5%, 50% and 95%tile

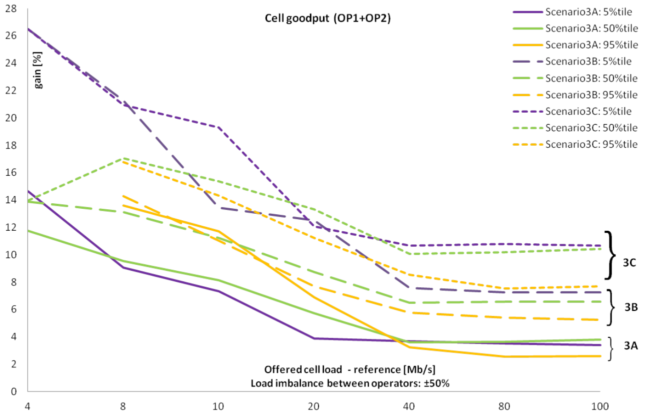

Figure 6. Total goodput for Scenario 3A, B, C for 5%, 50% and 95%tile

load imbalance. This can be easily explained by the fact, of simple resources re-use by the network which has higher load, utilizing the spectrum resources of the operator with lower valuations provided during auctions. Once the load imbalance between two networks is decreasing, the valuation functions do not allow any of the auction players to become much stronger and dominant, but as presented above, sharing gains are still clearly visible across various radio conditions.

Based on the presented spectrum utilization gains, it was concluded, that the described spectrum sharing algorithm extended with appropriate business model for the operators coalition formation, might bring additional money revenue gains to the network operators.

CONCLUDING REMARKS

We have observed, that the short time interval spectrum sharing in the collocated HSDPA network, can provide the spectrum utilization gains, despite of low spectrum granularity of the HSPA physical layer. Gains were presented in case of low to medium granularity of auctioned spectrum resources. Furthermore, traffic patterns de-correlation proves to offer global spectrum utilization improvements. It is expected, that consideration of different valuation functions, as well as other scheduling rules will also impact the results, what is left for further study. The auction based resources distribution system as proposed, besides technically improving spectrum utilization, can also be seen as a tool to monetize the spectrum resources, or even to release chunks of unused licensed spectrum for opportunistic secondary usage.

The introduced valuation functions can easily be used to assign monetary values to the radio resources. The example of Google Adwords market (i.e. pay-per-usage) clearly demonstrates, that such monetization stimulates participation and may lead to the development of new services. The proposed solution may also be seen as a tool to create a transparent market of radio resources enhancing the revenue generation as well as creating new business models on the mobile services market.

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