Fair and Regulated Spectrum Allocation in Licensed Shared Access Networks

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***Abstract*—We propose a novel Licensed Shared Access (LSA) spectrum allocation framework in this paper. The spectrum is made available to the licensee mobile network operators (MNOs) at specific time instants, in a specific service area, and for a specific time period. We propose a spectrum allocation algorithm which aims at providing resources to the MNOs in such a way that they can utilize them to serve their users and the resource allocation is fair at the same time. We also introduce a penalty mechanism whose output is a reduced spectrum allocation for the MNOs which violate the LSA spectrum use regulations. Our proposed algorithms are evaluated numerically and our results show that we can both guarantee fairness in spectrum allocation and penalize the MNOs that misbehave in regards to the LSA spectrum usage limitations imposed by the incumbent.**

***Index Terms*—Licensed Shared Access, Dynamic spectrum access, Cognitive radio, Fair resource allocation, Spectrum use regulation enforcement.**

I. Introduction

The advent of mobile Internet has led to phenomenal growth of the mobile data traffic over the past few years. As the features of the envisioned technologies and services of the future fifth generation (5G) mobile communication systems dictate, this trend is expected to continue for the years to come. In order to address the corresponding wireless capacity demand, it is required to allocate additional spectrum for mobile broadband (MBB) communication services. This goal can be reached with the following methods: (1) Clearing (a.k.a. refarming) spectrum and allocating it to MBB; (2) Sharing spectrum between existing incumbents and mobile network operators (MNO); (3) Using millimeter wave (30GHz-300GHz) technology.

In particular, spectrum sharing is seen by national regulators, in both Europe and USA, as a viable solution for allocating additional spectrum to MBB in a timely fashion, since technologies that are capable to implement it already exist. There are three main approaches to spectrum sharing:

- Exploitation of TV white spaces (TVWS) by uncoordinated unlicensed secondary users (SU). The lack of QoS provision guarantees to the SUs has rendered this solution unattractive to MNOs.
- Authorized Shared Access / Licensed Shared Access (ASA/LSA) [1], [2]. In ASA/LSA, MNOs can use (on an exclusive basis) the licensed spectrum owned by other incumbents when and where these incumbents are not using it. In this way, the incumbents are protected from harmful interference and the licensees benefit from the provision of predictable QoS. The band under consideration for LSA use is 2.3-2.4GHz in Europe.
- Spectrum Access Systems (SAS), which, in addition to highest-priority incumbents and high-priority licensed users, also allow low-priority unlicensed users to access the spectrum on a shared basis, as long as they do not interfere with higher priority users [3], [4]. However, for the latter type of users there are no QoS guarantees. The band foreseen for SAS deployment is the 3.5GHz band in the USA.

Several works have been appearing in recent years focusing on resource allocation problems for LSA systems. We report here an account of the works which we believe are mostly related to ours, and also explain shortly how our work differentiates as compared to them. In [5], a multi-carrier waveform based flexible inter-operator spectrum sharing concept is proposed for 5G mobile and wireless communication systems. By adapting waveforms with respect to the out-of-fragment radiation masks, inter-operator interference can be avoided. While [5] focuses on PHY aspects of resource allocation, our work is purely on resource allocation and system level aspects and considers a policy enforcement mechanism as well.

The authors of [6] propose a two-tier evolutionary game for dynamic allocation of spectrum resources enabling coexistence of incumbents and LSA licensees. The authors propose a mechanism to enable fair decisions for spectrum allocation but, they do not consider the policy enforcement dimension. In [7] a distributed antenna system (DAS) architecture is considered and LSA is investigated on the downlink cell edge in a network virtualization context. The authors derive a threshold of the LSA bandwidth ratio and associated capacity gain, providing insights on the decision making about using LSA bandwidth. In our work we consider a different architecture than DAS, i.e. a cellular one, and focus on system level resource allocation, rather than on multiple antenna techniques as in [7].

In [8] the authors present a mechanism to allocate incumbents idle spectrum to licensee access points from different operators. An LSA Auction (LSAA) mechanism is proposed that combines independent set selection by bidding. The target is a policy aiming for revenue and market regularity, while in our case we aim for fairness and enforcing the LSA spectrum usage rules from a purely technical standpoint. [9] focuses on studying a one-cell 3GPP LTE system using LSA, proposing a methodology to model the unreliable operation of an LSA frequency band, by employing a multi-line queuing system

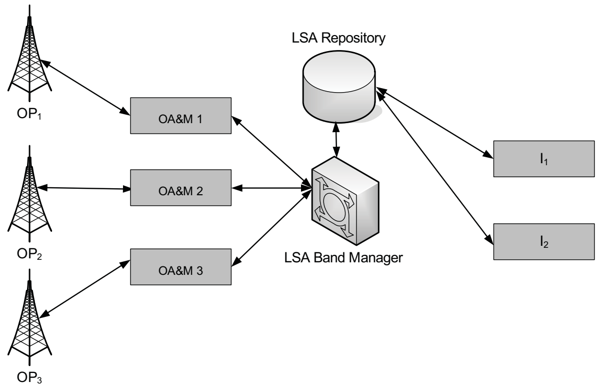

Fig. 1. System diagram for a typical LSA system with 3 independent MNOs and 2 incumbents.

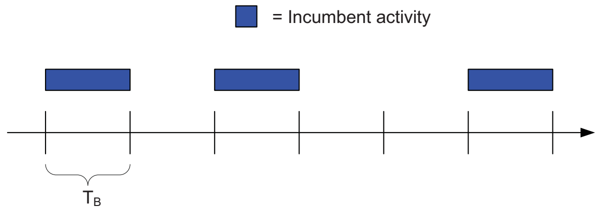

Fig. 2. Model for the incumbent's activity.

with unreliable servers. Our work differs from [9] in the sense that it focuses on a multiple cell system and investigates a resource allocation problem, besides the different theoretical tools used.

These are the main contributions of our work:

1) We propose a novel LSA spectrum allocation algorithm, providing resources to MNOs in a fair way.
2) We introduce a penalty mechanism, aiming to penalize MNOs violating the LSA spectrum use rules by reducing their spectrum allocation, and providing extra spectrum as incentive to the operators complying the regulations.
3) Our proposed algorithms are evaluated numerically and our results show that we can both guarantee fairness in spectrum allocation and penalize the MNOs that misbehave in regards to the LSA spectrum usage limitations imposed by the incumbent.

The rest of the paper is structured as follows. Section II describes the LSA architecture and the framework used in this work. The proposed spectrum allocation algorithm is discussed in Section III. We discuss our LSA spectrum use policy enforcement and associated penalties in Section IV. We then evaluate the performance of the proposed schemes in Section V and Section VI concludes the paper.

II. System Model for LSA

Fig. 1 shows the system diagram for a typical LSA system with 2 incumbents and 3 licensee MNOs. The LSA repository is responsible for managing the database record including information such as, availability of incumbent spectrum, which MNO is using what part of the spectrum, and how long it is permitted to use it in a specific service area [10]. It also contains the information about regularized/unregulated use of the assigned spectrum by the licensee operators. We discuss enforcement of spectrum use regulations in detail in Section IV.

The LSA band manager is responsible for controlling the spectrum access and provides information to the Operation, Administration, and Maintenance (OA&M) unit of each MNO about the allocated spectrum for its use. OA&M has a control channel for communicating such information. OA&M are the MNO interfaces to LSA system, and are responsible for the base station level allocation of the assigned incumbent spectrum to the MNO.

A. Model for incumbent's activity over time

In our LSA system, we consider N incumbents that act as primary users for the LSA spectrum. Each incumbent can reserve and use the spectrum for a given time frame, namely, T_B and this information is stored in the LSA repository. Fig. 2 shows an example of the incumbent's activity (as we model it). Our work focuses on dynamic spectrum access, by the MNOs, of the spectrum made available by the incumbent. For the ease of computational complexity, we assume that the spectrum (when available) is assigned to the MNOs at the beginning of T_B and the incumbent does not disrupt the MNO operation by taking back the spectrum before the end of T_B.

First, we define some terms which will be required in the discussion on spectrum access in the sequel.

Definition 1 (Level 1 Algorithm)**.** *The algorithm used to assign available spectrum from the incumbent at a specific time instant in a specific service area to one or multiple licensee MNOs is called level 1 (L1) algorithm.*

Definition 2 (Level 2 Algorithm)**.** *The algorithm used by the radio access network (RAN) of the individual licensee MNOs to (re)assign radio channels to the base stations is termed as level 2 (L2) algorithm.*

Once the MNOs acquire extra spectrum from the incumbent, they redistribute the resources according to their individual L2 algorithms. In this work, we focus on development of an L1 algorithm for the LSA scenario. The study of L2 algorithms pertains to traditional wireless networks research and is out of the scope of this work.

III. Proposed Level 1 Algorithm

The spectrum among the MNOs can be distributed using (any) L1 algorithm, depending on the utility function. In this work, we assume that there is no formal bidding process involved at the time of spectrum allocation, and that the MNOs have agreed a-priori on a fair use of shared resources such that every MNO pays the same $\$/Hz$ price. Thus, the utility function for the LSA system is to distribute the available bandwidth in a 'long and short term' fair manner. In contrast to the proposed fair spectrum allocation algorithm in [11], which distributes the available spectrum at each spectrum allocation instant in a proportionally fair manner, our work focuses on relatively longer term fairness.

Consider $n \in \{1 \ldots N\}$ is the MNO index out of N possible MNOs. For a recent spectrum allocation history window size W, let us define a priority index $PI_n(t)$ for MNO n in a time slot t by,

$$PI_n(t) = \frac{\text{Rewarded BW to MNO } n}{\text{Sum of rewarded BW by the incumbent}} \quad (1)$$

$$= \frac{1}{W} \sum_{j=t-W}^{t-1} \frac{B_n^a(j)}{\sum_{n=1}^{N} B_n^a(j)} \quad (2)$$

where $B_n^a(j)$ denotes the allocated bandwidth to MNO n.

Let us denote the available incumbent spectrum $B(j)$ at a spectrum allocation instant j by B for simplicity. The spectrum demand for an MNO n is denoted by B_n^d. The MNO computes its spectrum demand by evaluating rate requirements for its network.

The set of indices for all MNOs in a service area is defined by,

$$\mathcal{S} = \{1, \ldots N\} \quad (3)$$

The spectrum allocation works as follows:
If the incumbent offers spectrum at the beginning of frame T_B,

1) Select the MNO $n \in \mathcal{S}$ with the smallest PI and make an offer to the selected MNO n^*.
2) The selected MNO n^* is removed from the set $\mathcal{S}$ and:
   - If $B < B_{n^*}^d$ for the selected MNO n^*, the MNO has the option to refuse the offer and $B_{n^*}^a = 0$.
   - If the MNO accepts the offer, allocate $\min(B_{n^*}^d, B)$ to the MNO n^*, i.e., either the full spectrum demand or the maximum available spectrum.
3) Update $B = B - B_{n^*}^a$. Go back to step 1 if $B > 0$.
4) Terminate if $B = 0$ or $\mathcal{S} = \emptyset$.

Note that the spectrum allocation is not fair temporarily, but the MNO at the head of queue with the smallest PI is the one with the least amount of spectrum allocated in the past. This makes the proposed L1 algorithm fair to all MNOs.

IV. LSA Spectrum Sharing Policy Enforcement

When the spectrum is allocated to the licensee MNOs, they have to comply with the regulations of LSA operation. For example, an MNO n can access the spectrum borrowed from an incumbent within a certain service area, using a certain carrier frequency, and during the allocated time period. However, it is possible that the licensee MNO violates the regulations by:

1) Transmitting with more power and causing interference out of the service area.
2) Using a different carrier frequency than the allocated one.
3) Using spectrum for more time than permitted by the incumbent.

In this section, we propose a framework to penalize the misbehaving MNOs. The MNOs can violate the LSA spectrum use regulation in any of the above mentioned domain, i.e., power, frequency or time. However, our penalty framework can be introduced in one domain without any loss of generality. The amount of spectrum allocated to an MNO is the main utility for the licensee operators. If they commit any of the above mentioned violations of LSA spectrum use regulations, it is sufficient to penalize them in future spectrum assignment[1].

Let us define a Penalty Index (PEI) for an MNO n by,

$$PEI_n(t) = \quad (4)$$

$$\lim_{W \to \infty} \frac{\sum_{j=t-W}^{t-1} I(\text{Spectrum rule violated at instant } j)}{\sum_{j=t-W}^{t-1} I(\text{Spectrum assigned at instant } j)}$$

$$= \frac{N_{v,n}}{N_{a,n}} \quad (5)$$

where $I(.)$ denotes an indicator function, which is 1 if the argument is true. $N_{v,n}$ and $N_{A,n}$ denote the number of times spectrum rule was violated and the number of times spectrum was assigned to an MNO n, respectively. Please note that we do not explicitly consider 'severity' of the violation in this framework[2].

The proposed LSA L1 algorithm has fairness utility to be maximized, while the misbehaving MNOs can be penalized when performing spectrum allocation. We merge PEI with PI to have an L1 algorithm which encompasses the spectrum rule violation framework as well. A cumulative selection index (SI) is defined as,

$$SI_n = \omega PI_n + (1 - \omega) f(PEI) \quad (6)$$

where $0 \leq \omega \leq 1$ is a variable which we use to change the penalty weight and $f(PEI)$ is a general penalty function whose values vary between 0 and 1. The proposed L1 algorithm is implemented using SI_n index instead of PI_n in the algorithm presented in Section III. This belongs to a class of scheduling algorithms where different scores (ω in our case) are assigned to different utilities and it is left to the individual network operators to set 'scores' according to their preferences [13].

A careful look at the use of SI calculation in (6) for L1 algorithm unfolds a negative feedback dilemma. A $PEI > 0$ reduces the probability of spectrum access for an MNO at the current allocation instant. However, by not allocating spectrum in the current spectrum allocation instant, we enhance the MNO's priority for the next spectrum allocation instant, because the proposed L1 algorithm attempts to improve fairness by decreasing PI, if the spectrum share of an MNO reduces. The PI calculation has no mechanism to know whether the spectrum reduction is due to 'deliberate' penalty imposed by the LSA regulator. Thus, a penalty imposed on a misbehaving

[1] Please note that a time domain penalty can be specified in terms of reducing assigned spectrum's usage time, which implies average rate penalty, and is equivalent to spectrum penalty.

[2] The area of system level mechanisms to identify misbehaving MNOs in LSA is well researched upon [12] and is out of the scope of this work.

MNO will not hurt the MNO in the long run. This is what we mean by negative feedback.

To overcome this problem, we propose a slight modification in the originally proposed L1 algorithm. We propose to do the spectrum allocation in step 1 of the algorithm based on SI as before. At the same time, we perform spectrum allocation decisions based on PI (solely). The 'fictitious' spectrum allocation decisions made on the basis of PI are stored in a separate database (without actual spectrum allocation). At the next spectrum allocation instant, the algorithm computes the value of PI (to be used in SI calculation) on the basis of the 'fictitious' spectrum assignment from the database. In this way, PI computation is completely oblivious of the negative penalty due to regulatory violation and avoids negative feedback phenomenon.

A. Penalty Functions

In this section, we propose two penalty functions which have specific characteristics:

1) **Linear function:** In this case, $f(PEI) = PEI$ and all the MNOs are penalized on a linear scale depending on their regulatory violation statistics in (5).
2) **Exponential function:** In this case, $f(PEI) = (PEI)^c$ where c is a positive constant. This function grows slowly in the beginning and much faster as PEI increases. It is left to the individual LSA regulators to decide how to construct the exponential function. The rationale behind the exponential penalty function is to penalize the offenders mildly in the beginning and increase the penalty exponentially as the offense increases. We believe that it is possible that the MNO misbehaving marginally might have done it unintentionally due to some hardware issues or lack of proper control plane signalling.

We discuss the effect of choosing weight ω and parameter c through numerical evaluation in Section V.

V. Performance Evaluation

We use Monte Carlo simulations to evaluate the performance of the proposed algorithms. The window size W for computing PI is set to 20 to ensure more short term fairness; we will return to this point later in this Section. As PI computation for each MNO requires spectrum allocation in last W instants, we initialize simulations by having W time slots with zero spectrum allocation and random PI (between 0 and 1) values for every MNO. In the simulations, we consider $N = 4$ and incumbent spectrum B is normalized to 100 units without loss of generality. At each spectrum allocation instant, MNO $1, 2, 3$ choose the demand randomly out of a vector of values [50,100] with uniform probability, while MNO 4 demands for a fixed spectrum of 100 units in each time slot. We simulate 10,000 spectrum allocation instants to compute mean spectrum allocation for each MNO. Without loss of generality, we assume that an MNO accepts whatever spectrum is offered by the LSA band manager after running L1 algorithm.

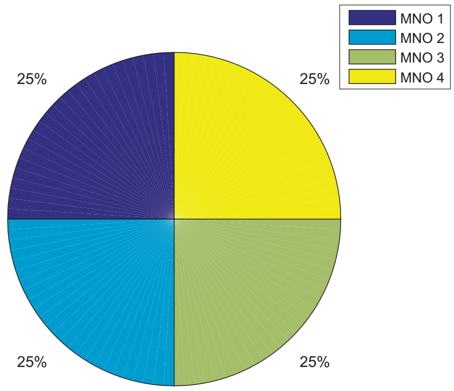

Fig. 3. Mean spectrum allocation for 4 licensee MNOs in percentage.

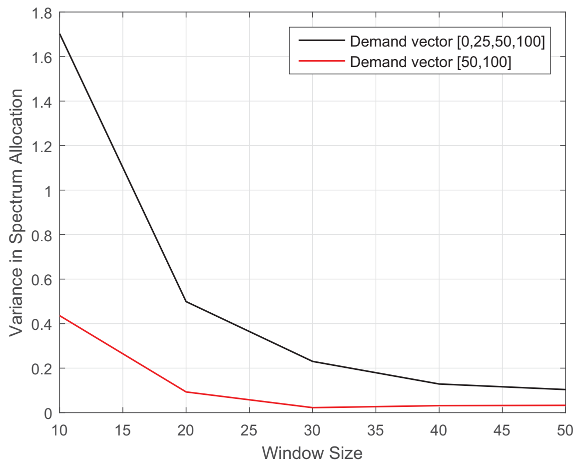

Fig. 4. Variance of mean allocated spectrum for 4 licensee MNOs for different window sizes to compute PI.

Fig. 3 shows the mean spectrum allocation to 4 MNOs. It is clear that the algorithm is fair in the long term and divides spectrum among the MNOs uniformly in spite of more demand from the MNO 4.

We observe marginal (not visible in Fig. 3) difference in mean spectrum allocation for fair L1 algorithm, which is attributed to small window size $W = 20$ for PI computation. We used small W in our experiments as small window size helps to maintain short term fairness and is one of the features of state of the art spectrum allocation algorithms. However, as confirmed in Fig. 4, if we increase the window size W, the variance of mean allocated spectrum to the MNOs decreases and disparity almost vanishes. We also plot a variance curve for a more variable demand, when the MNOs 1,2,3 choose the random demand from a vector $[0, 25, 50, 100]$ with uniform probability. In this case, the variance is affected by small window size even more severely, but the characteristics of the algorithm remain the same.

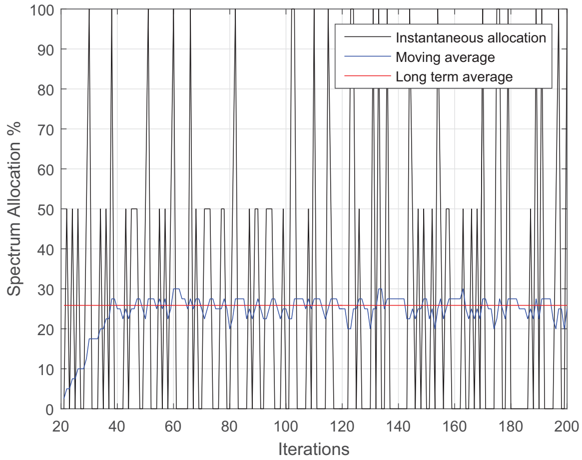

Fig. 5. Performance evaluation for short term spectrum allocation for MNO 1. The 21-200 spectrum allocation instants are plotted with first 20 instants are initialized with a random PI for every MNO.

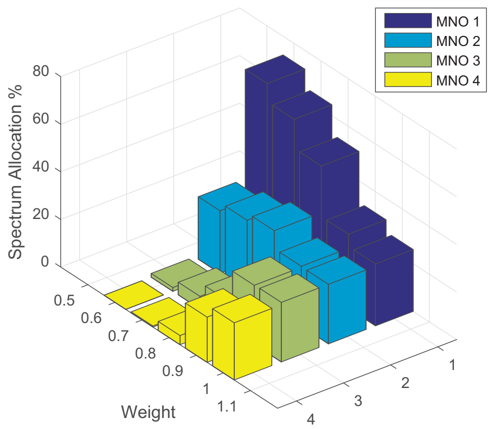

Fig. 6. Mean spectrum share for 4 licensee MNOs when using linear penalty function.

Fig. 5 shows the instantaneous spectrum allocation statistics for our proposed L1 algorithm. For illustration purposes, we only plot statistics for MNO 1. The instantaneous allocation for the operator varies between either zero or its demand. As clear from Fig. 5, when the MNO is allocated full spectrum, it has little chance of accessing the spectrum in the next a few allocation instants. Similarly, a long sequence of zero allocation is usually followed by full allocation. This justifies the algorithm's aim to achieve fairness in spectrum allocation for the MNOs.

To study the convergence of the proposed algorithm, let us define moving average of the allocated spectrum to an MNO in a time slot t by,

$$\bar{B}_n(t) = \frac{\sum_{j=t-W+1}^{t} B_n^a(j)}{W} \tag{7}$$

It is evident that moving average of the allocated spectrum for MNO 1 converges to its mean after very few iterations and diverges from mean marginally afterwards.

We evaluate the effect of penalty for violating the spectrum use regulations in Fig. 6 and Fig. 7. We assume that all the MNOs choose their demand from a vector of values [50,100] with uniform probability. We plot the mean allocated spectrum as a function of weight ω. Note that an increasing value of ω implies more weight (importance) towards fairness. As ω decreases, the weight for regulatory violation penalty increases, proportionally. We model the parameter PEI such that MNOs 1, 2, 3 and 4 have average PEI values 0, 0.1, 0.2 and 0.3 respectively; the value of 0 implies no violation for MNO 1.

In Fig. 6, we evaluate the mean spectrum allocated to each MNO when our penalty function is linear as stated in Section IV. When $\omega = 1$, the available spectrum is distributed among the MNOs equally (and fairly). When ω starts decreasing, the MNO 3 and MNO 4 with large PEI suffer while the other MNOs receive proportional incentive for behaving within the regulations. The MNO 1 gains incentive monotonically as a function of decreasing ω. However, MNO 2 gets incentive initially, but is penalized when ω is very low due to increasing weight for violation penalty and its (relatively) small PEI becomes significant.

In Fig. 7, we evaluate the effect of violation penalty when the penalty function is exponential, i.e. $(PEI)^c$. In numerical evaluation, we use $c = 2$. In general, the larger the c, the slower the penalty function growth rate in the beginning and steeper afterwards. As in Fig. 6, the MNOs with large PEI suffer more in terms of spectrum access as ω decreases. In contrast to linear function, the exponential function penalizes the MNOs at a smaller rate initially; indeed the MNOs do not lose much share (as compared to linear function) of spectrum when ω is relatively large. As ω decreases further, the MNOs with large PEI are penalized. It is interesting that contrary to linear function case, MNO 2 with $PEI = 0.1$ is not penalized at all due to its small PEI, which validates our idea behind the exponential penalty that the MNOs with small violations are not penalized much.

VI. Conclusions

We study dynamic spectrum access algorithms for LSA networks. The proposed spectrum allocation algorithm provides both long and short term fairness to the licensee MNOs. Then, we discuss the spectrum use regulation enforcement framework and propose two penalty functions. The linear function imposes heavier penalty in spectrum access as compared to the exponential function. We quantify the effect of these penalties on the spectrum allocation to the MNOs and show numerically that the MNOs with large regulatory violations suffer more in spectrum access.

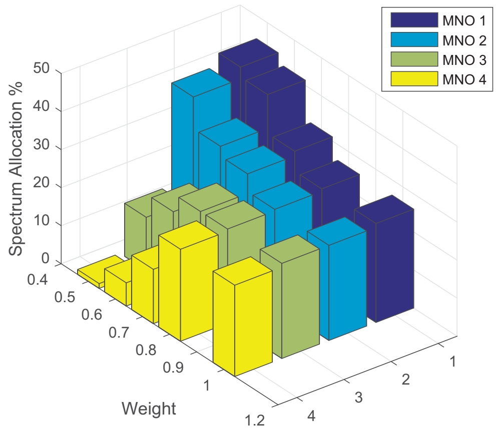

Fig. 7. Mean spectrum share for 4 licensee MNOs when using exponential penalty function.

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