This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2011 proceedings.

Cognitive Radio Resource Management exploiting Heterogeneous Primary Users

Anna Vizziello*†**, Ian F. Akyildiz***‡**, Ramon Agusti**‡**, Lorenzo Favalli**†**, Pietro Savazzi**†
* Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332, USA
Email: anna.vizziello@ece.gatech.edu
† Department of Electronics, University of Pavia, Pavia, 27100 Italy
Email: {name.surname}@unipv.it
‡ Telecommunication Engineering School (ETSETB) - Department of Signal Theory and Communications (TSC)
Technical University of Catalonia (UPC), Barcelona, 08034 Spain
Email: ian@ac.upc.edu, ramon@tsc.upc.edu

Abstract—**In this paper, a novel Cognitive Radio Resource Management (RRM) is proposed to improve the spectrum utilization efficiency. In this system, heterogeneous Primary Users (PUs) with multiple features are considered where these PU features are exploited to improve the adaptability in Cognitive Radio (CR) networks and, thus, to design an efficient Cognitive RRM. An optimization framework is developed by considering heterogeneous PUs and variable CR demands while assuring interference protection towards PUs. A suboptimal solution is proposed after showing that an optimal solution is computationally infeasible. Simulation results are conducted in terms of total achieved data rate and satisfaction of CRs requirements.**

I. INTRODUCTION

Radio Resource Management (RRM) is the key control functionality in wireless communication systems that enables the efficient utilization of limited radio spectrum and network resources. Moreover, Cognitive Radio (CR) is considered as a promising solution to improve wireless spectrum utilization and it can be exploited to overcome the limited spectrum efficiency of the classical wireless systems. Specifically, spectrum utilization can be significantly improved by allowing CR users (CRs) to access the unused spectrum resources of the Primary Users (PUs). The spectrum awareness and frequency agility of CR are among the fundamental functionalities that extend the RRM capabilities allowing RRM to identify spectral resource opportunities, called white spaces, and thus achieving a more flexible spectrum utilization [1]. As a result, it is possible to improve the spectrum efficiency.

However, in existing Cognitive RRM systems, all PUs' signals are observed as signals of higher access priority to spectral resources [5]. Grouping these signals into a single abstract utilization category removes some PU information regarding specific features, such as allowable interference level, bandwidth and activity pattern, which can otherwise be exploited by the RRM system to improve spectrum efficiency. The PU features have different values depending on the different PUs, called PU types in the following.

This paper presents a new RRM design that exploits the opportunities provided by the heterogeneity of different PUs. In particular, it is assumed that the PUs employ Orthogonal Frequency Division Multiplexing (OFDM) based standards, and the OFDM parameters are used to classify different PU types. In this context, the existence of a specific PU type influences the amount of available capacity for CRs. Thus, after calculating the available capacity of the CR network, the RRM regulates the sharing of available capacity among CRs. In particular, a cluster of CRs that share the same available resources is defined around each PU type. In other words, as it will be explained in Sec. II-B, the available capacity calculated for each specific PU type represents the capacity available for the group of CRs that share it.

The main contributions of this paper are:

- An *Optimization framework* for Cognitive RRM that exploits multiple features of heterogeneous PUs. The objective of the optimization framework is to maximize the spectral resource utilization. This is equivalent to minimize the difference between the total available capacity and the achievable CR data rates while satisfying CR demands and interference constraints.
- A *Suboptimal solution* for Cognitive RRM that requires feasible computational requirements. This solution is proposed after showing that an optimal solution is computationally infeasible. It is comprised of two stages: First, through an Admission Control Policy, the RRM assigns CRs to the appropriate cluster based on CRs demands and available capacity in the cluster. Then, based on Orthogonal Frequency Division Multiple Access (OFDMA) technique, the RRM allocates the required resources to the admitted CRs in that cluster.

The remainder of the paper is organized as follows: Sec. II presents the proposed system architecture. Sec. III explains the optimization framework. The proposed suboptimal solution is given in Sec. IV. Simulation results are shown in Sec. V and finally the conclusions are presented in Sec. VI.

II. PROPOSED SYSTEM ARCHITECTURE

The proposed system architecture is shown in Fig. 1, which consists of three different PU types with their associated CR clusters. We consider an infrastructure-based CR network with a centralized entity, such as a CR base station, which coordinates the resource allocation for CRs. The CRs send their sensing information to the CR base station, which fuses the received sensing information to detect PUs and classify their type. The CR base station maintains a table of different PU types and their specific features. The CR base station broadcasts the features associated with the detected PU types to all CRs, which will adapt their transmission parameters accordingly. In this way, the adaptability of CRs is improved

---

The work of Dr. Ian F. Akyildiz and Dr. Ramon Agusti was supported by the European Commission in the framework of the FP7 FARAMIR Project (Ref. ICT- 248351).

978-1-4244-9268-8/11/$26.00 ©2011 IEEE

through the heterogeneity of PUs, and it can be further exploited to design an efficient and flexible Cognitive RRM.

The wireless channel is modeled as frequency selective Raleigh fading, and the Additive White Gaussian Noise (AWGN) is considered with single-sided Power Spectral Density (PSD) level of N_0 for all subcarriers.

We assume that the heterogeneous PU signals utilize OFDM, and they are characterized by different values of OFDM parameters, such as guard interval length, symbol duration, and subcarrier spacing. Specifically, we use the value of subcarrier spacing to classify heterogeneous PUs [4]. After the classification process, the PU features are used for the calculation of the available capacity in a given cluster and for the Cognitive RRM design. To achieve this purpose, two steps are required:

1) The *PU type features extraction*: bandwidth, allowed interference level, activity pattern.
2) The *calculation of the available capacity* based on the identified PU features.

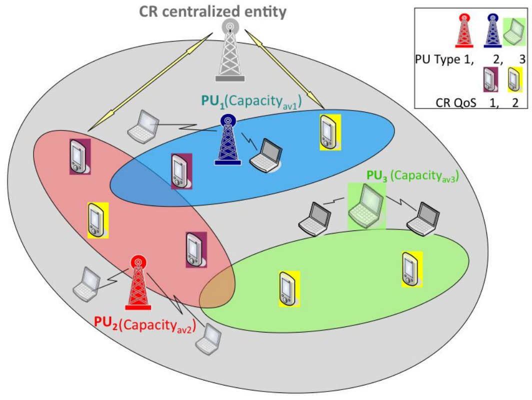

Fig. 1. Proposed System Architecture

A. PU Type Features Extraction

To extract the features of the heterogeneous PUs, first, it is necessary to detect and classify the PU signals. For this purpose, a Cyclostationary Autocorrelation Function (CAF) is utilized, which detects and classifies OFDM PU signals by exploiting the periodicities of the OFDM signals [4]. Moreover, a new PU activity index $\phi^j(i)$ [2] is considered to capture the PU activity fluctuation, successfully overcoming the drawbacks of the usual Poisson modeling.

The PU activity index is useful for the definition of the PU idle time, while the detection and classification process [4] is used for the extraction of the PU bandwidth and the allowed interference level. In fact, the detected PU types may have different value of the bandwidth and the allowed interference level according to each standard recommendations.

The CR transmitter parameters are strictly related to the PU features, i.e., the CR transmission power depends on the PU allowed interference level, the bandwidth available for CR varies according to the bandwidth used by PU, and the CR transmission time varies according to the PU idle time. More details about the CR transmitter parameters will be provided in the formulation of the optimization framework.

B. Available Capacity Calculation

At this stage, the CRs hold the information about the detected and classified PU signals with their features. Based on the capacity formulation in [4], we calculate the available capacity C_{av}^j for the j^{th} recognized PU type, whose value depends on the features of the specific PU type. In this work, we refer to the available capacity C_{av}^j determined by a specific PU type as the capacity available for a cluster of CRs that share it. C_{av}^j is defined as in the following

$$C_{av}^j = \gamma^j \left[C_1(1-P_f)P_{idle} + C_2 P_d P_{busy} + C_3(1-P_d)P_{busy}\right] \tag{1}$$

where $\gamma^j = T_{tx}^j / \left(T_{tx}^j + T_s\right)$ and T_{tx}^j is the transmission time available for the CRs that transmit on the band of the j^{th} detected PU type. As it will be explained in Sec. III, this is related to the activity index $\phi^j(i)$ [2]. T_s is the sensing time required to detect and classify the PU signal. P_{idle} and P_{busy} are the probability that a PU is absent and the probability that a PU is present, respectively, and they depend on the PU activity model [2]. P_f is the probability of false detection and P_d is the probability of detection of the used PU detector/ classifier [4]. C_1,C_2, and C_3 are the capacity terms related to different considered scenarios. The first term, in which C_1 appears, is referred to the situation in which PU is absent and CRs correctly detect the idle state without false alarm. C_1 is expressed as

$$C_1 = \frac{B^j}{N^j}\sum_{n=1}^{N^j}\log_2\left(1 + \frac{\frac{P_{s_{max}}}{N^j}\left|H_n^j\right|^2}{N_0\frac{B^j}{N^j}}\right) \tag{2}$$

in which B^j is the transmission band of the j^{th} PU, N^j is the number of subcarriers used by the j^{th} PU. H_n^j is the channel gain for the generic CR transmitting on the n^{th} subcarrier of the band B^j, and N_0 is the power spectral density of AWGN. $P_{s_{max}}$ is the total transmission power of the CRs sharing the available capacity of the j^{th} PU. When the idle state is correctly detected, the CRs can transmit to their maximum transmission power $P_{s_{max}}$.

The second term, in which C_2 appears, refers to the scenario in which the PU is present and CRs detect the PU correctly; CRs transmit and coexist with PU by lowering the total transmission power from $P_{s_{max}}$ to P_s. C_2 is given as

$$C_2 = \frac{B^j}{N^j}\sum_{n=1}^{N^j}\log_2\left(1 + \frac{\frac{P_s}{N^j}\left|H_n^j\right|^2}{P_I + N_0\frac{B^j}{N^j}}\right) \tag{3}$$

Briefly, P_s is lower than $P_{s_{max}}$ to assure interference protection towards PUs. Moreover, the value of P_s varies according to the PU type. More details on P_s are given in Sec. III. In (3), the noise is composed of AWGN with power spectral density N_0 plus P_I, the interference power of PU measured at CRs. We have simultaneous PU and CR transmissions in the same band and P_I takes into account for the interference suffered by CRs.

In the third term, in which C_3 appears, the PU is present, but the CRs fail in the detection and cause interference towards PU. The capacity C_3 is expressed as

$$C_3 = \frac{B^j}{N^j}\sum_{n=1}^{N^j}\log_2\left(1 + \frac{\frac{P_{s_{max}}}{N^j}\left|H_n^j\right|^2}{P_I + N_0\frac{B^j}{N^j}}\right) \tag{4}$$

As explained before, each available capacity C_{av}^j defined by (1) is associated to the cluster j of CRs that share it.

III. OPTIMIZATION FRAMEWORK

Once the available capacity is derived for each cluster, the achievable rate for each CR, assigned to a specific cluster, may be computed. We consider OFDMA for the CR Resource Allocation inside the cluster to satisfy the CR demands, in terms of rate requirements.

The k^{th} CR, which belongs the j^{th} cluster with available capacity C_{av}^{j}, has a transmission rate R_k that is expressed as

$$R_k = \gamma_k \frac{B_k}{N_k} \sum_{n=1}^{N_k} c_{k,n} \log_2 \left(1 + \frac{P_{k,n} \left| H_{k,n} \right|^2}{\Gamma N_0 \frac{B_k}{N_k}} \right) \tag{5}$$

where $\gamma_k = T_{tx_k} / (T_{tx_k} + T_s)$. Here we assume the bandwidth B_k is assigned to a CR after it is determined to which cluster it belongs. Thus, the value of B_k is set equal to B^j of the cluster associated with the j^{th} PU. Also the transmission time T_{tx_k} is set equal to the transmission time T_{tx}^{j} available for the CRs that transmit on the band of the j^{th} detected PU. $c_{k,n}$ is the subcarrier assignment index indicating whether the k^{th} CR occupies the n^{th} subcarrier or not, in the j^{th} cluster. To simplify the notation the apex j is omitted in the parameters of the CRs belonging to j^{th} cluster. N_k is the number of subcarriers allocated to the k^{th} CR. $P_{k,n}$ is the power allocated to the k^{th} CR in the n^{th} subcarrier. $H_{k,n}$ is the channel gain of the n^{th} subcarrier for the k^{th} CR. Γ is a factor that takes into account the effects of PU towards CR depending on the scenario. If CR correctly detects the idle state then $\Gamma = 1$, if CR is transmitting at the same time of PU or does not detect correctly the busy state, $\Gamma > 1$ for the interference suffered by CR.

In the proposed optimization framework the objective is to minimize the difference between the sum of the available capacities, $\sum_{j=1}^{J} C_{av}^{j}$, and the sum of the achievable CR date rates, $\sum_{k=1}^{K} R_k$, while assuring interference protection towards PUs, satisfying CR demands and other additional constraints. Thus, the optimization problem is formulated as

Objective:

$$\min_{P_{k,n}, B_k, T_{tx_k}, R_k^*, c_{k,n}} \quad \sum_{j=1}^{J} \sum_{k=1}^{K^j} C_{av}^{j} - R_k \tag{6}$$

Subject to:

$$c_{k,n} \in \{0,1\} \quad \forall k,n \tag{7}$$

$$\sum_{k=1}^{K} c_{k,n} = 1 \quad \forall n \tag{8}$$

$$P_{k,n} \geq 0 \quad \forall k,n \tag{9}$$

$$\sum_{k=1}^{K^j} \sum_{n=1}^{N^j} P_{k,n} \leq P_{total} \tag{10}$$

$$P_{total} = \begin{cases} P_{s_{max}} & H_0 \\ P_s & H_1 \end{cases} \tag{11}$$

$$T_{tx_k} = n_k T^j \tag{12}$$

$$T_{tx_k} \leq T_{tx}^{max} \tag{13}$$

$$R_k = R_k^* \tag{14}$$

The constraints (7) and (8) are used to ensure that each subcarrier c_n is assigned to only one CR user k.

The constraints (9), (10) and (11) are on power allocation. In particular, P_{total} in (10) is the total transmission power of the K^j CRs assigned to the j^{th} cluster over all the subcarriers N^j. As shown in (11), P_{total} must be chosen according to the scenario: besides CR transmissions when the PU is absent we consider the simultaneous transmission when a PU is present, provided that tolerable interference is satisfied. Thus, P_{total} can assume two possible values, $P_{s_{max}}$ and P_s: when the idle state is detected (scenario H_0), the CRs transmit using their maximum transmission power and P_{total} is set to $P_{s_{max}}$; when the busy state is detected (scenario H_1), the CRs transmit and coexist with PU by varying the total transmission power P_{total} from $P_{s_{max}}$ to P_s. The value of P_s is lower than $P_{s_{max}}$ to assure interference protection towards PU. Moreover, the value of P_s varies according to the PU type. We consider various interference limits, in terms of received interference power allowed by PU, related to standard recommendations. Thus, the value of P_s is chosen according to the allowed interference limit of the detected PU type. In this way, given different PU allowed interference limits, a CR adapts more efficiently its transmission power [4]. If CRs do not detect any PU, CRs are allowed to transmit with their maximum power; if a PU is detected, CRs change their transmission power depending on the PU type.

Eq. (12) and (13) are related to the transmission time. Specifically, (12) means that the CR transmission time is equal to a certain number of OFDM symbols, whose duration time is specified for the assigned j^{th} cluster, while (13) fixes the upper bound on the CR transmission time T_{tx_k}. It is connected to the PU activity index $\phi^{j}(i)$, which represents the traffic patterns on a certain band at a given time instant. The mean value of the PU arrival rate is defined as the average value of the activity index. Thus, the mean inter-arrival time is equal to the inverse of the mean value of the activity index, which is the value of the average idle time. In a CR network, it is a reasonable assumption that the CR transmission time is short compared to the average idle time. Thus, when PU is not detected, the maximum achievable value of CR transmission time T_{tx}^{max} is set equal to the average PU idle time $\frac{1}{E[\phi^{j}(i)]}$. When PU is detected and there are simultaneous PU and CR transmissions, T_{tx}^{max} is set to $\frac{1}{1-E[\phi^{j}(i)]}$.

Eq. (14) denotes that the data rate R_k of the k^{th} CR to be served must satisfy its rate requirement R_k^*. As it will explained in Sec. IV, the data rate R_k is varied to fulfill the requirement R_k^* by allocating the subcarriers $c_{k,n}$, the power level $P_{k,n}$ and the transmission time T_{tx_k}, according to (5). Moreover it should be noticed that R_k^* can have one or I_k possible values as shown in (15).

After describing the constraints (7)$-$(14), it is possible to deduce that the optimization problem, given in (6)$-$(14), is difficult to solve. In fact, it involves binary variables $c_{k,n}$ for subcarrier assignment, continuous variables $P_{k,n}$ for power allocation, and discrete time slots, T^j. In fact, the resource allocation problem consists of assigning a CR to a cluster and then allocating power and time slots to a subset of the subcarriers available to meet CR demands and minimize the objective function (6). The time interval over which these demands must be satisfied can be interpreted as a time horizon over which the Quality of Service (QoS) requirements must be met. The discrete version of the problem, where the time axis is divided into a number of discrete time slots, is in general np-hard. The additional constraint in (14) further increases the difficulty in finding the optimal solution because the feasible set is not convex. Ideally, the CR assignment to a cluster, the subcarrier and power allocation inside the cluster, along with the time interval, should be carried out jointly which leads to high computational complexity. Therefore, a low complexity algorithm with acceptable performance is much preferable than the unfeasible optimal solution.

IV. PROPOSED SUBOPTIMAL SOLUTION

In this section, we describe a low complexity algorithm for Cognitive RRM. The key factors exploited by our solution are the different values of the available capacities, according to the features of heterogeneous PUs, and the CRs capability of changing their rate requirements. The objective of the overall optimization framework is to minimize the function given by (6) according to the constraint (7)-(14). The suboptimal solution consists in decomposing the overall optimization problem into two different sub-problems: the CRs assignment to the clusters, according to their rate requirements, and the resource allocation inside the cluster, in terms of subcarriers, power and time slots allocation. We call the first sub-problem Admission Control Policy and the second one Resource Allocation inside the cluster:

- In the first sub-problem we deal with the assignment of CRs to the clusters only according to their requirements. For this reason, in (6) R_k must be replaced by R_k^*.
- After assigning the CRs to the clusters, in the second sub-problem we allocate subcarriers, power and time slots, so that, according to (5), the data rate R_k meets the requirement R_k^*. The two sub-problems are described in detail in the following sections.

A. Admission Control Policy

As explained before, the entire system consists of several CR clusters. In particular, each cluster is related to a different available capacity. Through an Admission Control Policy, we decide on a cluster to which a CR must be assigned, in order to minimize the objective function given by (6), where R_k is replaced by R_k^* for the considered sub-problem. Moreover, we consider that CRs may have different requirements, and they may modify their requirements depending on the available resources. We consider different levels of requirement for each CR. In particular, the difference between consecutive levels and the number of levels I_k can be different from user to user. At the beginning, each CR has its preferable requirement and it can vary from user to user depending on the CR needs.

In the following, the algorithm is described in detail:
Each CR choose its required R_k^* among several demand levels $L_{k,i}$, with $i = 1, ..., I_k$. The difference D_k between the levels $L_{k,i}$ is calculated as:

```
if $1 \leq i < I_k$
    $D_k = L_{k,i+1} - L_{k,i}$
else
    $D_k = 0$
end
```
(15)

The preference of the k^{th} CR is defined by selecting a value among the possible demand levels $L_{k,i}$. After ordering the CR preferable requirements from the lowest to the highest value, we start to serve the CRs. At each new request by a CR to enter the system, the available capacity C_{av}^j is calculated for each cluster. The calculation is based on (1). The request of the new CR is subtracted from the expected available capacity of each cluster and, if the amount is a positive value at least in one case, the new CR is allowed to enter the system. The CR will be assigned to the cluster that has the maximum value in the previous calculation. If, on the other hand, the value of the difference between the available capacity and the new request is a negative number for each cluster, then, the cluster with the minimum absolute value of the calculated difference is selected. The new CR is asked to decrease its demands to its lower level, e. g. by moving to a lower quality coding, in order to enter the cluster. If the CR is on its lowest level of requirement, or if the requested decrease is not enough, then another CR is asked to decrease its demand of one level, among the CRs already assigned to the selected cluster. The CR chosen to decrease its demand is the user for which a decrease in its requirement allows to minimize the unused available capacity in the cluster. On the contrary, if all CRs belonging to the selected cluster decrease their demands and the difference between the available capacity and the demand of the new CR is still negative, the process is repeated by decreasing of another level the requirements. The procedure is conducted level by level in order not to move, as much as possible, from the preferences. If it is not possible to further reduce the CR requirements in the chosen cluster, then the new request is rejected.

After considering all the CR requests, independently of whether all the users are served or not, if there is still available capacity in some of the clusters, the CRs belonging to the cluster with available resources are asked to increase their demands. The first to be satisfied is the CR whose increasing demand minimize the unused available capacity. When CRs are assigned to the clusters and their final requirements are defined, the resource allocation for power, subcarrier and time slot allocation is conducted to achieve the CR rate requirements as explained in Sec. IV-B.

B. Resource Allocation inside the cluster

After the CRs are assigned to the clusters, power, subcarriers and time slots are selected through the Resource Allocation such that the CR rate requirements are satisfied. In particular, for the allocation of available resources in each cluster we consider an OFDMA system. We refer to K^j as the total number of the CRs served in the j^{th} cluster and N^j as the number of subcarriers of one OFDM symbol for the j^{th} cluster. In the proposed subcarrier and power allocation algorithm, after initializing all the parameters, the procedure consists of N^j iterations. At each iteration, the CR, that is assigned to the cluster first, is given priority to choose its best available subcarrier. Assuming at the beginning a flat transmission power over the entire bandwidth, each subcarrier adds an equal portion of the total power P_{total}/N^j to the CR it has been assigned to. As explained in Sec. II-B and in (11), P_{total} is equal to $P_{s_{max}}$ or P_s depending on the scenario. The current power P_k of the user k is then allocated to its subcarriers by a water filling policy as in [3]. At the end of each iteration, the assigned subcarrier is excluded from the set of available subcarriers S. The procedure continues for a number of OFDM symbols, satisfying the upper bound of the CR transmission time in (13), so that all the available subcarriers are assigned to CR in order to satisfy its rate requirement. The Admission Control Policy, explained in Sec. IV-A, assures that all CRs admitted to j^{th} cluster will meet their requirements. By reallocating the power at each iteration, we ensure that each CR achieves its maximum data rate within its allocated power in order to satisfy its requirement.

V. SIMULATION RESULTS

The performance of the proposed suboptimal algorithm, described in Sec IV, is evaluated in terms of total data rate $\sum_{k=1}^{K^j} R_k$ achieved by the CRs for each cluster, so that the unused available capacity $C_{av}^j - \sum_{k=1}^{K^j} R_k$ is computed. Moreover, the satisfaction of CRs is calculated in terms of percentage of non-served CRs, CRs decreasing their data rates, CRs transmitting with their preferable requirements, and CRs increasing their data rates.

A. Simulation Environment

We implement a system composed of two PU types, 802.16 and UHF TV signal, which use OFDM transmission, and a CR centralized network. The CRs send their sensing information to a CR base station that broadcasts the presence of PU types and their features to all CRs. Moreover, we take into account different levels of interference limits allowed by the two PU types. The PU activity index $\phi^j(i)$ is randomly distributed between 0.1 and 0.4 [2]. The wireless channel is modeled as Rayleigh fading multipath with an exponential power profile. The delay spread is equal to $4 \times t_s$, where t_s is the sampling period and lasts 0.1 μs. A perfect knowledge of subchannel gains is assumed. The available capacities are computed by using the same simulation parameters in [4]. The normalized available capacities $\overline{C}^j_{av}$ are calculated as $C^j_{av}/\sum_{j=1}^{J} C^j_{av}$ and the same normalization is used for the achieved CR data rates. Moreover, we consider a system with CRs transmitting two different kinds of video stream, with the capability of changing the rate requirement depending on the available resources. The first type of video stream allows two quality versions, with mean bit rate of 400 Kbps and 90 Kbps respectively, while the second type allows three quality versions, with mean bit rate of 192 Kbps, 128 Kbps, and 64 Kbps respectively. The CR preferable requirements are randomly distributed among the mean bit rates of the two or three quality versions of the two video stream, respectively. Furthermore, three different cases are considered depending on the amount of CR requests: *Low*, *Medium*, and *High Load*.

B. CRs achieved data rates and satisfaction

We evaluate the performance of the proposed suboptimal solution by calculating the CR data rates achieved in each cluster. Fig. 2 compares the available capacity C^j_{av} and the CR data rates $\sum_{k=1}^{K^j} R_k$ achieved in each cluster according to the Cognitive RRM, whose values are normalized as explained before. As shown in Fig. 2, the value of the available capacity C^j_{av} of the j^{th} cluster varies according to the detected PU type. Specifically, the value of C^1_{av}, the available capacity for Cluster 1, is higher than C^2_{av}, the available capacity for Cluster 2. In fact, C^1_{av} and C^2_{av} are calculated by (1) and their values depend on the features of the detected PU type, 802.16 and UHF TV signal respectively.

In Fig. 2, we consider two cases:

- CRs with variable data rate requirements (VRR),
- CRs with fixed data rate requirements (NO-VRR).

In Fig. 2 we also compare the satisfaction of different CRs with VRR and with NO-VRR. In Fig. 2(a), 2(b) and 2(c) we show the normalized available capacities and achieved CR data rates in different cases. In Fig. 2(d), 2(e) and 2(f) we show the satisfaction of CRs calculated in terms of percentage of non-served CRs, CRs decreasing their data rates, CRs transmitting with their preferable requirements, and CRs increasing their data rates.

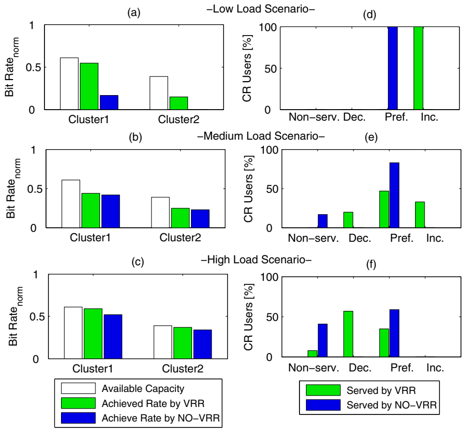

Fig. 2. Simulation Results

In a low load case, the number of CRs requests is much lower than the available resources. The total unused available capacity is 30% of the total available capacity with the VRR algorithm. When NO-VRR algorithm is used, the unused capacity is 98% of the total available capacity. With the VRR, the CRs can increase their data rates, while with the NO-VRR algorithm they can only satisfy their preferences.

In a medium load case, the total unused available capacity is 26% of the total available capacity when the VRR algorithm is used, while it becomes 35% with the NO-VRR. In the latter case, even if more CRs transmit with their preferable requirements, some CRs are not served. With the VRR some CRs decrease their requirements but others increase their data rates, while assuring that everybody is served.

In a high load case, the total unused available capacity is 4% of the total available capacity when the VRR algorithm is used, and the 14% with the NO-VRR algorithm. As expected, less CRs are not served with the VRR than with the NO-VRR.

Simulation results show that the value of the available capacity for CRs varies according to the detected PU types. Moreover, these results show that the overall performance of the network, in terms of the achieved data rate, is improved when variable CR requirements needed. These improvements are observed by higher achieved data rates, and hence less wasted available capacity and higher satisfaction rate, in terms of percentage of served CRs out of total number of CRs.

VI. CONCLUSION

In this paper, an optimization framework for Cognitive RRM has been developed. The key point of the approach is the exploitation of multiple features of heterogeneous PUs and variable CR rate requirements for the efficient utilization of spectrum resources. Being the optimal solution unfeasible, a suboptimal solution has been proposed, which satisfies the CRs demands through an efficient and adaptive use of available resources. The procedure has the objective to minimize at each step the difference between the available capacity and the achieved data rates of the CRs. In this way, the number of operations to adjust the CR data rates are reduced, while pursuing the satisfaction of the CR demands and balancing between the number of CRs served and the available capacity.

REFERENCES

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer Networks, Elsevier*, Vol. 50, no. 13, pp. 2127-215, Sept. 2006.

[2] B. Canberk, I. F. Akyildiz, and S. Oktug, "Primary User Activity Modeling Using First-Difference Filter Clustering and Correlation in Cognitive Radio Networks," *IEEE/ACM Transactions on Networking*, Vol. 19, No. 1, pp. 170-183, February 2011.

[3] C. Mohanram and S. Bhashyam, "A sub-optimal joint subcarrier and power allocation algorithm for multiuser OFDM," *IEEE Communications Letters*, vol. 9, no. 8, pp. 685687, 2005.

[4] A. Vizziello, I. F. Akyildiz, R. Agusti, L. Favalli, and P. Savazzi, "OFDM Signal Type Recognition and Adaptability Effects in Cognitive Radio Networks," *in Proc. of IEEE GLOBECOM 2010*, Miami, Florida, USA, 6-10 Dec. 2010.

[5] B. Wang, K. J. R. Liu, "Advances in Cognitive Radio Networks: A Survey," Selected Topics in Signal Processing, *IEEE Journal of*, vol.5, no.1, pp.5-23, Feb. 2011.