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# Cognitive radio resource management exploiting heterogeneous primary users and a radio environment map database

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**Abstract** The efficient utilization of radio resources is a fundamental issue in cognitive radio (CR) networks. Thus, a novel cognitive radio resource management (RRM) is proposed to improve the spectrum utilization efficiency. An optimization framework for RRM is developed that makes the following contributions: (i) considering heterogeneous primary users (PUs) with multiple features stored in a radio environment map database, (ii) allowing variable CR demands, (iii) assuring interference protection towards PUs. After showing that the optimal solution is computationally infeasible, a suboptimal solution is consequently proposed. Performance evaluation is conducted in terms of total achieved data rate and satisfaction of CR requirements.

**Keywords** Radio resource management · Optimization · Interference protection · Cognitive radio networks

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## 1 Introduction

In wireless communication systems, radio resource management (RRM) is the key functionality that enables the efficient utilization of the limited radio spectrum and network resources. The achievable spectrum efficiency of RRM in current wireless systems is limited by the wasteful static frequency assignment and fixed radio functionalities.

Cognitive radio (CR) is considered as a promising solution to improve wireless spectrum utilization, thus overcoming the limited spectrum efficiency of the classical wireless systems. Specifically, spectrum utilization can be significantly improved by allowing the CR users to access the unused spectrum resources of the primary users (PUs). However, to avoid interference towards PUs, a CR has to vacate the spectrum band as soon as a PU is detected in the same channel.

The spectrum awareness and frequency agility of CR technology are among the fundamental functionalities that extend RRM capabilities. These functionalities allow RRM to identify new spectral resource opportunities called white

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spaces, thus enabling a more efficient and flexible spectrum utilization [1].

In recent years, several RRM designs have been developed for CR networks using various control strategies and implementation mechanisms [14]. In [9] the authors propose a cognitive resource manager (CRM) approach that contains specific methods to collect and store RF environment data in memory locations. These data are accessible by all communication layers for optimization purposes and learning processes.

Existing RRM designs [9, 14] group PU signals into a single abstract utilization category with higher priority access to spectral resources, regardless of its particular features. On the contrary, a RRM system can improve its spectrum efficiency by considering heterogeneous PUs with all their different characteristics.

This paper exploits the opportunities provided by heterogeneous PUs, also called PU types in the following. Once the PUs are classified, information about their features, such as allowable interference level, bandwidth and activity pattern, are stored in a radio environment map (REM) database and exploited to develop an efficient RRM scheme.

In this context, the existence of a specific PU type along with its spectral features influences the amount of available capacity for CRs. Thus, after calculating the available capacity of the CR network, the RRM manages 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. Consequently, the CR system will be composed by several clusters, one per each detected PU type.

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 one is computationally infeasible. It is comprised of two stages: first, through an Admission Control (AC) policy, the RRM assigns the CRs to the appropriate cluster based on CR demands and available capacity in the clusters. Then, through a Cluster Resource Allocation (CRA) procedure, the RRM allocates the required resources to the admitted CRs in each cluster.

The remainder of the paper is organized as follows: Sect. 2 presents the proposed system architecture. Section 3 explains the optimization framework. The proposed suboptimal solution is given in Sect. 4. Simulation results are shown in Sect. 5 and finally the conclusions are presented in Sect. 6.

## 2 Proposed system architecture

As shown in Fig. 1, we consider an infrastructure-based CR network with a centralized base station (BS) that

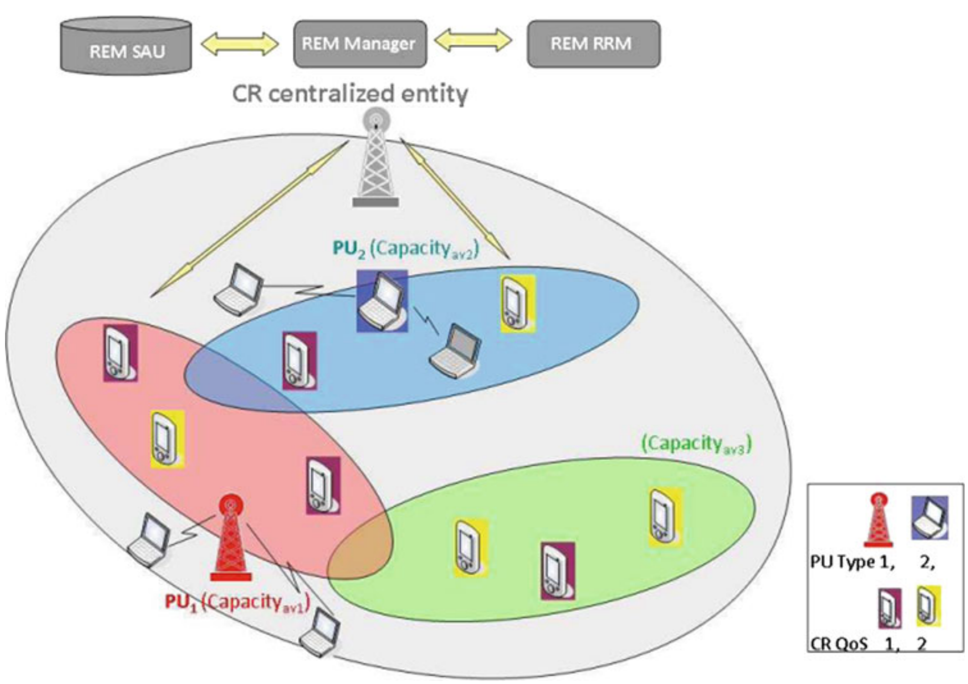


**Fig. 1** Proposed system architecture

coordinates the resource allocation for CRs. According to this scenario, CRs send sensing information to the CR BS for processing and storing it in a REM database.

In particular, radio environment maps (REMs) have been proposed as integrated databases that provide an abstraction of the radio environment conditions [10, 15]. REMs are used to obtain the required geo-localized spectral activities, policy information, propagation models and other radio frequency (RF) environment information, which are then used to estimate the available spectrum resources. A REM covers multi-domain environmental information such as geographical features, available services, spectral regulations, location of diverse entities of interest (e.g., radios, reflectors, obstacles) as well as radio equipment capability profiles, relevant policies and past experiences.

Specifically, the CR BS is responsible for collecting sensing data, constructing the REM, and coordinating the RRM. It is composed of:

- the *REM Manager*, which processes sensing measurements to construct REMs;
- the *REM storage and acquisition unit* (*SAU*), which stores in a local database both sensing measurements and output data of the REM Manager,
- the *REM RRM*, which is responsible for the resource management.

The measurements obtained by the CRs are collected in the REM SAU and processed by the REM Manager to identify the free bands and the PU types in the considered geographical area. This process [11] is not detailed in this paper because it is out of the scope of this work. After classifying the existing PUs, the REM Manager updates the stored information and for each detected PU type retrieves the following features: bandwidth, allowable interference level and activity pattern. The REM information is then used by the REM RRM to calculate the available capacity and perform resource management operations. More details about the way of disseminating such information throughout CR network can be found in [12].

Without loss of generality, we consider the scenario illustrated in Fig. 1 where two types of PU networks are considered, e.g., IEEE 802.16 and 802.11 standards. Each PU type identifies a cluster of CRs with the associated available capacity. As can be seen in Fig. 1, the CR clusters can overlap in space. Moreover, Fig. 1 shows a third cluster that is not associated with any PU and corresponds to a band that is completely free from PU transmissions in the geographical area of interest. For example, some bands in digital video broadcasting (DVB) spectrum range are not used at all, while other bands in the [1.240, 1.300] and [1.525, 1.710] MHz ranges are highly under-utilized (less than 2 %) [7]. Following this reasoning, we consider that the information about the free bands is known and stored in the REM. As it will be explained in Sect. 2.2, the available capacity of the cluster associated with a free band is calculated depending on the width of the free band and the maximum CR transmission power.

To complete the scenario, since CRs may have different demands in terms of quality of service (QoS), in Fig. 1 we show two types of CRs that may pose different QoS requirements to the resource allocation functionality.

Table 1 lists all the relevant notation used in this paper. The wireless channel is frequency selective, and additive white gaussian noise (AWGN) is considered with single-sided power spectral density (PSD) level of $N_0$ for all subcarriers.

Before detailing the proposed RRM scheme, the features of heterogeneous PUs are extracted since they directly influence the CR parameters, as explained in Sect. 2.1. The PU features are also used for calculating the available capacity for each cluster, as detailed in Sect. 2.2.

### 2.1 PU type features extraction

To detect and classify PU signals the algorithm introduced in [11] is exploited, as briefly recalled here below.

In particular, it is assumed that PUs employ orthogonal frequency division multiplexing (OFDM) based standards. A cyclostationary autocorrelation function (CAF) detects and classifies OFDM PU signals by exploiting the periodicities of OFDM modulations. The time interval in which the CAF exhibits the maximum is used to distinguish different PUs. In fact, this time interval turns out to be equal to $1/\Delta f_j$, where $\Delta f_j$ is the subcarrier spacing, and its value is dependent on the PU type.

Spectrum availability also depends on traffic patterns. As a consequence, a precise model of the PU activity is useful to characterize transmission opportunities. In our analysis, we consider the model introduced in [2], which follows the spiky fluctuations of the PU activities over time and models the PU traffic accurately. In this way, the drawbacks of the usual Poisson modeling can be successfully overcome. A new primary user activity index $\phi_j(i)$ [2] is derived to capture PU activity fluctuation.

The PU activity index $\phi_j(i)$ and the subcarrier spacing $\Delta f_j$ are used for *PU features extraction*, i.e. bandwidth, allowable interference level and idle/busy time that direct influence CR transmitter parameters:

- The PU activity index $\phi_j(i)$ is useful for the definition of PU idle/busy time. In particular, $\phi_j(i)$ represents the traffic patterns on the $j$th band at time $i$. The PU arrival rate is defined equal to the activity index $\phi_j(i)$. Thus, the inter-arrival time corresponds to $1/\phi_j(i)$, which is the idle time $T_j^{idle}$. The busy time $T_j^{busy}$ is set equal to

**Table 1** Notation

| Symbol | Definition |
|---|---|
| $H_0$ | Hypothesis of band free from PU transmissions |
| $H_1$ | Hypothesis of band with possible PU transmissions |
| $j$th | Index of the CR cluster built around the PU type or free band |
| $k$th | Index of the CR |
| $n$th | Index of subcarrier |
| $B_j$ | Bandwidth of the $j$th PU type or free band |
| $B_k$ | Bandwidth of the of the $k$th CR |
| $i$ | Instant of time |
| $T_j^{idle}$ | Idle time of the $j$th PU type |
| $T_j^{busy}$ | Busy time of the $j$th PU type |
| $T_j$ | OFDM symbol time in the $j$th cluster |
| $T_{tx_j}$ | Transmission time allowed in the $j$th cluster |
| $T_{tx_k}$ | Transmission time of the $k$th CR |
| $T_{tx}^{max}$ | CR maximum transmission time |
| $T_s$ | Sensing time |
| $\Delta f_j$ | Subcarrier spacing of $j$th PU type |
| $\phi_j(i)$ | Activity index of $j$th PU type |
| $C_j^{av}$ | Available capacity for the $j$th cluster |
| $\overline{C}_j^{av}$ | Normalized available capacity for the $j$th cluster |
| $\gamma_j$ | Efficiency time in the $j$th cluster |
| $\gamma_k$ | Efficiency time for the $k$th CR |
| $C_j^{(H_0)}$ | Available capacity under hypothesis $H_0$ |
| $C_j^{(H_1)}$ | Available capacity under hypothesis $H_1$ |
| $C_1$ | Capacity term of $C_j^{(H_1)}$ |
| $C_2$ | Capacity term of $C_j^{(H_1)}$ |
| $H_{j,n}$ | Channel gain on the $n$th subcarrier of the $j$th band |
| $N_0$ | Power spectral density of AWGN |
| $N_j$ | Number of subcarriers in the $j$th band |
| $N_k$ | Number of subcarriers of $k$th CR |
| $K_j$ | Number of CRs in the $j$th cluster |
| $P_f$ | Probability of false detection |
| $P_d$ | Probability of detection |
| $P_{idle}$ | Probability of idle state |
| $P_{busy}$ | Probability of busy state |
| $I_j^{th}$ | Interference threshold allowed by $j$th PU type |
| $P_{k,n}$ | Power of the $k$th CR on the $n$th subcarrier |
| $P_{total}$ | Total power of the CRs cluster |
| $P_{s_{max}}$ | Maximum CR transmission power |
| $P_s$ | CR transmission power (contemporary PU and CR transmissions) |
| $P_I$ | Interference power of PU measured at CR |
| $R_k$ | Transmission rate of the $k$th CR |
| $R_k^*$ | Rate requirement of the $k$th CR |
| $L_{k,i}$ | Demand level value of the $i$th level for $k$th CR |
| $D_{k,i}$ | Difference between demand level $i$th and $(i-1)$th for $k$th CR |
| $I_k$ | Number of demand levels for $k$th CR |
| $\Gamma$ | Factor accounting for the effects of PU towards CR |
| $u_{k,j}$ | Variable for the allocation of the $k$th CR to the $j$th cluster |
| $c_{k,n}$ | Variable for the assignment of the $n$th subcarrier to the $k$th CR |
| $n_k$ | Number of OFDM symbol assigned to the $k$th CR |
| $\eta$ | Propagation factor |
| $d_{j,k}$ | Distance between the $k$th CR and the receiver of the $j$th PU type |

$1/(1-\phi_j(i))$. As deducible, the transmission time allowed to a CR is strongly related to the idle/busy time of PUs.

- The subcarrier spacing $\Delta f_j$ is used to extract the value of PU bandwidth and allowable interference level. In particular, the value of $\Delta f_j$ obtained by the CAF detector is compared with the known subcarriers spacing of PU standards in order to extract its type. It is assumed that the values of bandwidth and allowed interference levels are known for each standard and stored in the REM. The achievable CR data rate directly depends on the bandwidth used by PU transmissions, and the PU allowed interference levels influence the CR transmission power. In fact, besides CR transmissions when the PU is absent, we consider simultaneous CR and PU transmissions when a PU is present, provided that tolerable interference level is satisfied. Various interference limits are defined according to the robustness of a PU standard transmission.

Figure 2 shows how CR parameters, i.e. transmission time, power, and bandwidth, are adapted according to the PU features. The scenario represented in the figure accounts for one band free from PU transmissions and two bands where different PU types have been detected.

In particular, the CRs assigned to transmit in the free band will use the maximum transmission power until they reach their rate requirements. On the contrary, the CRs allocated in the band where a PU has been detected will vary their parameters not only depending on their requirements but also according to PU features. Let us consider one of the two PU bands in the figure. The CRs assigned to transmit in that band can use the maximum transmission power for a time period equal to the idle time of the detected PU type in that band. When the PU resumes its transmission, there are contemporary PU and CRs transmissions, and the CRs must lower the transmission power according to the interference threshold allowed by the detected PU itself. This is done for a time period equal to the PU busy time in order to avoid interference.

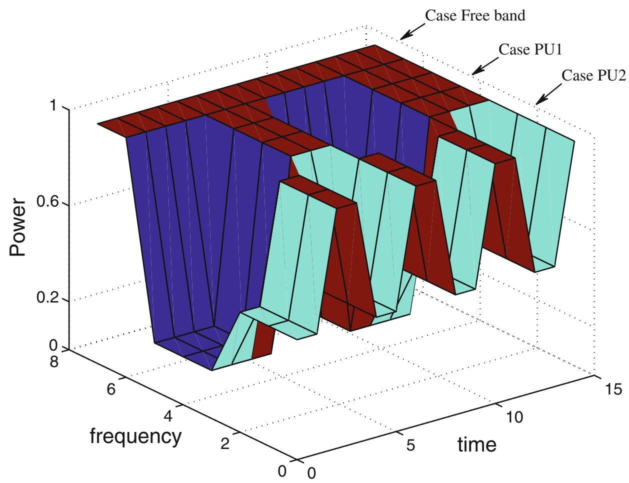


**Fig. 2** CR parameters adaptation depending on the features of heterogeneous PUs: transmission time, power, bandwidth

More details about CR transmitter parameters will be provided in the following formulation of the optimization framework.

## 2.2 Available capacity calculation

At this stage, the CRs have the information about the detected heterogeneous PUs and their features. A group of CRs allowed to transmit in the $j$th band forms a cluster of CRs. The $j$th band can be free or occupied by a specific PU type. Based on the formulation in [11], we calculate the available capacity $C_j^{av}$ for the $j$th cluster of CRs that share it.

In more details, $C_j^{av}$ is defined as:

$$C_j^{av} = \gamma_j C_j \tag{1}$$

where $\gamma_j = T_{tx_j}/(T_{tx_j} + T_s)$ is the efficiency, expressed as the ratio between the transmission time allowed in the $j$th cluster $T_{tx_j}$ and the transmission plus sensing time $T_s$. Specifically, $T_s$ is equal to $T_c + T_r$, where $T_c$ is the time useful to detect and classify PUs, and $T_r$ is the time required for consulting the REM in order to recover the values of PU features. $C_j$ is defined as

$$C_j = \begin{cases} C_j^{(H_0)} & \text{Hypothesis } H_0 \\ C_j^{(H_1)} & \text{Hypothesis } H_1 \end{cases} \tag{2}$$

where $C_j^{(H_0)}$ is the capacity of the $j$th cluster of a free band (hypothesis $H_0$) and $C_j^{(H_1)}$ is the capacity of the $j$th cluster in which PU can be transmitting (hypothesis $H_1$). Note that the hypothesis $H_0$ refers to a band completely free from PU transmissions, whose information is stored in the REM; while the hypothesis $H_1$ refers to a band that can only be temporally free.

Under the hypothesis $H_1$, $\gamma_j$ in (1) varies according to the features of the detected PU. In particular, the available CR transmission time available $T_{tx_j}$ will depend on PU activity index $\phi_j(i)$ [2]. In case of completely free band (hypothesis $H_0$) there is not any restriction about CR transmission time, and $T_{tx_j}$ will be equal to the time necessary to fulfill CR requirement.

$C_j^{(H_0)}$ is expressed as

$$C_j^{(H_0)} = \frac{B_j}{N_j} \sum_{n=1}^{N_j} \log_2 \left( 1 + \frac{P_{s_{max}} \left| H_{j,n} \right|^2}{N_0 \frac{B_j}{N_j}} \right) \tag{3}$$

in which $B_j$ is the width of the $j$th band free from PU transmissions, $N_j$ is the number of subcarriers in the $j$th band, $H_{j,n}$ is the channel gain on the $n$th subcarrier of the $j$th band and $N_0$ is the AWGN power spectral density. $P_{s_{max}}$ is the maximum total transmission power of CRs sharing the available capacity of the considered cluster.

The case of temporally free band is considered in the definition of $C_j^{(H_1)}$, which is computed as:

$$C_j^{(H_1)} = \left[ C_1(1 - P_f)P_{idle} + C_2 P_d P_{busy} \right] \tag{4}$$

The first term is referred to the situation in which the PU is absent and the CRs correctly detect the idle state without false alarm. The second term refers to the case in which the PU is present and the CRs correctly detect it. If the first case happens, the CRs can transmit at the maximum power $P_{s_{max}}$ for a time period $T_{tx_j} = T_j^{idle} = 1/\phi_j(i)$. In the second case, the CRs have to lower the transmission power to $P_s$ for a period $T_{tx_j} = T_j^{busy} = 1/(1 - \phi_j(i))$ to coexist with the PU without causing interference. More details on $P_s$ are given in Sect. 3.

$P_{idle}$ and $P_{busy}$ are respectively the probability that a PU is absent and the probability that a PU is present and they depend on the PU activity model [2]. $P_f$ is the probability of false detection, while $P_d$ is the probability of correct detection of the PU detector/ classifier [11], briefly summarized in Sect. 2.1.

$C_1$ is expressed as:

$$C_1 = \frac{B_j}{N_j} \sum_{n=1}^{N_j} \log_2 \left( 1 + \frac{P_{s_{max}} \left| H_{j,n} \right|^2}{N_0 \frac{B_j}{N_j}} \right) \tag{5}$$

where $B_j$ is the transmission band of the $j$th PU, $N_j$ is the number of subcarriers that can be used by the $j$th PU. $H_{j,n}$ is the channel gain on the $n$th subcarrier of the band $B_j$, and $N_0$ is the power spectral density of AWGN.

$C_2$ refers to the case in which the PU is present and the CRs correctly detect it; the CRs transmit and coexist with the PU by lowering the total transmission power from $P_{s_{max}}$ to $P_s$. $C_2$ is given by

$$C_2 = \frac{B_j}{N_j}\sum_{n=1}^{N_j}\log_2\left(1 + \frac{P_s|H_{j,n}|^2}{P_I + N_0\frac{B_j}{N_j}}\right) \quad (6)$$

Briefly, $P_s$ is lower than $P_{s_{max}}$ to assure interference protection towards PUs and varies according to the PU type. Since we have simultaneous PU and CR transmissions, in (6) the noise is composed of AWGN with power spectral density $N_0$ plus the interference power $P_I$ of PU measured at CRs.

## 3 Optimization framework

After deriving the available capacity for each cluster, the achievable data rate for each CR may be computed. We assume to use an OFDMA protocol for CR resource allocation inside the cluster.

Let us consider the $k$th CR that belongs to the $j$th cluster with available capacity $C_j^{av}$. Since we are now focusing on a single cluster, to simplify the notation in (7) we omit the apex $j$ in the parameters of the $k$th CR. The transmission rate $R_k$ is expressed as

$$R_k = \gamma_k \frac{B_k}{N_k}\sum_{n=1}^{N_k} c_{k,n}\log_2\left(1 + \frac{P_{k,n}|H_{k,n}|^2}{\Gamma N_0\frac{B_k}{N_k}}\right) \quad (7)$$

where $\gamma_k = T_{tx_k}/(T_{tx_k} + T_s)$. The transmission time $T_{tx_k}$ in $\gamma_k$ depends on the transmission time $T_{tx_j}$ available for the CRs transmitting in the $j$th cluster. If the cluster is associated with the $j$th detected PU type, we must take into account the idle/busy time for computing the upper bound of the available transmission time $T_{tx_j}$, as expressed in (1), (2) and (4); this is not required if the cluster is associated with a free band. Besides, in the latter case the sensing time $T_s = T_c + T_r$ is given only by the time $T_r$ required for consulting the REM. In fact, we reasonably assume that detection time $T_c$ is equal to zero because the information about completely free bands is stored in the REM database.

In (7) $B_k$ is set equal to $B_j$ of the cluster the $k$th CR belongs to. $c_{k,n}$ is the subcarrier assignment index indicating whether the $k$th CR occupies the $n$th subcarrier or not, in the $j$th cluster. $N_k$ 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. $\Gamma$ is a factor that takes into account the effects of PU towards CR depending on the scenario. If the idle state has been correctly detected then $\Gamma = 1$, otherwise if the busy state has not detected or simply there are contemporary CR and PU transmissions as in (6), $\Gamma > 1$ for the interference suffered by the CR.

In the proposed optimization framework the objective is to minimize the difference between the sum of the available capacities, $\sum_{j=1}^{J} C_j^{av}$, and the sum of the achievable CR date rates in each cluster, $\sum_{k=1}^{K_j} R_k$, while assuring interference protection towards PUs as main constraint. The optimization problem is formulated in the following.

Objective:

$$\min_{u_{k,j},\, c_{k,n},\, P_{k,n},\, T_{tx_k},\, R_k^*} \sum_{j=1}^{J}\sum_{k=1}^{K_j} C_j^{av} - R_k \quad (8)$$

Subject to:

$$u_{k,j} \in \{0,1\} \quad \forall k,j \quad (9)$$

$$c_{k,n} \in \{0,1\} \quad \forall k,n \quad (10)$$

$$\sum_{k=1}^{K_j} c_{k,n} = 1 \quad \forall n \quad (11)$$

$$P_{k,n} \geq 0 \quad \forall k,n \quad (12)$$

$$\sum_{k=1}^{K_j}\sum_{n=1}^{N} P_{k,n} \leq P_{total} \quad (13)$$

$$P_{total} = \begin{cases} P_{s_{max}} & (H_0\,|\,H_1 \text{ with PU silent}) \\ P_s & (H_1 \text{ with PU transmitting}) \end{cases} \quad (14)$$

$$T_{tx_k} = n_k T_j \quad (15)$$

$$T_{tx_k} \leq T_{tx}^{max} \quad (16)$$

$$R_k = R_k^* \quad (17)$$

Constraints (9)–(17) are explained in the following.

Constraint (9) accounts for the allocation of the $k$th CR to the $j$th cluster.

Constraints (10) and (11) are used to ensure that each subcarrier $c_n$ is assigned to only one CR user $k$.

Constraints (12), (13) and (14) deal with power allocation. In particular, $P_{total}$ in (13) is the total transmission power of $K_j$ CRs assigned to the $j$th cluster over all the subcarriers $N_j$. As shown in (14), $P_{total}$ must be chosen according to the scenarios: in case of $H_0$, the CRs can transmit at $P_{s_{max}}$; in case of $H_1$, the CRs can transmit at $P_{s_{max}}$ or at lower level $P_s$, as expressed in (4)–(6).

Specifically, when $H_1$ holds, a PU has been detected and we consider two possible situations: CR transmissions when the PU is absent and simultaneous transmission when the PU is present, provided that tolerable interference is satisfied. During the idle state, the CRs transmit using their maximum transmission power and $P_{total}$ is set to $P_{s_{max}}$; during the busy state, the CRs transmit and coexist with the PU by lowering the total transmission power $P_{total}$ from $P_{s_{max}}$ to $P_s$ to assure interference protection towards the PU. The time period in which $P_{total}$ is set to $P_{s_{max}}$ or $P_s$ is equal to PU idle time or busy time respectively, and it is calculated according to Sect. 2.1.

The value of $P_s$ is chosen according to the allowed interference limit $I_j^{th}$ of the detected PU type, as expressed in (18). In particular, we consider the interference limits in terms of received interference power allowed by PU as defined in the standard recommendations. $P_s$ for $K_j$ CRs transmitting in the $j$th cluster is calculated by the path-loss propagation model:

$$P_s = I_j^{th} + 10\eta \sum_{k=1}^{K_j} \lg_{10}(d_{j,k}) \quad (18)$$

where $\eta$ is the path loss exponent, and $d_{j,k}$ is the distance between the $k$th CR and the receiver of the $j$th PU type. Without loss of generality, we assume that $d_{j,k}$ can be calculated using information stored in the REM. Considering different PU allowed interference limits, a CR adapts more efficiently its transmission power. Briefly summarizing, 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 PU type.

Constraints (15) and (16) are related to the transmission time. Specifically, (15) means that CR transmission time is equal to a certain number of OFDM symbols, whose duration time $T_j$ is specified for the assigned $j$th cluster; while (16) fixes the upper bound on CR transmission time $T_{tx_k}$ depending on PU activity. Obviously, we do not take into account (16) in the $j$th cluster that is completely free from PU transmissions (hypothesis $H_0$). On the contrary, in a cluster associated with a detected PU type (hypothesis $H_1$), the CR transmission time is bounded by the PU idle/busy time. Thus, when a PU is not transmitting, then $T_{tx}^{max} = T_j^{idle}$, while when it is transmitting and there are simultaneous PU and CR transmissions, then $T_{tx}^{max} = T_j^{busy}$, as expressed in (1), (2) and (4).

Constraint (17) denotes that the data rate $R_k$ of the $k$th CR must satisfy its rate requirement $R_k^*$. As it will be explained in Sect. 4, $R_k$ can vary by allocating subcarriers $c_{k,n}$, power level $P_{k,n}$ and transmission time $T_{tx_k}$, according to (7). Moreover it should be noticed that $R_k^*$ can have one or $I_k$ possible values as shown in (20).

The optimization problem given in (8)–(17) is difficult to solve, as it involves binary variables $c_{k,n}$ for subcarrier assignment, continuous variables $P_{k,n}$ for power allocation, and discrete time slots $T_j$. The resource allocation problem consists in 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 (8). The time interval over which these demands must be satisfied can be interpreted as a time horizon over which 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 [6]. The additional constraint in (17) further increases the difficulty in finding the optimal solution because the feasible set is not convex. Ideally, CR assignment to a cluster, subcarrier, power, and time slots allocation inside the cluster should be carried out jointly, which leads to a high computational complexity. Following this reasoning, a reduced complexity strategy with acceptable performance becomes necessary.

## 4 Proposed suboptimal solution

In this section, we describe the proposed low complexity cognitive RRM (CRRM) scheme. Before going into details, an overview of the solving methodology is given in the following.

### 4.1 Overview on the solving CRRM methodology

The key points of the proposed solution are the opportunities provided by heterogeneous PUs and the information stored in a REM database. In particular, after the detection and classification of different PU types, we consider their spectral information provided by the REM to improve the efficiency in CR resource management design. The REM information, i.e. PU features and propagation features, is summarized as follows:

- PU allowed interference levels $I_j^{th}$,
- PU activity patterns $\phi_j(i)$,
- PU bandwidth $B_j$,
- propagation features, such as propagation factor $\eta$.

This information is valid for the geographical area where CRs operations are applied.

Figure 3 shows the developed cognitive RRM. For clarity, in the figure we omit the details about the CR BS functionalities, i.e. REM Manager, REM SAU, REM RRM, shown in Fig. 1. As a first step, sensing information is sent by the CRs to the CR BS, which detects PU types. The information on the detected PU types is then stored in the REM along with their features. The CR BS uses this information to calculate the available capacities $C_j^{av}$, as formulated in (1)–(6). $C_j^{av}$ is then used in the optimization framework for CRRM.

As shown in Fig. 3, the CR BS assigns the CRs to the appropriate cluster according to CR demands and available capacity in the clusters, through the Admission Control (AC) policy. Then, based on OFDMA technique, the REM manager allocates the required resources to the admitted CRs in each cluster, in terms of power, subcarriers, transmission time, through the Cluster Resource Allocation (CRA) protocol. This process is carried out by minimizing the objective function expressed in (8) subject to the constraints (9)–(17) and (18).

The PU features stored in the REM are involved in such optimization framework. In particular, PU allowed

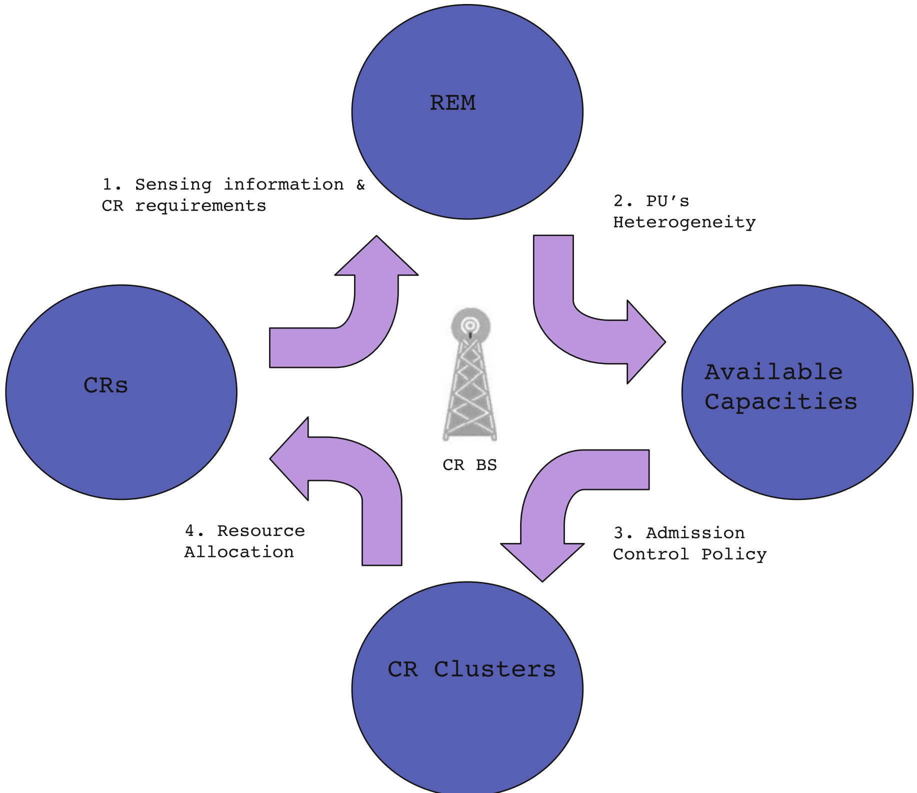


**Fig. 3** Solving methodology

interference level $I_j^{th}$ and propagation feature $\eta$ are involved in power allocation by (14) and (18), while activity index $\phi_j(i)$ is involved in time allocation by (16). The proposed suboptimal solution consists in decomposing the overall optimization problem into two different sub-problems: admission control policy and cluster resource allocation, described in more details in the following subsections.

## 4.2 Sub-problem 1: admission control policy

The entire system consists of several CR clusters (Fig. 1), where each cluster is related to a different available capacity $C_j^{av}$.

CRs are assigned to clusters by minimizing the objective function given in (8). The process is carried out by only considering available capacities and CR requirements. Thus, the formulation (8)–(17) becomes

Objective:

$$\min_{u_{k,j},R_k^*} \sum_{j=1}^{J}\sum_{k=1}^{K_j} C_j^{av} - R_k \tag{19}$$

Subject to:

$$u_{k,j} \in \{0,1\} \quad \forall k,j$$
$$R_k = R_k^*$$

where $u_{k,j}$ accounts for the assignment of the $k$th CR to the $j$th cluster. $R_k$ is replaced by $R_k^*$ to minimize the function (19). Moreover, we consider that the CRs may have different requirements, that may be adapted to the available resources. At the beginning, each CR has a preferable requirement that depends only on its own needs.

The algorithm is summarized in Table 2 and detailed in the following.

Each CR selects its required $R_k^*$ among several demand levels $L_{k,i}$, with $i = 1, ..., I_k$. The difference $D_{k,i}$ between the demand levels is calculated as:

$$\begin{aligned}&\textbf{if } 1 < i \le I_k\\ &\quad D_{k,i} = L_{k,i} - L_{k,i-1}\\ &\textbf{else}\\ &\quad D_{k,i} = 0\\ &\textbf{end}\end{aligned} \tag{20}$$

Note that the difference $D_{k,i}$ between consecutive levels and the number of levels $I_k$ can be different from user to user. The preference of the $k$th CR is defined by setting the requirement $R_k^*$ equal to one demand level $L_{k,i}$, among all possible $I_k$ ones. The CR preferable requirements are then sorted in ascending order and served accordingly.

At each new admission request issued by a CR, the available capacity $C_j^{av}$ is calculated for each cluster, based

**Table 2** Admission Control policy

1: $R_k^* = L_{k,i}\ \forall\ k,\ i$ (Choose CR preferable requests)
2: $R_k^* \le R_{k+1}^*\ \forall\ k$ (Order CR requests)
3: $u_{k,j} = 0$
4: $R_k$ is replaced by $R_k^*$ in (19)
5: **if** $\exists\ j$ s.t. $C_j^{av} - R_k^* \ge 0$
6: $u_{k,j} = 1$ with $C_j^{av} - R_k^* \le C_m^{av} - R_k^*\ \forall\ j \ne m$
  (i.e. assign CR $k$ to the cluster with the minimum $C_j^{av}$)
7: **else if** Step 5 is false
8: find $l$, $t$ s.t.
  $R_k^* \le C_j^{av} + R_{k\text{-}l}^* \le C_j^{av} + R_{k\text{-}n}^*$ &
  $C_t^{av} - R_{k\text{-}l}^* \le C_s^{av} - R_{k\text{-}l}^*$
  $\forall\ n \ne l;\ \forall\ n,\ l = 1{:}k-1,\ \forall\ t \ne s \ne j;\ \forall\ t,\ s,\ j = 1{:}J$
  (*cluster mobility*)
9: **if** step 8 is false & $i \ne 1$
10: find $j$ s.t. $\left|C_j^{av} - R_k^*\right| \le \left|C_m^{av} - R_k^*\right|\ \forall\ j \ne m$
  (select the cluster with minimum abs value of the unused capacity)
11: $R_k^* = L_{k,i\text{-}1}$ (decrease demand of CR $k$,
  i.e. put $R_k^*$ to a lower level $L_{k,i\text{-}1}$ according to (20))
12: **else if** step 8 is false & $i = 1$
13: find $p$ s.t. $R_p^* = L_{p,i\text{-}1}$ & $R_k^* \le C_j^{av} + D_{p,i} \le C_j^{av} + D_{w,i}$
  $\forall\ p \ne w;\ \forall\ p,w = 1{:}k-1$ with $D_{k,i} = L_{k,i} - L_{k,i\text{-}1}\ \forall\ k,\ i$
  (i.e. decrease demand of a CR already assigned to that cluster, choosing the CR whose decrease minimizes the unused capacity)
14: **while** $k = \ = K_j$ & $\sum_j \sum_k C_j^{av} - R_k^* > 0$
15: find $p$ s.t. $R_p^* = L_{p,i+1}$ & $C_j^{av} - D_{p,i+1} \le C_j^{av} - D_{w,i+1}$
  $\forall\ p \ne w;\ \forall\ p,w = 1{:}K_j$ (i.e. increase demand of a CR, choosing the CR whose increase minimizes the unused capacity)
16: allocate the resources (power, bandwidth, transmission time)
  to satisfy $R_k^*\ \forall\ k$, following Sub-problem 2

on (1)–(6). Specifically, the request of the new CR is subtracted from the available capacity of each cluster, i.e. $C_j^{av} - R_k^*\ \ \forall\ j$. The difference $C_j^{av} - R_k^*$ is defined as unused capacity. 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 corresponding to the minimum value of the unused capacity.

If, on the other hand, $C_j^{av} - R_k^*$ results negative for each cluster, a *cluster mobility* procedure is started: an already served CR is chosen and moved to another cluster. In this way the unused capacity of the source cluster increases, so that the new CR request can be satisfied.

In case the cluster mobility procedure fails, it is necessary to reduce CR requirements. Specifically, the new CR decreases its demands $R_k^*$ to its lower level $L_{k,i-1}$ in order to enter in the cluster with the minimum absolute value of $C_j^{av} - R_k^*$. This can be done, for instance, by moving to a lower quality coding scheme.

If the decrease is not enough, the same procedure is applied to another CR of the selected cluster (i. e. the one with the minimum absolute value of $C_j^{av} - R_k$). In case the unused capacity is still negative after considering all CRs in the selected cluster, the process is repeated by decreasing on another level the requirements $L_{k,i-2}$.

The procedure is conducted level by level in order to stay as much as possible within the preferred requests. In case it is not possible to further reduce CR requirements in the chosen cluster, the new request is rejected. Note that, for simplicity, the procedure in Table 2 changes only one level of CR requirements.

Once CR cluster assignments and final requirements are defined, the resource allocation inside each cluster is conducted as explained in the following Sect. 4.3.

### 4.3 Sub-problem 2: cluster resource allocation protocol

At this stage, subcarriers, powers and time slots are allocated to get the data rate $R_k$ through (7), in order to meet the requirement $R_k^*$. The AC policy explained above assures that all CRs admitted to $j$th cluster will meet their demands.

The formulation (8)–(17) becomes

Objective:

$$\min_{c_{k,n},P_{k,n},T_{tx_k}} \sum_{j=1}^{J}\sum_{k=1}^{K_j} C_j^{av} - R_k \tag{21}$$

Subject to:

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

$$\sum_{k=1}^{K_j} c_{k,n} = 1 \quad \forall n$$

$$P_{k,n} \ge 0 \quad \forall k,n$$

$$\sum_{k=1}^{K_j}\sum_{n=1}^{N} P_{k,n} \le P_{total}$$

$$P_{total} = \begin{cases} P_{s_{max}} & (H_0\,|H_1 \text{ with PU silent}) \\ P_s & (H_1 \text{ with PU transmitting}) \end{cases}$$

$$T_{tx_k} = n_k T_j$$

$$T_{tx_k} \le T_{tx}^{max}$$

As stated above, a CR multiple access scheme based on OFDMA is assumed. We refer to $K_j$ as the total number of CRs served in the $j$th cluster, and to $N_j$ as the number of subcarriers of one OFDM symbol for the $j$th cluster.

Once all parameters are initialized, the algorithm proceeds iteratively. At each iteration, the best available subcarrier is chosen by the first CR assigned to the cluster.

Assuming at the beginning a flat transmission power over the entire bandwidth, each subcarrier adds an equal

**Table 3** Sub-problem 2: Cluster Resource Allocation protocol

1: Initialization
$c_{k,n} = 0 \ \forall\ k, n$
$R_k = 0 \ \forall\ k$
$S = 1, 2, \ldots, N_j$
$U = 1, 2, \ldots, K_j$
2: Subcarrier Allocation
**while** ($S \neq \emptyset$ or $U \neq \emptyset$)
choose $k$ following the ordered list of CR preferable requirements
$n = argmax_{n \in A} H_{k,n}$
$c_{k,n} = 1,\ S = S - n$
$R_k$ (updated with water filling policy)
**if** $R_k = R_k^*$ then $U = U - k$
**end**

portion of the total power $P_{total}/N_j$ to the CR it has been assigned to. As explained in (14), $P_{total}$ is equal to $P_{s_{max}}$ or $P_s$ depending on the scenario. The current power $P_k$ of the $k$th CR is then allocated to its subcarriers by a water filling policy as in [8].

At the end of each iteration, the set of available subcarriers $S$ is updated by excluding the assigned ones. In Table 3, a description of the algorithm is presented for each OFDM symbol. The procedure continues for a number of OFDM symbols until all the available subcarriers are assigned, satisfying the CR rate requirements.

## 5 Simulation results

The proposed suboptimal CRRM algorithm is evaluated in terms of available capacity, CR achieved data rates and satisfaction of CR requirements.

Specifically, the total data rate $\sum_{k=1}^{K_j} R_k$ achieved by CRs in each cluster is calculated. $K_j$ is the number of CRs served in the $j$th cluster, so that the unused available capacity $C_j^{av} - \sum_{k=1}^{K_j} R_k$ 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.

### 5.1 Simulation environment

The proposed system has been implemented in MATLAB$^{TM}$. The considered scenario includes three PU types using OFDM transmissions, i.e. 802.11, 802.16 and DVB signals, and a frequency band completely free from PU transmissions.

A CR centralized network is assumed, in which CRs send their sensing information to a CR BS, which updates the stored REM information and broadcasts the presence of heterogeneous PUs and their features to all CRs.

The available capacities are computed according to (1)–(6) by using the same simulation parameters as in [11]. In particular, the interference $I_j^{th}$, allowed by a PU device receiving CR interferences, are set equal to 0.9, 9.9 and 31.5 pW respectively, which correspond to the 802.11, 802.16 and DVB PU standards. The bandwidth $B_j$ is set equal to 5 MHz bandwidth if a 802.16 PU signal has been detected, 8 MHz for DVB PU signal, and 20 MHz for 802.11 PU signal. PU activity index $\phi_j(i)$ is randomly distributed between 0.1 and 0.4 [2]. The wireless channel is modeled as fading multipath with an exponential power profile. The delay spread is equal to 0.4 μs. Without loss of generality, the subchannel gains are known at CR receiver, since they can be estimated using known techniques [5].

Further, 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. We use the trace statistics of actual MPEG-4 Part 2 streams in case of simple profile from [3] and H.264 streams in case of the baseline profile. For MPEG-4 Part 2 stream, the high and low quality versions are considered, with mean bit rate equal to 400 and 90 Kbps respectively. For H.264 stream, the high, medium and low quality versions are considered, with mean bit rate equal to 192, 128 and 64 Kbps respectively. CR preferable requirements are randomly distributed among the mean bit rates of the two or three quality versions of MPEG-4 Part 2 and H.264 stream, respectively.

Furthermore, three different cases are considered depending on the amount of CR requests: *Low*, *Medium*, and *High Load*.

### 5.2 Available capacity and CRs achieved data rates

Figure 4 shows the effects of the PU features on the available capacity expressed by (1), whose value is normalized to the bandwidth. When the REM is not used, the time $T_r$ to recover the PU features from the REM is equal to zero, thus increasing the available capacity $C_j$. However, without REM, it is not possible to extract the exact value of the PU features. In this case the values are set to minimum in order to avoid interference towards each type of PU. Specifically, without using REM, the bandwidth is set equal to 5 MHz, the mean value of the activity index $\phi_j$ is set to 0.4 and a null value is considered for the interference threshold $I_j^{th}$ allowed by the PU. In other words, the term $C_2$ does not contribute to $C_j$ computation.

As shown in Fig. 4, there is a benefit in using the REM and, as deducible, the maximum available capacity is achieved in case of completely free band. However, among

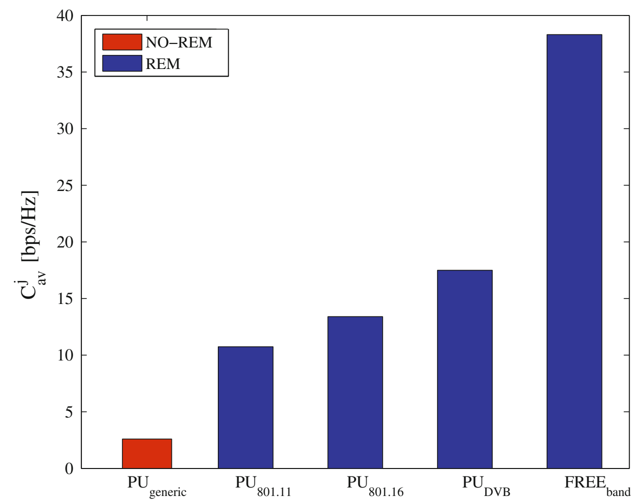


**Fig. 4** Available capacity

all types of PUs, DVB signal is the one that allows the maximum normalized available capacity.

In the following Fig. 5 and 6, 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 CR data rates $\sum_{k=1}^{K_j} R_k$ achieved in each cluster. Figure 5 compares the normalized available capacity and CR data rates in each cluster obtained through CRRM algorithm. As shown in Fig. 5, the value of the normalized available capacity $\overline{C}_j^{av}$ of the $j$th cluster varies according to the detected PU type. In the figure we also compare the performance of the proposed CRRM solution, named Mobility&VRR algorithm, with a simplified version, named VRR solution. VRR is the acronym for taking into account variable CR rate requirements. The main difference between the two algorithms is the cluster mobility procedure.

Different scenarios are considered: low traffic load (Fig. 5a), medium load (Fig. 5b), and high load (Fig. 5c). In a low load case, the number of CR requests is much lower than the available resources, thus all CRs are satisfied by both VRR and Mobility & VRR algorithms. Under this scenario, there is not any improvement in considering the mobility of CRs among clusters because there are enough resources to satisfy them. On the contrary, in medium and high load scenario, there is a benefit in carrying out the mobility. In fact, the achieved CR data rates per each cluster is higher using mobility and VRR than using only VRR.

Figure 5 shows that both algorithms work better in medium and high load case than in low load scenario. In fact, when there are few CR requests, the total available capacity is underused and the less used cluster is just the one with higher capacity. This drawback comes from

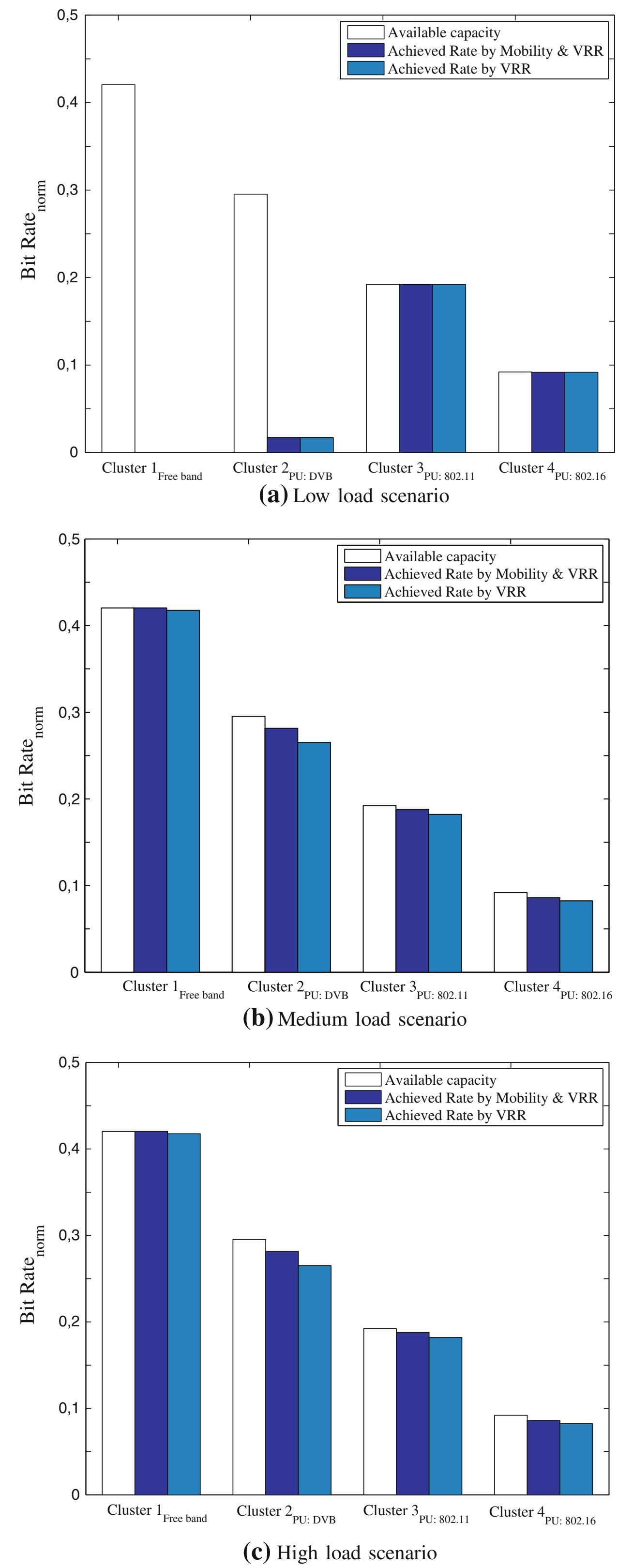


**Fig. 5** Available capacity versus achievable CR data rates

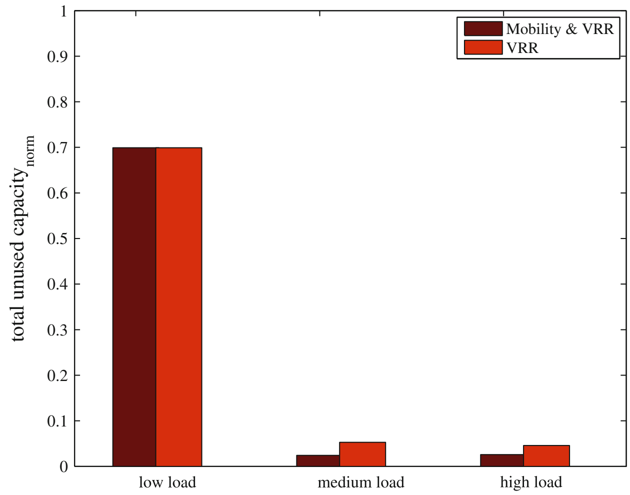


**Fig. 6** Objective function: total unused capacity

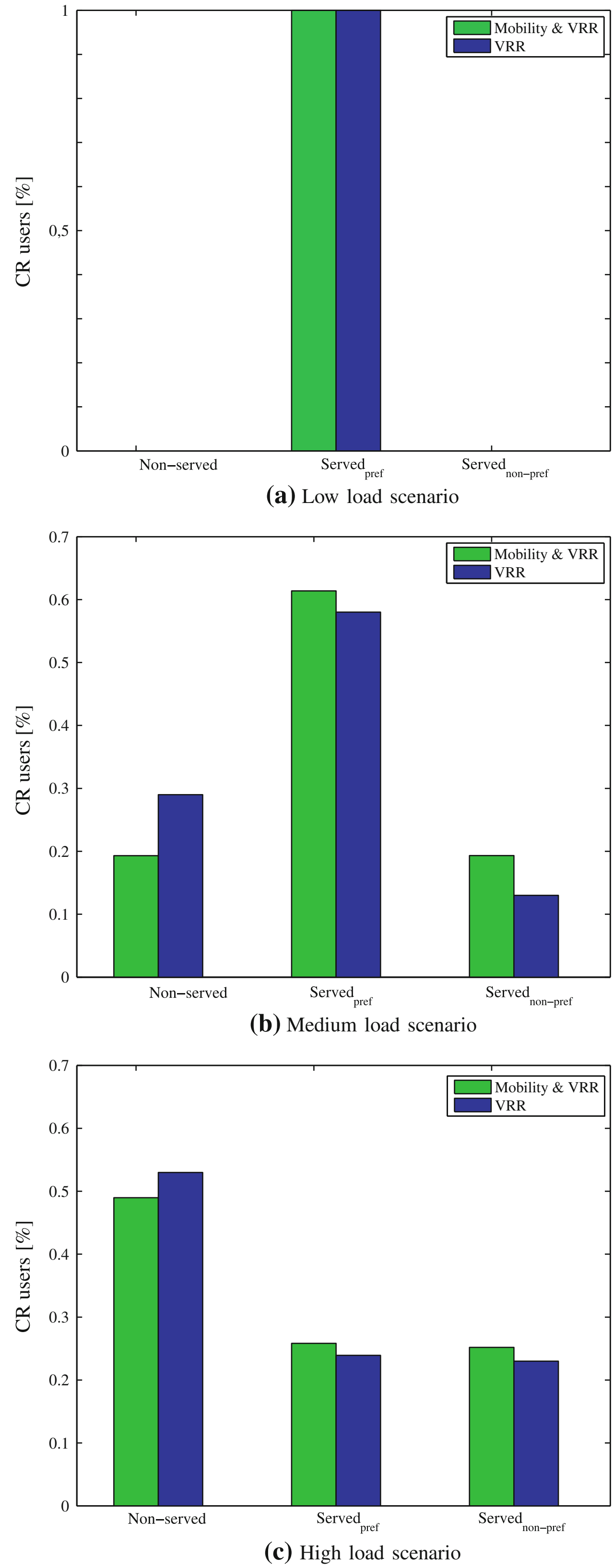


**Fig. 7** CR users satisfaction

specific characteristics of the proposed solutions. In fact, the algorithms minimize the unused capacity at each step, by assigning CRs to the cluster with the minimum unused capacity. In this way we reduce the number of operations to satisfy CR requests respect to a solution that just assigns CRs to the cluster with the maximum available capacity. Thus, the algorithms work well when there are several CRs, satisfying their requests and reducing the number of operations at the same time.

Figure 6 shows the value of the objective function expressed in (8) to be minimized in different scenarios. As expected, in low load scenario Fig. 6 shows high wasted available capacity for both algorithms. On the contrary, in the other two scenarios there is an improvement in using the mobility. In a medium load case, the total unused available capacity is 5 % of the total available capacity when VRR algorithm is used, while it becomes 2 % with Mobility & VRR algorithm. The high load case shows a similar improvement.

### 5.3 CRs satisfaction

In Fig. 7 we compare the satisfaction of different CRs when using only VRR and when applying both mobility and VRR procedures. The satisfaction of CRs is calculated in terms of percentage of non-served CRs, CRs changing their data rates, CRs transmitting with their preferable requirements out of total number of CRs. In low load scenario, there are enough resources to satisfy the preferable requirements of all CRs, thus both algorithms give the same results. In the medium and high load cases, there is an improvement in using mobility combined with VRR respect to only using VRR.

## 6 Conclusion

In this paper, an optimization framework for Cognitive RRM has been developed. The key points of the proposed approach is the exploitation of the features of heterogeneous PUs, which are stored in a REM, the interference protection to 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 CR demands through an efficient and adaptive use of available resources. The CRMM algorithm has the objective to minimize at each step the difference between the available capacity and the achieved CR data rates. In this way, the number of operations to adjust CR data rates are reduced, while balancing the number of served CRs and the available capacity.

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**Favalli Lorenzo** graduated in Electronic Engineering form Politechnic of Milano in1987 and obtained the Ph.D. from the same university in 1991. Since 1991 he is with the University of Pavia first as Assistant Professor and, from 2000 as Associate Professor. During his career Dr. Favalli has been recipient of several prizes, such as the grant from SIP (now Telecom Italia) for his graduation thesis titled "Telephone service on the C-NET local area network". The same work won the 1987 "Oglietti" prize from AEI-CSELT as the best thesis work on communication and switching. In 1989 obtained a AEI-ISS grant and spent about one year as a visiting scientist at the Computer Communications Research Center of the Washington University in St. Louis (USA). In 1988 he also won the special prize at the international contest "Computer in the Cathedral" sponsored by NCR and International Cathedral Association developing a multimedia hypertext system for the fruition of cultural heritage. He is a member of the commission for Distance Learning activities of the Faculty of Engineering and has served as the head of the Scientific Board of the Engineering Library and he is still a member of the board. He has participated in many research projects funded by public institutions (MIUR- PRIN and FIRB projects) and private companies (STmicroelectronics, Ericsson, Alenia, Marconi). His research activity has covered various aspects of signal analysis, in particular video, and transmission in both wireless and wired networks.

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