Dynamic Spectrum Allocation in Non-Continuous Blocks for Future Wireless Networks

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***Abstract*—The radio spectrum is a scarce and thus expensive resource. The exclusive licenses of today's practice for spectrum usage easily solve the problem of interference, but are clearly inadequate for providing optimal spectrum efficiency for dynamically varying demands. In our previous work we proposed a new model for Dynamic Spectrum Allocation (DSA) to increase spectral efficiency that handles interference issues in a flexible way. Now we extend the model by allowing the allocation of non-continuous spectrum blocks for the service providers, taking into account the granularity of spectrum blocks that is in harmony with the providers' technology. The rules for a feasible spectrum allocation are given, and the optimal allocations that maximize the achievable gain or minimize the overall interference are calculated using heuristics. Simulation results show the increased effectiveness of the proposed solution for different scenarios.**

I. Introduction

Nowadays rigid and static spectrum allocation results in highly inefficient spectrum utilization. First, the spatial distribution of spectrum usage is uneven. In today's allocations frequency usage rights are given for large areas, typically for the area of a whole country. By scaling down the size of the region we are looking at, high spatial spectrum utilization variations can be noticed. Second, radio communication networks are designed for "busy hours" but the spectrum is not fully utilized in the rest of the time. Furthermore, "old-fashioned" legacy services tend to take a back seat while still possessing a large slice from the spectrum, and at the same time new services emerge and try to get access to a fair slice of the spectrum. These spatial and temporal spectrum variations result in the fact that a substantial fraction of the spectrum is wasted at a given time and place [1] [2] [3].

This is the motivation for Dynamic Spectrum Allocation (DSA) techniques, where the assigned spectrum blocks may vary in time and space. The key enabling technologies of DSA networks are the software-defined and cognitive radios. Cognitivity refers to the ability of the radio technology to sense the information from its radio environment, and enables the radio to be dynamically programmed to transmit and receive on a variety of frequencies, and to use different transmission technologies supported by its hardware design [3] [4]. The concept of DSA first came up in the DARPA XG Program [5], where the goals were 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 are easily realizable and lead to a simpler solution. Buddhikot *et al.* gave a detailed description of an implementation architecture for coordinated DSA [6]. 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 [7] and executed spectrum measurements in order to study the achievable spectrum gain [8]. The IST-DRiVE project [9] 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 [10] [11].

The IST-OverDRiVE project [12] 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). In the proposed model providers have to allocate continuous spectrum blocks because they insert unused spectrum blocks (extra guard bands) at the border areas in order to avoid interference. In the project IST-WINNER [13], mechanisms for cooperation between the radio segments of different RANs are described. This cooperation is established to enhance the functionality, performance, flexibility and radio coverage with respect to the single-RAN case. One of the goals of this project was the development and deployment of flexible, optimized mobile radio networks which will be able to adapt to the spatial and temporal variations in capacity demands in order to increase the overall spectral efficiency of the joint set of radio networks.

Besides coordinated equal-right access solutions, there are other, priority access based proposals as well. In these solutions spectrum is dedicated to the primary system and the secondary system may only access the same spectrum as long as it does not cause significant interference to the primary system [14]. We described a spectrum management model for coordinated DSA networks in [15]. The complexity of the problem was reduced by separating it into temporal and spatial DSA problems. The problem of interference and spectrum degradation between neighboring regions was captured by the so-called efficiency decrease factor. The idea was that in order to compensate the efficiency loss caused by interference, it was necessary to allocate larger spectrum blocks.

A related but different solution was proposed in [16]. The approach we used in our model [16] was similar to that of [12] and [17]. We defined DSA regions in which the spatial distribution of the traffic demands was homogenous, only temporal changes were allowed. We also used distributed architecture elements called Regional Spectrum Brokers to coordinate the spectrum allocation inside each region. However, in our model it was not necessary to insert extra guard bands at the region borders. The key difference to previous solutions was that in [16] we described a spatio-temporal coordinated DSA framework where interference was modeled by general coupling parameters between the regions and between providers. In our model interference caused degradation in spectrum efficiency. The sensitivity of the providers to spectrum efficiency degradation was modeled by two interference-tolerance parameters. By these general parameters we defined a scalable and flexible DSA model that included other proposals as special cases of the parameter setting. The proposed model was also appropriate for describing providers whose service area consists of more than one region, as well as providers which are capable to operate using the same frequency band inside a region. We defined gains from the regulator's point of view and we derived the optimal spectrum allocation for the region-based DSA model as the one that maximizes the guaranteed regulator gain.

In this paper we give an extension of the allocation model proposed in [16]. The extension makes it possible to allocate non-continuous spectrum blocks for the service providers. It also takes into account the granularity of spectrum blocks that does not conflict with the providers' technology. We also derive the optimal spectrum allocation that maximizes the guaranteed regulator gain for the proposed model. Furthermore, we also investigate how to allocate the spectrum blocks so that the overall interference is to be minimized. The achievable gains in the non-continuous model are compared to those in the previous proposal. Since the radio spectrum is a finite and expensive resource a small increase in gain may have a considerable cost impact, but it also increases the computational complexity.

II. Spatio-temporal DSA

A. Architecture

In [16] we considered regions within which we assumed 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, NSP). Inside the regions, besides given conditions, service providers can use the allocated spectrum for whatever they want. 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 disjoint and continuous spectrum blocks to the requesters. The size of the blocks may vary in time.

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 between 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 sent by the RSBs to the Spectrum Broker Coordinator (SBC). Note, that when joint re-allocation in more than one region is needed, it is only the SBC that has all necessary information to perform this. The hierarchy of the RSBs and the SBC is shown on Figure 1.

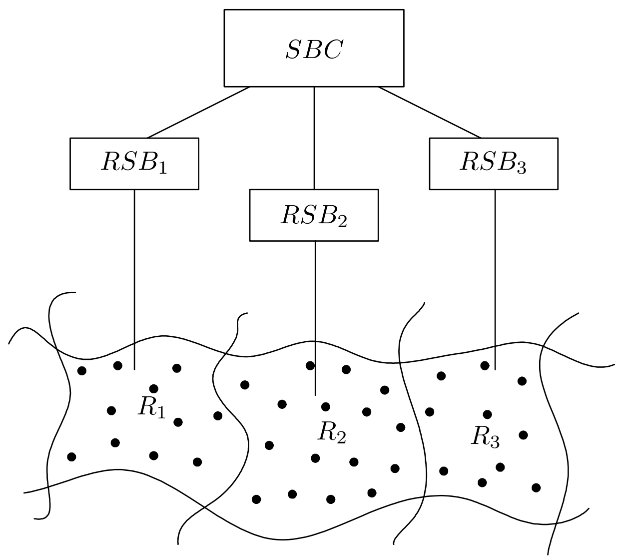

Fig. 1. Proposed spatio-temporal DSA architecture

B. Continuous DSA model

We assumed that the spectrum block, which is distributed among all service providers, is a frequency range $(\check{s}, \hat{s})$. In this model spectrum can be allocated for a service provider only in one continuous block. The whole area is divided into *K* non-overlapping regions (R_k). Within the given region, *M* network service providers compete for the spectrum. The allocation is performed by the Regional Spectrum Broker (RSB) together with the Spectrum Broker Coordinator (SBC), their task is to allocate spectrum to the NSPs so that their demands are satisfied. The RSBs divide the spectrum band into blocks and assign different blocks to different NSPs within each region. 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 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 in the followings.) Furthermore, let $|S_{m,k}|$ denote the size of the allocated spectrum block, i.e., $|S_{m,k}| = \hat{s}_{m,k} - \check{s}_{m,k}$. 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 $b_{m,k}$.

III. Interference tolerant DSA model allowing non-continuous spectrum blocks

A. Interference tolerant DSA model

In [15] and [16] we extend the model with interference handling. We take into account interference as a source of 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. (For example, carefully designed microcell structure with directed and low-power antennas cause much limited interference than a central undirectional transmitter placed in the middle of the region.) 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 geographical coupling the better from the interference 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. By looking at the two extremes, if the two NSPs have the same spectrum slice within the same region and $\eta_{m,n}$ is zero, the NSP$_n$ does not affect NSP$_m$ at all, while $\eta_{m,n}$ equals one means that the spectrum is ruined for NSP$_m$.

The cumulative effect of the geographic and radio technology coupling 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, $\varepsilon_{l,k}^{(m)} \cdot \eta_{m,n}$. 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$_m$'s point of view in region R_k, that is

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

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. In the spatio-temporal continuous DSA model the requirement of feasibility can be interpreted as follows. An *allocation* $S = (S_1, \ldots, S_M)$ with $S_m = (S_{m,1}, \ldots, S_{m,K})$ is *feasible*, if the spectrum blocks $\{S_{m,k}\}$ used by the NSPs satisfy the following conditions:

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

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

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

In words, (4) makes sure that each allocated spectrum block is big enough to satisfy the NSP's capacity request. Conditions (5) and (6) assure that the spectrum "quality" is good enough for the given service. Inequality (5) gives the condition that the *average* spectrum quality is above a pre-defined threshold (e.g., β equals 0.95 means that maximum 5% of the allocated spectrum block is lost due to interference). Figure 2 shows this situation where two spectrum slices are overlapping, so they cause interference to each other. Spectrum efficiency is reduced in the overlapping band (only 85% of the whole spectrum can be utilized), consequently, the efficiency of the whole block is reduced as well. Providers can define the spectrum efficiency with the help of this value.

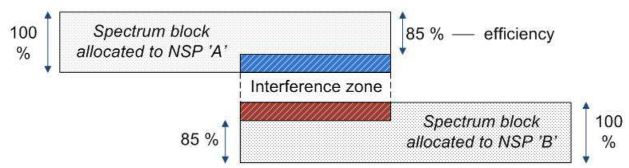

Fig. 2. Meaning of interference parameter β

However, it can happen that interference occurs only within a narrow sub-band of the allocated block, making certain frequencies completely unusable. Some technologies cannot tolerate this. (For example, certain pilot signals at given frequencies must be available to instruct the users on service availability.) To avoid this, another threshold (typically $\alpha < \beta$) can be given to assure that all slices of the given block can be utilized at least with a minimum (α) efficiency. Figure 3 illustrates the meaning of this parameter. The spectrum block tolerates some interference everywhere inside a block, but there is a definite value (α) which cannot be stepped over. (The block on Figure 3 harms these terms two times, where the columns - indicating the size of the interference - step over the dashed line.)

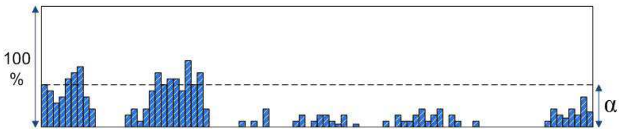

Fig. 3. Meaning of interference parameter α

To allow a great flexibility, our model have the geographic coupling (ε) and the radio technology coupling parameters (η) to capture and handle interference issues between different regions and providers, and interference tolerance parameters α and β to describe the sensitivity of providers to spectrum degradation. The parameter values can be different for each provider as well as for each region or between region pairs.

B. Allowing non-continuous blocks

In previous proposals the allocation of non-continuous spectrum blocks was not permitted. The current proposal enables the providers to allocate non-continuous spectrum blocks if the used technology allows it. Providers have the right to determine the granularity of the demanded spectrum block. For example, if an UMTS provider needs 20 MHz of spectrum for a region it is technologically feasible to provide the service in four non- consecutive 5 MHz spectrum blocks. Permitting non-continuous spectrum blocks increases the achievable spectrum gains because there are more possible allocation schemes that lead to better spectrum utilization. According to this we have to adapt the former formulas so we can distinguish every single spectrum slice. Equation (7) gives the spectrum block allocated to the m^{th} NSP within the k^{th} region. Index j refers to certain slices of spectrum allocated to provider m in region k.

$$S_{m,k} = \{(\check{s}^{(1)}_{m,k}, \hat{s}^{(1)}_{m,k}), \ldots, (\check{s}^{(J_{m,k})}_{m,k}, \hat{s}^{(J_{m,k})}_{m,k})\}, \tag{7}$$

where $\check{s}^{(j)}_{m,k}$ means the lower margin, $\hat{s}^{(j)}_{m,k}$ means the upper margin of the j^{th} spectrum slice. The size of the j^{th} spectrum slice is:

$$|S^{(j)}_{m,k}| = \hat{s}^{(j)}_{m,k} - \check{s}^{(j)}_{m,k}. \tag{8}$$

The full size of the spectrum allocated to the m^{th} provider in the k^{th} region is given as

$$|S_{m,k}| = \sum_{j=1}^{J} |S^{(j)}_{m,k}|, \tag{9}$$

where J means the number of spectrum blocks allocated to the m^{th} provider in the k^{th} region. The spectrum efficiency is expressed as

$$\xi(S^{(j)}_{m,k}) = \frac{1}{|S^{(j)}_{m,k}|} \int_{S^{(j)}_{m,k}} \xi^{(j)}_{m,k}(\lambda) d\lambda. \tag{10}$$

$S = (S_{1,1}, \ldots, S_{M,K})$ is a feasible allocation if:

$$|S^{(j)}_{m,k}| \geq b^{(j)}_{m,k} \quad \forall m,k,j \tag{11}$$

$$\xi(S^{(j)}_{m,k}) \geq \beta_m \quad \forall m,k,j \tag{12}$$

$$\min_{\lambda \in S^{(j)}_{m,k}} \xi_{m,k}(\lambda) \geq \alpha_m \quad \forall m,k,j \tag{13}$$

In words, equation (11) ensures that every single spectrum block is large enough to satisfy the demand of the providers ($b_{m,k}$). Conditions (12) and (13) assure that the quality of the allocated spectrum is good enough for the given service. Inequality (12) declares that the *average* quality of the spectrum block is above a certain value. For example, β equals 0.95 means that maximum 5% of the assigned spectrum can be wasted by the interference. Inequality (13) means that the spectrum slice can tolerate some interference, but it has a maximum value, which should not be violated.

IV. Simulated Annealing

To find the optimal allocation we use heuristics with Simulated Annealing (SA), which is a generic probabilistic meta-algorithm for the global optimization problem (see [18] for details). Now the energy functions are introduced for both tested algorithms.

We define the state vector as

$$\mathbf{s} = (\check{s}^{(j)}_{1,1}, \ldots, \check{s}^{(j)}_{1,K}, \ldots, \check{s}^{(j)}_{M,1}, \ldots, \check{s}^{(j)}_{M,K}). \tag{14}$$

Note, that the spectrum allocation S is uniquely defined by the state vector $\mathbf{s}$ and the allocation vector $\tilde{\mathbf{a}}$, since $S^{(j)}_{m,k} = \{(\check{s}^{(j)}_{m,k}, \hat{s}^{(j)}_{m,k})\}$ where $\hat{s}^{(j)}_{m,k} = \check{s}^{(j)}_{m,k} + \tilde{a}_{(m-1)K+k}$.

The energy E of the system in state $\mathbf{s}$ when maximizing the achievable gain is defined as

$$E(\mathbf{s}) = -|S_{m,k}| + P_f, \tag{15}$$

where the penalty function P_f is given by

$$P_f = \sum_{m=1}^{M} \sum_{k=1}^{K} \left(I_{\{\xi(S^{(j)}_{m,k}) < \beta_m\}} + I_{\{\min_{\lambda \in S^{(j)}_{m,k}} \xi_{S^{(j)}_{m,k}}(\lambda) < \alpha_m\}} \right). \tag{16}$$

The energy E of the system in state $\mathbf{s}$ when minimizing the overall interference is defined as

$$E(\mathbf{s}) = -\xi(S^{(j)}_{m,k}) + P_f, \tag{17}$$

where the penalty function P_f is given by

$$P_f = \sum_{m=1}^{M}\sum_{k=1}^{K}\left(I_{\{\xi(S_{m,k}^{(j)})<\beta_m\}} + I_{\{\min_{\lambda\in S_{m,k}^{(j)}} \xi_{S_{m,k}^{(j)}}(\lambda)<\alpha_m\}}\right). \quad (18)$$

The penalty function P_f is constructed so that it is zero only when the feasibility conditions (12) and (13) are met for all allocated spectrum blocks, and is at least one otherwise. As a result, the energy function E is always positive if the allocation is not feasible, and negative if all feasibility conditions are satisfied. Minimizing this energy function yields finding a feasible allocation that provides the highest overall spectrum utilization efficiency, which means the minimal overall interference.

At each step, the SA heuristic considers some neighbor $\mathbf{s}'$ of the current state $\mathbf{s}$, and probabilistically decides between moving the system to state $\mathbf{s}'$ with energy $e' = E(\mathbf{s}')$, or staying in state $\mathbf{s}$ of energy $e = E(\mathbf{s})$.

In our solution new neighbors are generated from the current state vector by adding a Gaussian-distributed random variable to one of the elements, i.e.,

$$\mathbf{s}' = \mathbf{s} + X\mathbf{e}_Y, \quad X \sim \mathcal{N}(0,\sigma), \quad Y \sim \mathcal{U}_{MK}, \quad (19)$$

where $\mathbf{e}_i$ is the unit vector whose ith element is one, Y is a uniformly distributed discrete random variable in $[1, MK]$. The mean of the state-shift variable X is zero.

The probability of making the transition from the current state $\mathbf{s}$ to a candidate new state $\mathbf{s}'$ is a function $P(e, e', T)$ of not just the state energies e and e', but a global time-varying parameter T called the temperature. A transition probability function that can be used has the form

$$P(e, e', T) = e^{\frac{e-e'}{T}}. \quad (20)$$

The time evolution of T is determined by the so-called annealing schedule. (Note, that the term Simulated Annealing stems from here.) The principle underlying the choice of a suitable annealing schedule is that the initial temperature should be high enough to "melt" the system completely and should be reduced towards its "freezing point" as the search progresses.

For the annealing schedule we used the simplest and most common temperature decrement rule $T_{k+1} = \alpha \cdot T_k$ with $T_0 = 1$ and $\alpha = 0.98$ (see [18] for parameter settings).

V. Simulation results

A. Maximization of the achievable gain

The first aspect of optimization is the maximization of the achievable regulator gain. Spectrum is an expensive resource, so the goal is to "compress" the necessary spectrum amount, which can fully satisfy the spectrum demand of the NSPs. Continuous and non-continuous DSA algorithms were also investigated and compared to fixed spectrum allocation. Assume that there are more service providers in a given area, and there are more neighboring areas in a given region. Number of neighboring areas multiplied by the number of NSPs gives the number of the *nodes*, which is signed by n. In our simulation, we have 3 neighboring areas; each area has 2 service providers, so the number of nodes (n) are 6. Provider dependent interference parameters (α and β) are n-long vectors. In our simulation:

$$\alpha = [0.6 \quad 0.8 \quad 0.6 \quad 0.8 \quad 0.6 \quad 0.8],$$

$$\beta = [0.9 \quad 0.95 \quad 0.9 \quad 0.95 \quad 0.9 \quad 0.95],$$

where the first number is the interference parameter of NSP *A* in area *1*, the second belongs to NSP *B* in area *1*, the third belongs to NSP *A* in area *2*, the fourth belongs to NSP *B* in area *2*, and so on. Providers have the right to change this parameter from area to area according to geographical changes.

Providers can define the size of the spectrum slices that will be distributed to them. In the continuous case, the demand vector is:

$$[20 \quad 50 \quad 10 \quad 10 \quad 50 \quad 20],$$

where the first number is the spectrum demand of NSP *A* in area *1*, the second is of NSP *B* in area *1*, the third is of NSP *A* in area *2*, the fourth is of NSP *B* in area *2*, and so on.

The providers' demand vector in non-continuous case is:

$$[15 \quad 5][30 \quad 20][5 \quad 5][10][20 \quad 10 \quad 10][10 \quad 10],$$

where it can be seen, that NSP *A* in area *1* requires one time 15 units and one time 5 units of spectrum instead of the one continuous 20 units of spectrum in the continuous case. One more input parameter was considered, namely, a given spectrum amount, which is the initial state of the optimization, and will be minimized.

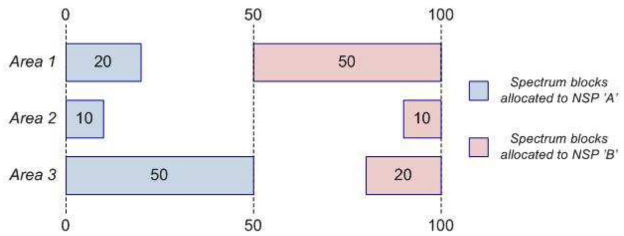

Fig. 4. Fixed Spectrum Allocation

Figure 4 shows the fixed spectrum allocation, where no allocation algorithms were used. There is no interference, because we use guard bands to separate the different providers in the neighboring areas. To satisfy the requirements, 100 units of spectrum are needed. When the continuous allocation algorithm is used, interference is allowed between the providers. Figure 5 shows the allocated spectrum blocks, where it can be seen that interference occurs at the striped parts. We need 84 units of spectrum in this case, which means that spectrum efficiency increased with 16%.

Using the non-continuous allocation algorithm, we have more spectrum blocks, consequently we have more opportunity to find the optimal allocation scheme. Further 7% gain was realized with our new non-continuous DSA algorithm as

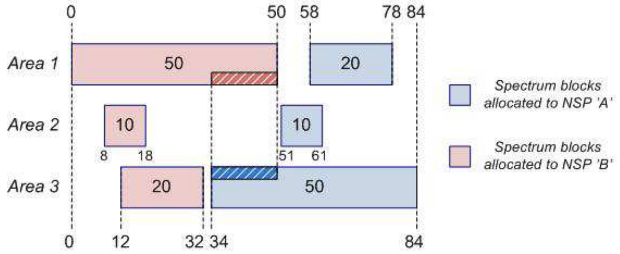

Fig. 5. Allocation with continuous DSA algorithm

it can be seen on Figure 6. 77 units of spectrum are needed to satisfy the demands in contrast to the 84 units in the continuous case, and to the 100 units in the fixed spectrum allocation. The maximum achievable gain in this simulation is 23%.

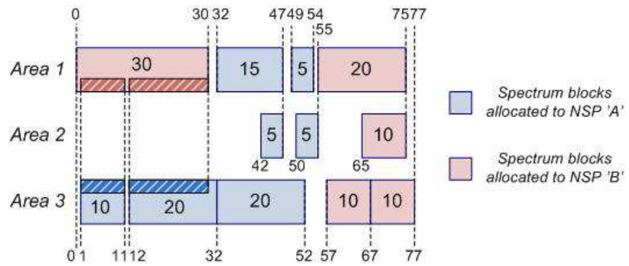

Fig. 6. Allocation with non-continuous DSA algorithm

B. Minimization of the overall interference

Fixed spectrum allocation solves the "interference problem" with the help of dedicated spectrum blocks and guard bands. Dynamic spectrum allocation allows the interference at the borders of areas in some measure according to the interference parameters α and β. Consequently, the other aspect of optimization was minimizing the overall interference. It is a common situation that the Spectrum Broker has a certain size of spectrum to satisfy the NSPs' demands, so the goal is not to "compress" the allocated spectrum as much as we can, but to allocate the spectrum blocks so that they cause the least interference to each other in the neighboring areas. Continuous and non-continuous algorithms were also investigated and compared to fixed spectrum allocation.

In this case we have 2 areas and 2 providers, so n equals 4. The two provider dependent interference parameters are n-long vectors, in our simulation they were:

$$\alpha = [0.6 \quad 0.8 \quad 0.6 \quad 0.8],$$

$$\beta = [0.9 \quad 0.95 \quad 0.9 \quad 0.95],$$

In the continuous case, the demand vector is:

$$[50 \quad 25 \quad 25 \quad 50]$$

The providers' demand vector in non-continuous case is:

$$[20 \quad 10 \quad 20][5 \quad 10 \quad 5 \quad 5][10 \quad 10 \quad 5][20 \quad 30],$$

where can be seen, that NSP *A* in area *1* requires two times 20 units and one time 10 units of spectrum instead of the one continuous 50 units of spectrum in the continuous case. One more input parameter was considered, namely a given spectrum amount, on which the demands will be satisfied.

Figure 7 demonstrates the fixed spectrum allocation, where each provider has dedicated spectrum blocks and no interference occur between the providers, but the efficiency is poor. We need 100 units of spectrum to satisfy the providers' demands.

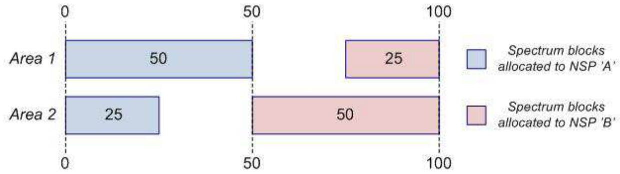

Fig. 7. Fixed Spectrum Allocation

As the next step the continuous DSA algorithm is analyzed. The given spectrum amount is 90 units, the demands are $[50 \quad 25 \quad 25 \quad 50]$. Figure 8 shows the allocated spectrum blocks. It can be seen that 10 units of spectrum suffer from interference. The level of interference is 3.3 units. The full size of the allocated blocks is $50+25+25+50 = 150$. The relative interference is $3.3 \div 150 = 0.022$, which means that 2.2% of the whole spectrum amount is wasted by the interference.

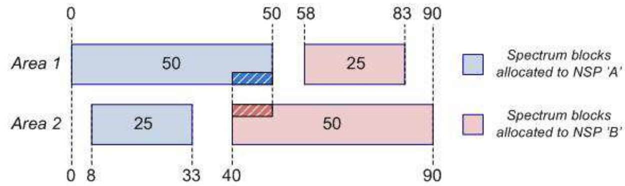

Fig. 8. Allocation with continuous DSA algorithm

Using the non-continuous DSA algorithm we achieved a small growth in efficiency, which is demonstrated on Figure 9. 10 units of spectrum are overlapping here, too, but the algorithm found the optimum allocation scheme, in which the two overlapping blocks cause the minimum overall interference. The level of interference, is 2.97 units. The full size of the allocated blocks was not changed, it is 150. The relative interference is $2.97 \div 150 = 0.0198$ now, which means that the 1.98% of the whole spectrum amount is wasted by the interference.

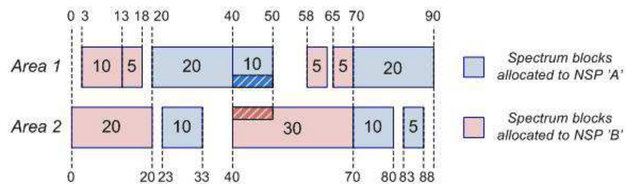

Fig. 9. Allocation with non-continuous DSA algorithm

C. Examples

Several tests were performed, the results are summarized below. The achievable gain (Table I) can be maximized if the non-continuous algorithm is used instead of the continuous or fixed ones.

TABLE I
ACHIEVABLE GAINS

#	Continuous	Non-continuous
Test 1	20%	23%
Test 2	6%	18%
Test 3	16%	23%

TABLE II
MINIMAL INTERFERENCE

#	Continuous	Non-continuous
Test 1	2.2%	1.98%
Test 2	0%	0%
Test 3	2.63%	2.63%

VI. CONCLUSIONS

In our paper we introduced a new model for Dynamic Spectrum Allocation that allows to allocate non-continuous blocks and also handles interference issues. After describing the non-continuous model, the requirements for a feasible spectrum allocation were given. The solution to find the optimal allocation was given using heuristics with Simulated Annealing. Two algorithms were tested using computer simulations, one for the maximum achievable gain, and one for the minimal overall interference. Examples for both algorithms were presented and compared to the fixed spectrum allocation and to the continuous dynamic spectrum allocation. We gave the results of 3 tests for both algorithms, which showed that the maximum achievable gain is higher, the minimum overall interference is less, or at least the same, than that using the rigid or even the continuous DSA allocation.

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