Dynamic Spectrum Allocation using Regional Spectrum Brokers

László Kovács and Attila Vidács
Budapest University of Technology and Economics
Dept. of Telecommunications and Media Informatics
Magyar tudósok krt. 2
H-1117 Budapest
Hungary

kovacs.l@tmit.bme.hu / vidacs@tmit.bme.hu

ABSTRACT

Currently radio network resource is rigidly partitioned for dedicated purposes. Most of the spectrum is already allocated, but a large part of it is underutilized and the utilization varies greatly in time and space. The exclusive license of fixed size spectrum blocks separated by fixed guard bands easily solves the interference problems; however the fixed allocation of spectrum is clearly inadequate for providing optimal spectrum efficiency for spatially and temporarily varying loads. Dynamic spectrum allocation is a new and promising alternative to fixed allocation schemes. In Dynamic Spectrum Access (DSA) networks the assigned spectrum block may vary in time and space, too.

We describe a new spectrum management model for Dynamic Spectrum Access (DSA) networks. We also propose an architecture that splits the complex problem into Temporal and Spatial Dynamic Spectrum Allocation (TDSA and SDSA).

In our model Regional Spectrum Brokers (RSB) coordinate the temporal dynamic spectrum allocation for a given region within which we assume that the spatial distribution of the spectrum demand is homogeneous. To coordinate the spatial dynamic spectrum allocation between the neighboring regions, the Regional Spectrum Brokers need to communicate to take into account the overlapping regions. One solution is to deploy a centralized entity also, called Spectrum Broker Coordinator (SBC), which stores the spectrum demands of the regions, and the spectrum management at the borders of the regions is realized based on this information. A more robust and scalable solution is to build the network without the central SBC where the regional brokers communicate peer-to-peer and on demand.

We propose algorithms for managing at the region-borders and brokering inside the regions and between the regions

1.0 INTRODUCTION

The current method of assigning spectrum to different radio systems is the fixed spectrum allocation scheme. With this technique fixed size spectrum blocks separated by guard bands are allocated for dedicated purposes. However, communication networks are designed for “busy hours”, which is the time of the peak use of the network. This way, in the rest of the time the spectrum is not fully utilized. The demands for different services depend on location, too. So the bandwidth demand can vary along the space dimension (from region to region) and along the time dimension (from hour to hour). Consequently, a substantial fraction of the spectrum may be wasted at a given time and place. 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.

Kovács, L.; Vidács, A. (2006) Dynamic Spectrum Allocation using Regional Spectrum Brokers. In *Dynamic Communications Management* (pp. 6-1 – 6-14). Meeting Proceedings RTO-MP-IST-062, Paper 6. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Communication plays a very important role in the field of military applications as well. The more advanced forms of communication (e.g. real-time video streaming) require more amount of spectrum. The demand for spectrum is growing constantly, but spectrum is a finite resource. The demands of military applications also depend on time (in case of military operation- related communication) and changes in space, too (the demand moves with the troops), so for military applications the Dynamic Spectrum Allocation technique can be more efficient.

The concept of DSA first came up in the DARPA XG Program [1]. The goals are to develop, integrate, and evaluate the technology in order to enable equipment that automatically selects spectrum and operating modes to both minimize disruption of existing users, and to ensure operation of U.S. systems. Due to the military application there is no central entity, it requires complex spectrum sensing at individual radio nodes and distributed coordination protocols.

In commercial applications, because of the existing architecture, the aggregation of regional demands and the centralization of spectrum management decisions is easily realizable and leads to a simpler solution (coordinated DSA). The ISTDRIVE project [2] 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 [3][4] and had some interesting results [5][6].

Buddhikot *et al*. gave a detailed description of an implementation architecture for coordinated DSA [7]. In their model a spectrum broker controls and provides a time-bound access to a band of spectrum to service providers. They also investigated algorithms for spectrum allocation in homogenous CDMA networks [8] and executed spectrum measurements in order to study the realizable spectrum gain that can be achieved using DSA [9].

Our paper describes a new spectrum management model for coordinated Dynamic Spectrum Access networks. We reduced the complexity of the problem by separating it into Temporal Dynamic Spectrum Allocation (TDSA) problem and Spatial Dynamic Spectrum Allocation (SDSA) problem. We present an architecture that realizes this separation, and solutions for the TDSA problem and SDSA problem.

The rest of the paper is organized as follows. Section II describes an architecture that splits the complex DSA problem into TDSA problem and SDSA problem. Section III describes our DSA model in more details, and gives the requirements of a feasible spectrum allocation. The definitions of various gains that can be achieved using DSA are also given. Section IV discusses the key point of the proposed architecture, namely, the solution to the problem of overhearing and spectrum degradation. A solution to find an optimal spatio-temporal DSA is also outlined. Section V gives an illustrative example on how the proposed methods work. Finally, Section VI concludes the paper with further outlook.

2.0 TEMPORAL AND SPATIAL DSA

In the fixed spectrum allocation scheme the problem of allocation is modeled by a conflict graph in which the nodes are the base stations, and the edges denote where conflict exists. This way the solution of the problem leads to the NP-hard list coloring problem. If the base stations were to demand unequal spectrum slices, this solution could be generalized for dynamic spectrum allocation as well. However, the demand for radio network resources varies greatly in time and space. The temporal and spatial variations of the demands require frequent reallocation of the spectrum. Considering that the graph of the network contains a large number of nodes, and that the problem is NP-hard it is practically impossible to be solved in real-time. In order to reduce the complexity of the resource-allocation problem, we propose an architecture that splits the problem into Temporal and Spatial Dynamic Spectrum Allocation (TDSA and SDSA) tasks.

2.1 Architecture

In our 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.) The spectrum of a given region is owned by the Regional Spectrum Broker (RSB) that grants short-time licenses for the requesters (Network Service Providers). Inside the regions, besides given conditions, service providers can use the allocated spectrum for whatever they want. (There are limitations for usage at the region borders only where overhearing can happen from the neighboring region.)

Within the regions Temporal Dynamic Spectrum Allocation (TDSA) is realized. In the TDSA method service providers of the region send their demands for spectrum to the RSB. The RSB allocates continuous spectrum blocks to the requesters separated by guard bands. The size of the blocks may vary in time. Besides demanding another spectrum blocks, service providers may return spectrum blocks that they do not need. The requests are batch-processed at given time-intervals.

The Spatial Dynamic Spectrum Allocation (SDSA) handles spectrum demands arising at the *same* time in *different* regions. The aim of the SDSA is to attune the different demands within different regions the way that the least interference arises in the overlapping regions. In order to realize this, the RSBs need to have information about the actual spectrum allocation of the neighboring regions. To collect this information, a time snapshot of the spectrum usage inside a region is created by the RSBs and is propagated to the neighboring RSBs. When processing the demands the RSBs query the time-snapshots of the neighboring regions, and based on this information manage overlapping spectrum allocations accordingly. The proposed architecture is shown on Figure 1.

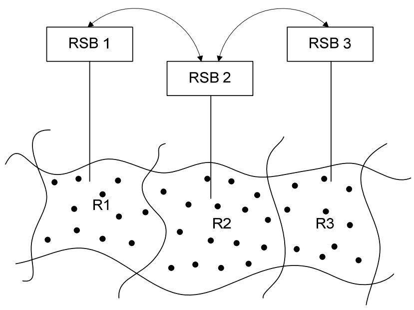

Figure 1: Architecture

3.0 DSA MODEL

Assume that the spectrum block to be distributed is the frequency range ($b; e$). The whole area is divided into K non-overlapping regions (R_i). Within the given region, M network service providers (NSPs) compete for the spectrum. The spectrum block allocated to the m^{th} NSP within the i^{th} region at time t is:

$$S_{m,i}(t) = (b_{m,i}(t), e_{m,i}(t)) \tag{1}$$

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 $l_{m;i}$ denote the "size" of the allocated spectrum block, i.e., $l_{m;i} = b_{m;i} - e_{m;i}$.

Note, that in our model spectrum is distributed along one dimension (i.e., frequency), but on the basis of the proposed algorithm below methods of spectrum allocation along more dimensions (time, frequency, code) can easily be constructed.

The first question is, how much spectrum is needed for the NSPs to provide their service to their customers, taking into account that more NSPs exist within the same arena, competing for spectrum block and possibly interfering with each other. Mapping demands to spectrum volume is the first task in DSA networks.

3.1 Spectrum estimator

Users of a service provider do not request for spectrum directly. Instead, they ask for digital transmission channels of given capacity (expressed in Mbps) for their applications. *Spectrum estimators* are able to relate those capacity requests to the required amount of spectrum to satisfy these requests [8]. However, mapping capacity demands to spectrum requests is not an easy task. It is radio technology specific, relies on the knowledge of network elements, the environment, supported by possible in-field measurements.

To formulate it, assume that the m^{th} provider has the capacity request c_m. The spectrum estimator relates a spectrum block of size l_m to this request, i.e., $f(c_m) = l_m$. Here we assumed that the relation between capacity and spectrum is linear. This is the case, for example, when a narrow-band carrier must be allocated for each 64 kbps data channel. In this case $f(c_m) = c_m s_0$ where s_0 is the size of the carrier.

However, in our DSA scenario providers can have different capacity demands in different regions. The spectrum estimator of the m^{th} provider in the i^{th} region gives back the spectrum needed in that particular region, i.e., $f(c_{m;i}) = l_{m;i}$.

3.2 Spectrum allocation

The task of a regional Spectrum Broker (RSB) is to allocate spectrum to the NSPs so that their demands are satisfied. The RSB divides the CAB into non-overlapping blocks and assigns different blocks to different NSPs within each region, i.e.,

$$S_{m,i} \subset CAB, \quad S_{m,i} \cap S_{k,i} = \emptyset, \quad \forall m,k,i \tag{2}$$

An allocation

$$S = (S_1, \ldots, S_M), \tag{3}$$

where

$$S_m = (S_{m,1}, \ldots, S_{m,K}), \quad \forall m, \tag{4}$$

is *feasible*, if the spectrum blocks $\{S_{m;i}\}$ used by the NSPs *within* a region are non-overlapping, are separated by at least a minimum guard band s_G, and fit in the CAB, i.e.,

$$s_G \le b_{m+1,i} - e_{m,i}, \quad \forall m,i,(m \ne M), \tag{5}$$

$$l_{m,i} \ge f(c_{m,i}), \quad \forall m,i, \tag{6}$$

$$l_{CAB} \geq \sum_{m=1}^{M} l_{m,i} + (M-1)s_G, \quad \forall i \tag{7}$$

An example of spectrum allocation with three providers is shown on Figure 2.

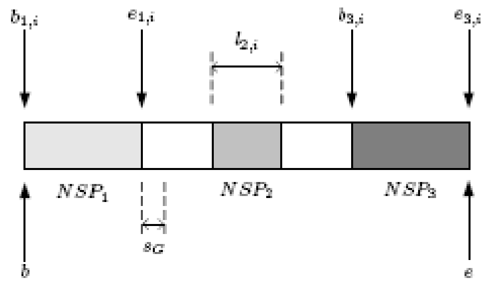

Figure 2: Example for spectrum allocation.

Although the feasibility conditions given above seem to be simple enough, this is because its present form hides the essence of spatio-temporal DSA. The key lies in the detailed expression of the spectrum estimator f(·). The amount of spectrum needed not only depends on the capacity demand $c_{m;i}$, but also on the position of the allocated block within the CAB, as well as on the allocations of the neighboring regions causing possible spectrum degradation within the overlapping areas. To express these dependences, we have

$$f(i, c_{m,i}, b_{m,i}, S_{-m}) = l_{m,i}, \quad \forall m, i, \tag{8}$$

where

$$S_{-m} = (S_1, \ldots, S_{m-1}, S_{m+1}, \ldots, S_M) \tag{9}$$

denotes the allocations of the competing providers. (For the details of the spectrum estimation in our model, please refer to Section IV later.)

Checking feasibility of a spectrum allocation is a must. However, feasibility on its own does not say anything about the *efficiency* of the allocation. Spectrum can be distributed badly, or in a more clever way. What is good or what is bad depends on how we define efficiency. In the following, we describe various gains that can be achieved by DSA. Depending on what we are aiming at, different allocation rules that lead to efficient spectrum usage can be defined.

3.3 Temporal Gains from DSA

The gain achieved by TDSA can be interpreted from two different aspects. (Since we concentrate on the temporal gains, the dependence on the region is omitted from the notations. Instead, the dependence on time *t* is explicitly noted.)

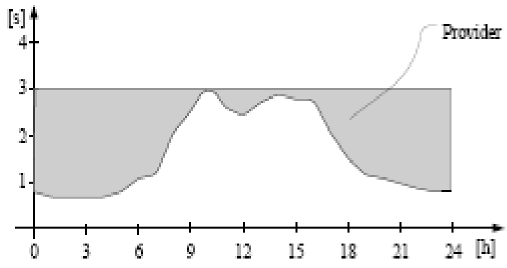

Figure 3: TDSA Provider Gain

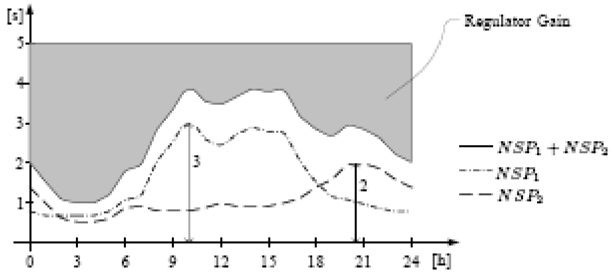

Figure 3: TDSA Regulator Gain

1) Provider Gain: This kind of gain is the gain of the provider, originating from the fact, that it is not required to allocate the spectrum needed to serve the "busy hour" in the whole time domain (see Figure 3). The gain of the m^{th} provider at time t is:

$$PG = 1 - \frac{l_m(t)}{\max_\tau \{c_m(\tau)s_0\}}, \tag{10}$$

The *average* gain of the mth provider in time interval T is:

$$PG_m^{ave} = T^{-1} \int_0^T PG_m(t)dt, \tag{11}$$

Note, that this formula represents the theoretically achievable gain. The actual gain is less than this, since the reallocation cannot be made on an arbitrary time scale. Furthermore, the NSPs cannot predict with arbitrary precision the spectrum demanded for the next epoch.

2) Regulator Gain: Compared to the rigid spectrum allocation where enough spectrum must be allocated in advance for *each* NSP to satisfy its peek demand, the Regulator Gain (RG) at time t can be computed as (see also Figure 4)

$$RG(t) = 1 - \frac{\sum_{m=1}^{M} l_m(t)}{\sum_{m=1}^{M} \max_\tau \{c_m(\tau)s_0\}}. \tag{12}$$

The *average* gain of the regulator in time interval T is:

$$RG^{ave} = T^{-1} \int_0^T RG(t)dt. \tag{13}$$

The minimal gain over the whole time interval can also be defined:

$$RG^{\min} = \min_t RG(t). \tag{14}$$

This is the gain that can be achieved at *all* times when compared to the fixed spectrum allocation. In other words, the size of CAB can be smaller by this factor than the total spectrum needed for the rigid allocation.

Note that the achievable gain strongly depends on the correlations between the NSP demands.

3.4 Spatial Gains from DSA

The spectrum demands of an NSP can be different in different regions. The main task of the SDSA is to handle this heterogeneity. (Since we concentrate on the spatial gain, a time snapshot is investigated. Hence the notation of time dependence is omitted.)

1) Provider Gain: Without SDSA one provider has to allocate the spectrum amount required to fulfill its highest demand, although in the major part of its service area a (much) smaller amount of spectrum would be enough. Using SDSA it is possible to allocate the spectrum amount that fulfills the demand of the given region, independent of the demands in the rest of the area. The difference is the DSA's spatial gain. The gain of the m^{th} provider in the i^{th} region is:

$$PG_{m,i} = 1 - \frac{l_{m,i}}{\max_j \{c_{m,j} s_0\}}. \tag{15}$$

The *average* gain of the provider over its total service area is:

$$PG_m = \sum_{i=1}^{K} (A_i / A) PG_{m,i}, \tag{16}$$

where A_i is the area of the i_{th} region, and is used in the formula as a weight for the local gain, allowing different size regions. The total service area is: $A = \sum_i A_i$.

2) Regulator Gain: Using rigid spectrum allocation, the amount of spectrum that must be allocated in *all* regions is $\sum_{m=1}^{M} \max_i \{c_{m,i} s_0\}$. Thus, the Regulator Gain from SDSA in region *i* is

$$RG_i = 1 - \frac{\sum_{m=1}^{M} l_{m,i}}{\sum_{m=1}^{M} \max_j \{c_{m,j} s_0\}}. \tag{17}$$

The *average* gain over the whole controlled area is

$$RG = \sum_{i=1}^{K} (A_i / A) RG_i, \tag{18}$$

where larger areas are taken with higher weights in the sum.

3.5 Spatio-Temporal Gains from DSA

Taking into account the temporal and spatial gains simultaneously, the following gains can be defined.

1) Provider Gain: By combining (10) and (16) we get

$$PG_m(t) = 1 - \frac{\sum_{i=1}^{K} (A_i / A) l_{m,i}(t)}{\max_j \max_\tau \{c_{m,j}(\tau) s_0\}}. \quad (19)$$

2) Regulator Gain: By combining (12) and (18) we get

$$RG(t) = 1 - \frac{\sum_{m=1}^{M} \sum_{i=1}^{K} (A_i / A) l_{m,i}(t)}{\sum_{m=1}^{M} \max_j \max_\tau \{c_{m,j}(\tau) s_0\}}. \quad (20)$$

4.0 SPATIO-TEMPORAL DSA

Allocating strictly disjoint spectrum blocks to NSPs within each region seems to solve the problem at first glance. However, this is not the case in spectrum allocation, since spectrum usage does not stop at region boundaries. If the same spectrum slice is allocated to two different providers in neighboring regions, certainly some overhearing occurs, radios will interfere. This problem of overhearing is also present to some extent in the rigid spectrum allocation used today. As an example, consider national service providers that have exclusive rights to use their allocated spectrum *only within* the country. Special rules apply to the border region, where operators are not allowed to interfere (above a certain limit) with the operators in the neighboring country. Antennas must be placed accordingly, and transmit powers need to be adjusted to obey the rules. However, the area of this "problematic" border region is very small compared to the size of the country, the overhearing is negligible.

On the contrary, in our proposed scenario the regions coordinated by dedicated RSBs are relatively small, thus the area of the overlapping area is not negligible compared to the size of the region.

4.1 Spectrum efficiency

In case of interference, the spectrum block cannot be fully utilized. This effect can be characterized by an *efficiency decrease* factor, η. To calculate it, consider two regions R_k and R_l. Let A_{kl} denote the size of the area *within* region k where interference from region l can happen. Similarly, A_{lk} is the area where interference can occur in region l from radios operating in R_k. Furthermore, denote A_k the total area of region R_k, and $\varepsilon_{kl} = A_{kl} / A_k$. We also assume that $A_{kl} \cap A_{kj} = \emptyset$. In our model, we assume that when the same spectrum slice is used by another NSP in the neighboring region, the "quality" of that spectrum within the interference zone is degraded so that its efficiency is halved ($\eta = 0.5$) from the operators point of view. (The "core" area outside the overlapping region is not affected by the interference of the neighboring region, the NSPs may use the whole allocated spectrum block freely there.) Thus, the spectrum efficiency decrease caused by all NSPs in region k on the spectrum used by the m^{th} NSP in the *neighboring* interference zone(s) is

$$\eta_{-m,k}(\lambda) = \begin{cases} 0, & \text{if } \lambda \notin S_{-m,k} \\ \eta & \text{if } \lambda \in S_{-m,k} \end{cases} \tag{21}$$

where

$$S_{-m,k} = \bigcup_{i=1}^{M} S_{i,k} \setminus S_{m,k} \tag{22}$$

Thus, the efficiency factor of frequency λ from the mth NSP's point of view in region R_k can be calculated as

$$\xi_{m,k}(\lambda) = 1 - \sum_{j=1}^{K} \varepsilon_{kj} \eta_{-m,j}(\lambda) \tag{23}$$

Let $\xi(S_{m,k})$ denote the *efficiency* of spectrum block $S_{m,k}$ that can be calculated as

$$\begin{aligned} \xi(S_{m,k}) &= \frac{1}{\left|S_{m,k}\right|} \int_{S_{m,k}} \xi_{m,k}(\lambda) d\lambda \\ &= 1 - \frac{1}{\left|S_{m,k}\right|} \sum_{j=1}^{K} \int_{S_{m,k}} \varepsilon_{kj} \eta_{-m,j}(\lambda) d\lambda \end{aligned} \tag{24}$$

i.e., the efficiency is one if no interference occurs within the region and less than one if there is spectrum degradation within the region in one or more interference zones.

Recall that a feasible allocation must satisfy (5), (6) and (7). In the spatio-temporal DSA case the requirement of (6) can be interpreted as follows. In order to satisfy the capacity request of the provider, the size of the allocated spectrum block must satisfy

$$\xi\left(S_{m,k}\right)\left|S_{m,k}\right| = c_{m,k} s_0, \tag{25}$$

where s_0 is a constant (i.e., the (unit) size of a narrow-band carrier). Note, that in (25) the efficiency factor $\xi(S_{m,k})$ is the function of the spectrum block size $\left|S_{m,k}\right|$, thus solving the equation is not so straightforward.

4.2 Efficient allocation

Checking feasibility of a spectrum allocation is a must. However, feasibility on its own does not say anything about the *overall efficiency* of the allocation. Spectrum can be distributed badly, or in a more clever way. Depending on what we are aiming at, different allocation rules that lead to efficient spectrum usage can be defined.

After ensuring feasibility, the task is to choose the most efficient allocation *S** that maximizes the regulator gain, which is equivalent to

$$\sum_{j=1}^{K}\sum_{i=1}^{M}\left|S_{i,j}\right|A_j \to \min \tag{26}$$

To propose an algorithm that solves the optimal allocation problem remains for further study. However, an approximate iterative allocation algorithm can be constructed to reach a near-optimal solution.

4.3 Iterative re-allocation

As demands change, NSPs would request and release spectrum dynamically. Assume an initial, feasible spectrum allocation among the NSPs to be $\left\{S_m^{(0)}, m = 1,\ldots,M\right\}$. Let the request of the m^{th} service provider during the n^{th} epoch be $r_m^{(n)}$, where $r_m^{(n)}$ stands for the number of carriers requested (or released, if negative) for the next interval. If feasible, the sizes of the spectrum blocks allocated by the RSB are

$$l_m^{(n+1)} = l_m^{(n)} + r_m^{(n)} s_0 . \tag{27}$$

When an NSP demands further spectrum blocks it can allocate new carriers towards the neighboring NSP that is "further" from it, i.e., where the guard band is wider in between. (Two NSPs are neighbors if their allocated spectrum blocks are adjacent.) Also, when an NSP returns spectrum resources, this will be done towards the "closer" neighboring NSP. Assuming frequent allocations and de-allocations, and (relatively) slowly changing demands, the iterative re-allocation methods result in spectrum allocations that are "breathing" and "sliding" back and forth in time.

Similarly, the spectrum degradation originating from overhearing can be avoided (or at least reduced) if the newly allocated blocks are chosen by taking into account the allocations in the neighboring region. Thus, coordination among the RSBs is clearly necessary.

However, it can happen that an NSP increases its demand so rapidly that it would "stuck" in between its two neighboring NSPs and its further demands cannot be satisfied without overlapping spectrum allocations, which is clearly not an option. In this case—because we stick to the assumption that spectrum is allocated in a continuous block—the forced reallocation of the spectrum blocks is unavoidable, the RSB must shift the affected blocks accordingly.

5.0 SIMULATIONS RESULTS

We have created a simple simulation scenario in order to examine the achievable gains using the proposed DSA method. In the simulation we examined two regions of equal size. The area of the overlapping zone was 20% of the whole area in both regions. The capacity demands of the NSPs were translated into carrier demand using the proposed spectrum estimator. This way the spectrum could be demanded in discrete units (narrow-band carriers). The size of the CAB was equal to the total size of 1000 carriers. The spectrum was re-distributed in every 30 minutes. The size of the guard band within a region was ten times the minimum allocatable spectrum block.

The capacity demand of the NSPs as a function of time corresponded to the ones shown on Figure 4 with the following modifications: its shape was left intact but its volume was modified to simulate different demands in different regions. In region 1 the demand of NSP_1 is much larger than that of NPS_2, while in region 2 it was just the opposite way.

Figure 5 and 6 show the number of carriers used by the providers in both regions as a function of time. The excess spectrum required to fulfill the demands in case of overhearing is denoted by a darker tone in the figures.

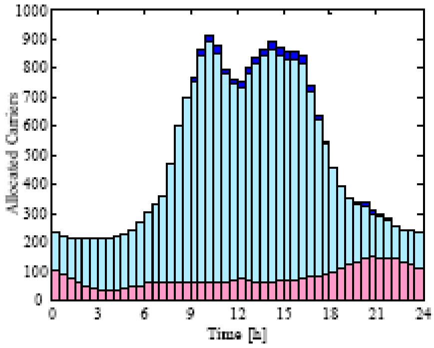

Figure 5: Allocated spectrum sizes for both providers in region 1.

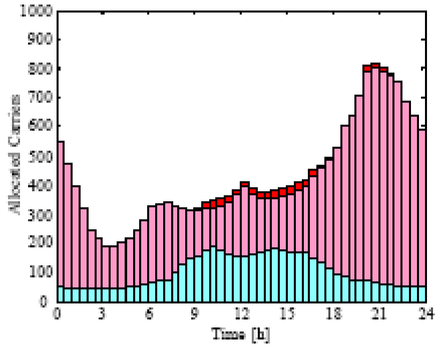

Figure 6: Allocated spectrum sizes for both providers in region 2.

Figure 7 and 8 show the spectrum allocation in the two regions at 6 am and 3 pm, respectively. At 6 am different spectrum blocks were allocated to neighboring providers, thus there was no spectrum degradation. On the contrary, at 3 pm the demands were so high that the overhearing could not be avoided. In this case some excess spectrum needed to be allocated in order to cope with the degraded spectrum quality.

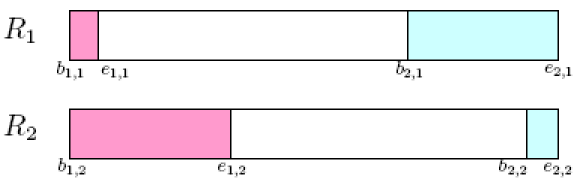

Figure 7: Allocation at 6 am.

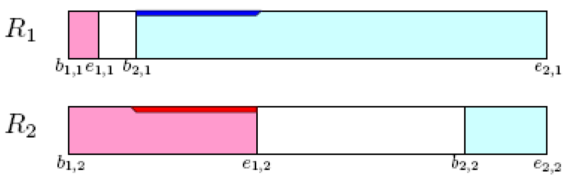

Figure 8: Allocation at 3 pm.

Table I lists the temporal, Table II the spatial, and Table III lists all spatio-temporal gains as defined previously in Section III. As can be seen from the values, significant gains can be achieved by the proposed model. For example the spatiotemporal regulator gains are above 50% at the examined time points, meaning that much less spectrum resource is enough to fulfill the requests in case of using dynamic spectrum allocation. In case of fixed spectrum allocation 1700 carriers would have been enough to fulfill the requests in this scenario. In the simulation the number of available carriers was 1000 only, but it was more than the required amount since the value of RG^{min} in the two regions was still 8,67% and 12,43%.

Table I. Temporal Gains in Different Regions

R_1		R_2	
PG_1^{ave}	46,68 %	PG_1^{ave}	46,68 %
PG_2^{ave}	45,43 %	PG_2^{ave}	45,43 %
RG^{ave}	45,61 %	RG^{ave}	46,45 %
$RG^{\min}$	8.67 %	$RG^{\min}$	12,43 %

Table II. Spatial Gains at Different Times

T=6h		T=15h	
$PG_{1,1}$	81,25 %	$PG_{1,1}$	81,25 %
$PG_{2,2}$	79,16 %	$PG_{2,2}$	79,16 %
PG_1	40,63 %	PG_1	40,63 %
PG_2	39,58 %	PG_2	39,58 %
RG_1	42,03 %	RG_1	25,00 %
RG_2	38,21 %	RG_2	54,80 %

Table III. Spatio-Temporal Gains at Different Times

T=6h		T=15h	
PG_1	75,62 %	PG_1	71,06 %
PG_2	79,17 %	PG_2	42,12 %
RG	54,98 %	RG	55,87 %

6.0 CONCLUSIONS AND FUTURE WORK

In our paper we introduced a new model for dynamic spectrum allocation. In this model we assumed regions in which the demand for spectrum was homogenous, only time changes were allowed. This way we could simplify the spectrum allocation problem and described an architecture that splits the complex problem into temporal and spatial parts. The Temporal Dynamic Spectrum Allocation (TDSA) is coordinated by Regional Spectrum Brokers (RSBs). The RSB handles the spectrum demands of the NSPs within one region. Based on the spectrum allocation in the different regions the RSBs can handle the problem of interference in the overlapping regions. After giving the requirements for a feasible spatio-temporal spectrum allocation, we defined various achievable gains, either from the providers as well as from the regulator's point of view, taking into account the temporal and spatial inhomogenities of spectrum usage. The solution to handle the problem of overhearing and spectrum degradation was proposed. The solution to find an optimal spatio-temporal spectrum allocation was outlined, the achievable gains were shown with simulation examples.

In the future we are planning to extend the model to handle the case when providers have to compete with each other for the available spectrum resources. In that case the optimal spectrum allocation within the regions and between the regions can be approximated using auction-driven pricing mechanisms. The RSBs use market models to avoid spectrum interference and to distribute the spectrum resource more equally. The price depends on the utilization of the spectrum and the allocation of the neighboring region. Another way of extending our model is to allow the allocation of more discontinuous blocks to a single provider instead of allocating only continuous spectrum slices. This way the flexibility and thus the efficiency could be further increased. Allowing partially overlapping spectrum allocations within regions would also extend the flexibility. Dividing spectrum in time and/or code instead of only frequency is also an option.

REFERENCES

[1] "DARPA XG Program," http://www.darpa.mil/ato/programs/xg/.

[2] "IST-DRIVE Project," http://www.ist-drive.org.

[3] P. Leaves, K. Moessner, D. Bourse, and D. Grandblaise, "Dynamic spectrum allocation in a multi-radio environment: Concept and algorithm," in *IEE Second International Conference on 3G Mobile Communication Technologies*, London, United Kingdom, 26-28 March 2001, pp. 53–57.

[4] P. Leaves, J. Huschke, and R. Tafazolli, "A summary of dynamic spectrum allocation results from drive,", in *IST Mobile and Wireless Telecommunication Summit*, Thessaloniki, Greece, 16-19 June 2002, pp. 245–250.

[5] J. Huschke, and P. Leaves, "Dynamic spectrum allocation algorithm including results of dsa performance simulations.", DRiVE Deliverable D09, http://www.ist-drive.org/, Jan. 2002.

[6] L. P. and T. R., "A time-adaptive dynamic spectrum allocation scheme for a converged cellular and broadcast system," in *IEEE Getting the Most Out of the Radio Spectrum Conference*, United Kingdom, 24-25 October 2002, pp. pp.18/1–18/5.

[7] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: New directions in wireless networking using coordinated dynamic spectrum access," in *Position Paper in IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM 2005)*, Taromina/Giardini Naxos, Italy, Jun 2005.

[8] M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks," in *Proceedings of the First IEEE International Symposium on New Directions in Dynamic Spectrum Access Networks*, Baltimore, MD, Nov 8-11 2005.

[9] T. Kamakaris, M. Buddhikot, and R. Iyer, "A case for coordinated dynamic spectrum access in cellular networks," in *Proceedings of the First IEEE International Symposium on New Directions in Dynamic Spectrum Access Networks*, Baltimore, MD, Nov 8-11 2005.