A Centralized Inter-Network Resource Sharing (CIRS) Scheme in IEEE 802.22 Cognitive Networks

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***Abstract*—IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) based on cognitive radio techniques. It allows sharing of geographically unused spectrum allocated to the Television Broadcast Service, without causing harmful interference to the licensed users. An open issue in cognitive 802.22 networks is represented by the resource distribution among WRANs. The contribution of this paper is a resource sharing algorithm which assigns resources to overlapped WRANs in such a way to avoid harmful interference among them. Specifically, we propose a collision free resource sharing method which, working in a multichannel environment, aims to assign band to the coexisting WRANs, satisfying their spectrum demand and determining a fair spectrum scheduling. The novel method adapts to the continuous changes of the spectrum availability due to necessity of vacating a channel in case of the incumbent primary users or otherwise due to the addition of unused band. Moreover, the introduced allocation scheme takes into account the issue of spatial diversity, i.e. the case where some channels do not spatially cover all the WRANs. The effectiveness of the proposed multichannel resource sharing scheme is proved through simulations, and the results, compared with other methods already known in literature, show that the algorithm makes a resource assignment which satisfies the requests and improve the use of the available channels, increasing the spectral efficiency.**

I. Introduction

A study of Federal Communications Commission (FCC) shows that several frequency bands occupied by the licensed users are not fully utilized [1]. With relation to this research the FCC, in 2003, released its Notice of Proposed Rule Making for cognitive radio, which allows secondary users to access licensed bands using Cognitive Radio (CR) technology [1]. Such a technology [2] has emerged as a premier technique to deal with the spectrum scarcity for communications enabling flexible, efficient and reliable spectrum use by adapting the radio band requests to the conditions of the environment.

The IEEE 802.22 standard for networks is the first standard for cognitive radio which exploits in an opportunistic way the idle or under-utilized spectrum in the TV broadcast band [3], [4]. The feature of the 802.22 standard is that the cognitive radio users, named secondary users (SU), must not interfere with primary incumbents, like TV transmitters and receivers. To this end the spectrum sensing is needed for detecting the spectrum holes. As soon as an incumbent is detected in any band, the CR user must immediately switch to another available channel or stop its transmission to avoid harmful interference to primary users (PU).

In cognitive networks, one of the main challenges in open spectrum usage is the spectrum sharing. The spectrum sharing techniques are classified as intra-network spectrum sharing and inter-network spectrum sharing [5]. Inside a 802.22 wireless regional area network (WRAN) the spectrum access process, named $intra-network$ spectrum sharing, is managed by the base station (BS). The BS, according to the spectrum availability and the policy of channel sharing and access, decides what is the customer premise equipment (CPE) of its network which has the possibility to access to the spectrum.

The $inter-network$ spectrum sharing technique is the solutions for spectrum sharing among multiple coexisting cognitive networks (CNs). When there are different overlapped WRANs the problem is due to the possibility that the same frequencies are simultaneously used by two or more overlapped WRANs, causing interference. In this case a coordination is needed to avoid interferences. Furthermore, the resource sharing techniques can be classified as centralized and distributed resource sharing [6]. In a centralized sharing scheme the WRANs are arranged in a community and only a BS of the network has the responsibility to allocate the spectrum among all participating WRANs. Usually, with this procedure, a distributed sensing scheme is proposed. Each WRAN in the network sends its sensing results to the central entity so that it is able to construct a spectrum allocation map. In contrast, in a distributed spectrum sharing scheme, all the stations in the network have the responsibility to make a decision for sharing spectrum efficiently.

Our contribution in this context is a *centralized internetwork resource sharing* (CIRS) scheme which coordinates the transmission of different overlapped 802.22 WRANs, determining a fair spectrum scheduling method among the coexisting networks.

The theory of coloring graph is used in the literature to increase the spectral efficiency and avoid interference among different WRANs [7], [8]. According to this method the graph is obtained starting from the topology of the network; each BS in the region is denoted by a vertex, and each vertex is connected to another if the corresponding WRANs are overlapped. Each vertex is colored, and the constraint is that if there is a connection between any two vertices, those two vertices cannot have the same color. The chromatic number of the graph is the minimum number of distinct colors needed to color the graph. If x is the chromatic number of a graph,

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it is said $x - colorable$. Then, if to each color corresponds a channel, the chromatic number is the minimum number of distinct channels required for the simultaneous transmission of all WRANs without causing interference among them. In [8] a spectrum allocation policy based on graph theory is proposed. In particular, after computing the chromatic number, and the group of WRANs which can utilize the same channel, the available spectrum is divided according to the principle of $max - min$ fairness criterion. Assuming that a graph is $x - colorable$ the total available band, namely F, is divided into x parts; so F/x is the band assigned to each group of WRANs with the same color in the graph. If the WRAN cluster needs less then F/x, the excess is redistributed evenly to the remaining group of WRANs. A detailed description of the mathematical method is reported in [9].

The drawback of these methods is that the same amount of band is assigned to the WRANs characterized by the same color in the graph, even if they do not have the same band requests. Moreover the $max - min$ fairness criterion gives a priority to the smaller flows, in the sense that the WRANs with low demands will be completely satisfied, unlike WRANs with high demands. Furthermore, these schemes are only implementable when the number of available channels is equal to the chromatic number; if there are more channels then the chromatic number, how to divide the overabundant band is not described. Similarly, if the number of available channels if less then the chromatic number these methods are not serviceable. What is more, these policies, based on the theory of the colored graph, assume that the channels are available for all the WRANs. The size of a 802.22 WRAN can reach up to 100Km, then it is possible that the WRNAs have different sensing results.

In [10] the authors present a resource sharing algorithm, named ESC (Exclusive Self-Coexistence), for CNs based on a fairness criterion. The algorithm is exploited for the situation of scarcity of resources, and it is suitable in the extreme condition where there is only an available channel. In [10] a solution is presented in the case where there are more available channels, but it is computed under a stringent conditions that a BS is able to manage only a channel at a time.

In this paper we propose a spectrum allocation algorithm which shares the available resources among all the WRANs according to their requests. The novel method unites the characteristic of spectrum efficiency with the fairness criterium. Moreover, it is able to adapt the allocation policy to the continuous changes of the channel availability which are proper to a CN. The introduced approach is suited to any scenario regardless of the number of available channels and the sensing results of each WRANs. The restriction introduced in [10] is released and the channel assignment process is less complex.

The paper is structured as follows. In Section II the proposed resource sharing algorithm is presented. The allocation policy is described in Section III. Section IV shows simulation results compared with solutions already known in literature.
Section V draws the conclusions.

II. Spectrum Allocation Among IEEE 802.22 Networks

In this Section we analyse a scenario which justifies the need of a scheme for resource sharing among WRANs in a CN. We refer to cognitive 802.22 networks, which form a community made by a coordinator and other memberships, namely WRANs. Each WRAN is made of CPEs and a BS.

The coordinator, which is the community leader, is elected among the BSs. In literature different methods are well known for electing a leader, [11], [12]. Among the multiple algorithms we suggest to use the one proposed by Sharifloo et al., [13], because it, using hierarchical structures, is appropriate for large groups; moreover, it introduces a solution in case of the crash of the coordinator.

In our method the coordinator manages the membership access to the channels. The scenario we are referring to is similar to that shown in Fig.1, where there are several overlapped WRANs. The transmissions may be coordinated in such a way to avoid harmful interference among the WRANs.

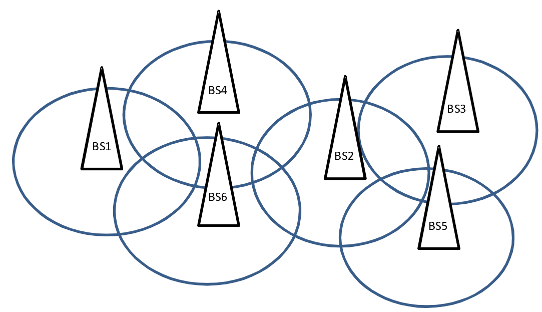

Fig. 1. Example of overlapped WRAN configuration.

Each BS is able to transmit information to the coordinator which exploits these data for resource sharing optimization. In particular, each BS conveys to the community leader the following information: its neighbourhood and overlapping WRANs, resource request and which channels the BS hears. We assume that if the BS hears a channel it is available for all the CPEs of the WRAN.

For the inter-network communication the 802.22 standard specifies a protocol, namely Coexistence Beacon Protocol (CBP) [14], i.e. a self-coexistence mechanism based on beacon transmissions among the coexisting WRAN cells. CBP allows CPEs and BSs to transmit coexistence beacons exchanging information to achieve coexistence and dynamic spectrum sharing among overlapping WRANs. In the proposed resource sharing algorithm the time is divided into three time windows: sensing, communication with the coordinator, and finally transmission period. The sequence of the operations made by the WRANs are illustrated in fig.2.

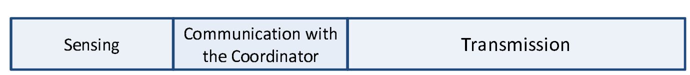

Fig. 2. Sequence of the WRAN operations.

In a IEEE 802.22 network the sensing operation must be done periodically, with a period no larger then two second [7]. For this reason the sum of the last two periods of the fig.2 should last no more than $2s$. After the sensing period, the BSs convey their sensing results to the coordinator, which manages the WRAN access to the channels, according to the WRANs' spectrum requests and the available resources. At the end of the second period the coordinator can dispense the channel access map to the community members. During the transmission period each WRAN BS manages the transmission of its CPEs according to the 802.22 standard and the channel access map. IEEE 802.22 is a time slotted protocol [15]; the operations are spread in a slotted structure composed by frames and superframes, as shown in fig.3.

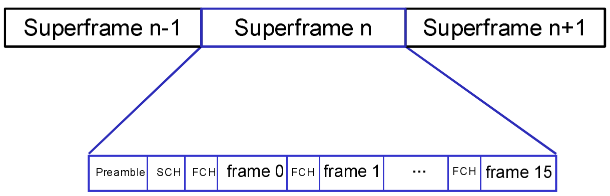

Fig. 3. 802.22 frame structure.

Fig.3 shows the hierarchical structure of the IEEE 802.22 superframe. At the apex there is the superframe, composed of 16 MAC frames, everyone is preceded by a preamble and a frame control header (FCH), [16]. The duration of a frame is 10 ms, then a superframe lasts 160 ms. At the start of each superframe, there is also a superframe control header (SCH) that is used so that the BS communicates to the CPEs the current available channels.

A. Channel Allocation Process

The features of the introduced assignment policy are:

- reuse of the spectral frequency;
- resource sharing with regards to the spatial diversity, i.e. the availability of some channels only for some WRANs;
- resource sharing according to the time diversity, i.e. the variance over time of the channel availability;
- channel distribution according to the spectrum demands.

To maximize the spectral efficiency, taking into account the spatial diversity, the coordinator has to verify, for each channel, the group of WRANs which are able to transmit simultaneously without causing interference.

After the coordinator has collected all the necessary information, it dispenses the channel access map to each WRAN. The allocation process involves a maximum of 12 superframes; since the maximum time that a channel may be occupied by a secondary user is $2s$ [3], and the superframe duration is $160ms$ [17]. After this period a new sensing is necessary, and the coordinator has to implement again the channel allocation process according to the new topology information.

The coordinator updates the *channel table* and the *overlay table* as soon as it receives new information by the members of the community. The (i, j) element of the channel table is equal to 1 if the $channelj$ is available for the $WRANi$. The overlay table is a square matrix, with size N, where N is the total number of WRANs. The (i, j) element of the matrix is equal to 1 if the $WRANi$ and the $WRANj$ are overlapped.

As an example we assume the WRAN configuration of fig.1, where there are six WRANs randomly distributed. According to the topology of the network the corresponding overlay table is a 6×6 matrix shown in tab.I. For reasons of compactness in tab.I and in the other tables of this paper the notation $W1$ stands for $WRAN1$, and so on.

TABLE I
OVERLAY TABLE

	W1	W2	W3	W4	W5	W6
W1	1	0	0	1	0	1
W2	0	1	1	1	1	1
W3	0	1	1	0	1	0
W4	1	1	0	1	0	1
W5	0	1	1	0	1	0
W6	1	1	0	1	0	1

The coordinator creates also the channel table on the basis of the received sensing information. We suppose that there are three available channels with different coverage area. In particular $channelA$ is available only for $WRAN1$, $WRAN4$ and $WRAN6$, $channelB$ is available only for $WRAN2$, $WRAN3$ and $WRAN5$, while the third channel covers all the network. The channel table is shown in tab.II.

TABLE II
CHANNEL TABLE

	$channelA$	$channelB$	$channelC$
WRAN1	1	0	1
WRAN2	0	1	1
WRAN3	0	1	1
WRAN4	1	0	1
WRAN5	0	1	1
WRAN6	1	0	1

Note that the amount of information exchanged among WRANs and the coordinator is exiguous; each WRAN has to communicate only the channel availability, the WRANs overlapped with itself and its requests. The concept of request will be clarified in the next Section.

According to the contents of the tables, the coordinator is able to compute for each channel the clusters of WRANs which may transmit simultaneously. It is worth noticing that if two WRANs are overlapped among them, they cannot use the same channel at the same time. Then, for each channel, i.e. *channel table* column, the coordinator checks which elements are not null, they are the WRANs which can use the channel. Considering only these WRANs the coordinator computes the non-overlapped WRANs groups. In the exposed example $channelA$ can be used by $WRAN1$, $WRAN4$, and $WRAN6$; they are all overlapped among them, then only one of these WRANs at a time can occupy the $channelA$. While more WRANs can transmit simultaneously using the $channelC$ without interfering. In tab.III are shown all the possible channel assignments. Precisely, each column of the table is referred to a specific channel. Each row shows the possible combinations of $WRAN$s which can transmit simultaneously without interfering each other. The resource sharing algorithm must select for each channel a single row. Tab.III can be obtained in a straightforward way exploiting the overlay and channel tables, which are tab.I and tab.II.

TABLE III
AVAILABLE CHANNEL TABLE

	$channelA$	$channelB$	$channelC$
WRAN	W1	W2	W1-W2
WRAN	W4	W3	W1-W3
WRAN	W6	W5	W1-W5
WRAN	-	-	W3-W4
WRAN	-	-	W3-W6
WRAN	-	-	W4-W5
WRAN	-	-	W5-W6

As soon as the community leader has a full knowledge of the network and the band requests, it has to determine which WRANs can transmit and when this happens. For each superframe and for each channel it decides which WRAN cluster can transmit among the groups exploited in tab.III. The goal is to assign the resources proportionally the requests, taking into account the spatial diversity. In the following section how to reach this objective is exposed.

III. Resource Sharing Algorithm

In this Section the resource sharing algorithm is explained in detail, demonstrating that it allows the best channel distribution among WRANs. The goal of the algorithm is to schedule in a fairness way the WRAN transmission, during the transmission period, see fig.2. To achieve this, for each superframe and for each available channel, the coordinator considers the WRAN clusters which may transmit simultaneously, and it chooses the fairest option among the ones which maximize the assigned resources. Below the policy is explained and after that an example is introduced to clarify the mechanism.

Each BS estimates the total amount of data which its CPEs need to transmit. The BSs communicate to the leader this information during the appropriate time. The coordinator for each $WRANi$ estimates $request_i$, which is the number of superframes requested by $WRANi$; $request_i$ is computed according to the channel bandwidth and the amount of data to be transmitted by $WRANi$.

According to the requests the coordinator computes the transmission probability p_i, for each WRANi, by using the following formula:

$$p_i = \frac{request_i}{\sum_{j=1}^{N} request_j}, \tag{1}$$

where N is the number of WRANs in the scenario. All the p_i of the community are included in the probability vector, where the ith element is the transmission probability of the WRANi. It deduces that the sum of all p_is is equal to one.

In the previous Section we introduced tab.III with all the combinations of WRANs, which can transmit simultaneously without producing interference, using the same channel. For each superframe, the coordinator must choose one of the above combinations of WRANs to assign the superframe. To explain the algorithm used to choose the WRAN cluster, we have to introduce the state_vector, namely s_v. It is a vector of N elements, where the *ith-element* indicates how many superframes have been totally assigned to the $WRANi$. As an example, vector [3,3,0,0,0,0] represents the state where 3 superframes have been assigned to $WRAN1$ and $WRAN2$. The s_v is updated superframe by superframe.

In the following we expose the chosen criteria exploited to determine the best final s_v. Specifically, the best s_v is the one which maximizes y, where:

$$y = \sum_{i=1}^{N} p_i \ln(n_i + 1), \tag{2}$$

with $n_i \geq 0$, where n_i is the number of superframes assigned to $WRANi$.

It is worth noticing that $n_i = 0$ implies $ln(ni + 1) = 0$ and thus does not give a contribution to the sum. The function y increases when the resources are assigned to the WRAN with higher requests: because they have higher p_i, then increasing the corresponding n_i the value of y will increase. However, the function y defines a logarithmic growth: in this way at the beginning y will increase quickly assigning superframes to the $WRAN$s with higher p_is. Subsequently, in the sum, the contributes of these will raise more slowly, then, for increasing y, to assign superframes to the $WRAN$s with lower p_is will be more convenient.

We prove that the criteria of our algorithm tries to satisfy the WRANs' requests, according to the available resources. Our criterion aims at maximizing y in eq.2; in the appendix is demonstrated that the optimal solution is obtained when $n_i = n \cdot p_i$, where n is the total number of assigned superframes. This means that in the optimal solution n_i is proportional to the related p_i, i.e. respecting the resource request of $WRAN_i$.

At the beginning of the assignment process the s_v is a null vector with length equal to the number of the WRANs. For the example of fig.1 it is s_v=[0,0,0,0,0,0]. Every time that the coordinator gives to the $WRANi$ the possibility to transmit during a superframe using a channel, the ith element of the s_v is incremented of a unit. For each available channel and for each superframe, the coordinator has to choose among the combinations of tab.III the one that gives the s_v which maximizes the function of eq.2. Moreover, we suppose that each BS is able to manage a maximum of M channels at time; then the coordinator cannot assign more than M channels to the same WRAN for the duration of a superframe. In the example reported above N has been fixed equal to 3.

To choose the WRAN clusters for the transmission, a greedy algorithm is implemented. Starting from the channel which covers a lower area, the coordinator evaluates all the possible values of s_v which could be chosen according to the cluster of tab.III. For each entry of tab.III, the result of eq.2 must be calculated, and finally the state which returns as result the highest value of y must be chosen. Then the s_v is updated. The procedure is repeated for each available channel.

In the above example, at first the coordinator schedules the transmission on the $channelA$, giving the transmission possibility to the WRAN which needs more among $WRAN1$, $WRAN4$, and $WRAN6$. To explain the assignment process, we suppose the probability vector is equal to [1/4,1/4,1/6,1/6,1/12,1/12]. Then the s_v is updated; since p_1 is greater than p_4 and p_6, s_v becomes [1,0,0,0,0,0]. Successively $channelB$ is assigned to another WRAN, and the s_v is again updated; considering that p_2 is greater than p_3 and p_5, s_v becomes [1,1,0,0,0,0]. Now the coordinator has to assign the last channel. It computes all the possible state vectors, according to the WRAN clusters allowed on the $channelC$, and it computes all the corresponding y values, as illustrated in the following table. Note that the initial s_v in this step is [1,1,0,0,0,0], which is the resulting vector of the last step, i.e. the scheduling process of the transmission on the $channelB$.

TABLE IV
ASSIGNMENT OF THE $channelC$ IN THE FIRST SUPERFRAME

$channelC$	$state\_vector$	y
W1-W2	[2,2,0,0,0,0]	0.5493
W1-W3	[2,1,1,0,0,0]	0.5635
W1-W5	[2,1,0,0,1,0]	0.5057
W3-W4	[1,1,1,1,0,0]	0.5776
W3-W6	[1,1,1,0,0,1]	0.5199
W4-W5	[1,1,0,1,1,0]	0.5199
W5-W6	[1,1,0,0,1,1]	0.4621

Each row of tab.IV shows a possible final s_v for the superframe. These vectors are used to compute the result of eq.2, and finally, the vector which gives the highest result is chosen. The result marked with red color, namely 0.5776, corresponds to the cluster chosen by the coordinator. The final s_v is $[1,1,1,1,0,0]$. In fig.4 is illustrated the WRAN access to the channels during the first superframe of the assignment period.

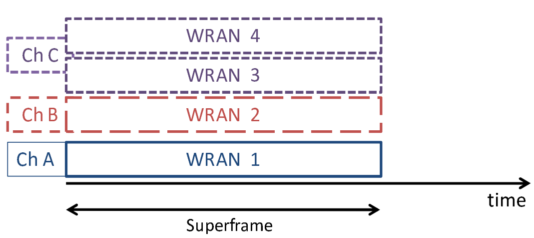

Fig. 4. Example of the channel access map for the first superframe.

For the following superframe the coordinator restarts with the same assignment process, using as inputs the last s_v, keeping unvaried the other parameters. As explained in Section II, the allocation process takes no more than 12 superframes; after this time the s_v is reset to the initial value, which is $[0,0,0,0,0,0]$, and the allocation operations start again with a new sensing phase.

IV. Numerical Results

In this section we show the result obtained developing a tool to simulate the proposed resource sharing algorithm. We intend to show the simulation results of certain scenarios, which we use to compare the novel method with other schemes already known in literature. For comparison we decided to introduce two methods Max_Min [8], and On Demand Spectrum Contention (ODSC), [18]. The first, already described in Section I, is a method with a centralized structure, where the resources are divided in relation with the WRAN necessities. The ODSC protocol does not need a coordinator because it is based on a contention mechanism. A depth description of this protocol is available in [18].

In the simulations we suppose a topology like one shown in fig.1. In the network there are 6 overlapped WRANs. The WRANs inform the coordinator of the total amount of data that its CPEs need to transmit. The amount of data are entered in a vector, namely $load$: the ith element of the vector reports the amount of data to be transmitted in the $WRANi$. We suppose that there are 2 available channels, with a $6MHz$ bandwidth, which is the width of a television channel. Considering and the spectral efficiency of the exploited modulation, the bandwidth of the available channels, the coordinator estimates how many superframes are required by the WRAN, to respond to its requests. The superframe WRAN requests are entered in a vector, namely $request$: the ith element of the vector returns the number of superframes requested by the $WRANi$.

In the simulations we supposed a transmission mode supported in IEEE 802.22 [19], in particular we referred to a QPSK modulation with spectral efficiency of 1.01.

In the tab.V the simulation parameters are summarized.

TABLE V
SIMULATION PARAMETERS

simulation time	$1.92s$
frame duration	$10ms$
WRAN number	6
load	[6.7, 6.7, 9.6, 9.6, 11.5, 11.5] $Mbit$
request	[7,7,10,10,12,12] $superframes$
available channels	2
channel bandwidth	6MHz

At first we assume that all the WRANs are able to hear all the channels. In the sequel we will release this hypothesis, and we will show how the allocation process results change.

In fig.5 are shown the requests of each WRAN, and the corresponding amount of transmitted data obtained utilizing three different methods: the novel CIRS, ODSC and Max_Min.

The WRAN requests, marked by the symbol $'\circ'$, are supposed increasing, as indicated in tab.V. The results show that in this context the ODSC is the less suitable method, because it is afflicted by the interference problem. Although the ODSC does not need a central coordinator, spectrum efficiency is considerably low due to the collisions. Moreover, this allocation policy does not take into account the WRAN requests, so the resources are allocated on the basis

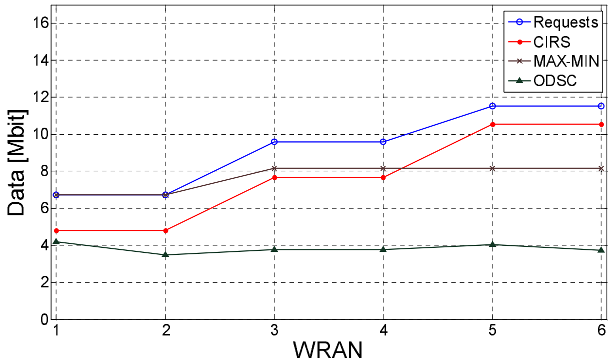

Fig. 5. Example of resource sharing.

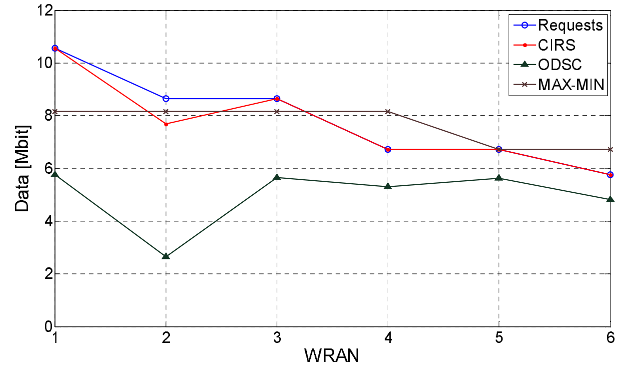

Fig. 6. Example of resource sharing.

of the contention mechanism. The Max_Min method aims to consider the WRAN demands, but in a way which does not assign the resource proportionately with the requests. In the exposed example the chromatic number is 3, and the the corresponding 3 clusters are: $WRAN1$-$WRAN2$, $WRAN3$-$WRAN4$, and $WRAN5$-$WRAN6$. Originally to each cluster is assigned a bandwidth of the $4MHz$, obtained by dividing the entire available bandwidth to the chromatic number. The total amount of data which is possible to transmit in $1.92s$ is obtained multiplying the bandwidth by the time and the spectral efficiency, i.e. *4·1.92·1.01=7.75Mbit*. $WRAN1$ and $WRAN2$ need to transmit 6.7 $Mbit$, it is clear that the $4MHz$ band is more than the first cluster needs. The excessive resources are divided among the other two clusters. However the resources assigned to the second and the third clusters are not sufficient to satisfy their requests. The simulation shows that, although $WRAN3$, $WRAN4$, $WRAN5$ and $WRAN6$ have different demands they obtain the same resources. Differently, with the introduced CIRS, even if the available resources are not sufficient to satisfy all the WRAN demands, the available band is divided proportionally with the requests.

In fig.6 the results of another example are shown, considering the scenario reported above, only the WRAN requests have been changed. The $CIRS$ scheduling does not satisfy only the $WRAN2$ requests, while the other demands are satisfied. The situation is different for the Max_Min scheduling. The formed clusters are 3, the same of the previous example, to which is assigned a bandwidth of the $4MHz$. This bandwidth is overabundant for the necessity cluster composed by $WRAN5$-$WRAN6$, so the cluster gives back resources. The total bandwidth assigned to the other clusters is not sufficient to satisfy their requests. It is important to note that the resources assigned to the second cluster, $WRAN3$-$WRAN4$, are more then $WRAN4$ needed and less then $WRAN3$ required. The same happened for the WRANs of the first cluster. In general, the Max_Min scheduling tends to be inefficient because there is a band wastage for some $WRANs$, which have more they need, while the resources are not sufficient for other members.

The last simulation example takes into account the spatial diversity. In this situation is not possible to implement the Max_Min method, because it is not allowed to compute the chromatic number if all WRANs do not hear the same channels. For this reason we can compare only ODSC with CIRS. In this scenario we suppose 3 available channels, distributed as described in tab.II, where only the $channelC$ is available for all the WRANs, while the other two channels are visible only to a subset of WRANs. The other parameters of the simulation are the same previously used. The numerical results are shown in fig.7.

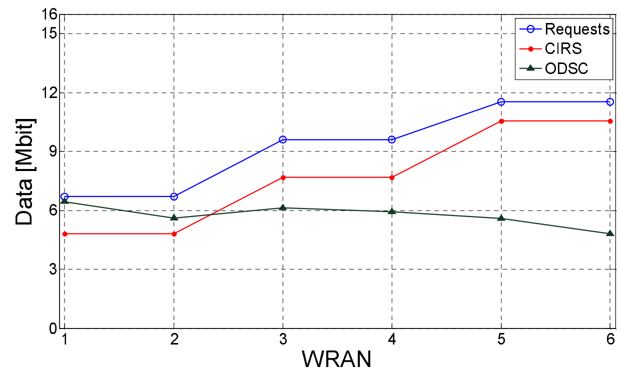

Fig. 7. Example of resource sharing with spatial diversity.

As already illustrated the protocol ODSC does not allow an efficient resource sharing, even if the ODSC is able to manage the spatial diversity condition. The CIRS scheme allows a proportional division of available resources.

The previous results are referred to particular scenarios. Below we show results of general validity obtained calculating the Jains fairness index, [20]. A fairness index (FI) is a real number that measures how fair or unfair the resources are shared among the competitors. The Jain's index is defined as:

$$FI = \frac{\left|\sum_{i=1}^{N} x_i\right|^2}{N \cdot \sum_{i=1}^{N} x_i^2}. \tag{3}$$

N is the total number of applicants resources, while x_i is defined as:

$$x_i = \begin{cases} \frac{all_i}{req_i} & \text{if } all_i > req_i \\ 1 & otherwise \end{cases}$$

Where all_i and req_i are respectively the allocated and required resources of the $user_i$.

This index was introduced because it has the following features:

- independent of population size (N);
- bounded between 0 and 1, making it easily interpretable;
- independent of amount of shared resources;
- it takes into account the required and the assigned resources.

To the aim to compute the fairness index we created different simulation sets. In the simulation set the WRAN number (N_{WRAN}) has been fixed, while we randomly varied the number of available channels (n_{ch}), the network topology and the channel coverage area. The variable n_{ch} was bounded in the range [2,5]. The randomization of the network topology was obtained randomly generating the overlapping table. It is a symmetric square matrix,with N_{WRAN} size, composed only by elements equal to 1 or 0, and with diagonal elements all equal to 1. The channel table has size equal to $N_{WRAN} \times n_{ch}$, and the elements are casually chosen between 0 or 1. For each simulation set the fairness index is computed as in eq.3.

In tab.VI the average fairness indexes are introduced, they were obtained fixing the variable N_{WRAN}, randomly varying the other simulation parameters. Each index is the average of 50 simulation sets. In tab.VI there are two columns which are referred to the index values evaluated in different conditions. In the first column the indexes are computed under the assumption of spatial diversity. While the values of the last column are calculated supposing a uniform channel coverage, i.e. all the *channel table* elements are equal to 1.

TABLE VI
FAIRNESS INDEX

N_{WRAN}	*Jain's Index*	*Jain's Index, without spatial diversity*
3	0.9549	0.9624
5	0.8636	0.9252
7	0.8427	0.9031
9	0.8057	0.8608
11	0.7514	0.8460

The FI is always greater then 0.75 this means that the allocation scheme is a fairness method.

It is worth noticing the fairness increasing releasing the assumption of spatial diversity, see the third column of the tab.VI. This happens because the index is independent of amount of shared resources but it depends on how they are distributed in the network.In other words if in the network there are few resources and high requests the index may be great if the resources are well shared, i.e. if the x_i values are all little but they are close among them. Otherwise if the available resource are not equally distributed in the network this may afflict the fairness index. As an example if a channel is available only for two WRANs, it is obvious that their x_i values will be around one. Since the two WRANs are favored, their x_i value may be much higher then the other, this decreases the final FI. However, the results show that adopting the CIRS spectrum sharing protocol, the scheduling transmission achieves desirable FIs in any condition.

V. Conclusions

In this paper a centralized inter-network resource sharing scheme for secondary users in centralized cognitive radio networks has been introduced.

The novel allocation scheme is a collision free internetwork fair resource sharing algorithm, which takes into account, the WRAN requests, and it results appropriate with any number of available channels. The assigned time unit is the superframe; this allows to schedule the transmission for long time periods, without excessively increasing the computational complexity.

In the SectionIV the numerical results obtained with the help of a simulation tool have been shown. The results prove that the CIRS scheme is significantly better than other methods based on the theory of coloured graphs or decentralized solutions because it increases the spectral efficiency .

Moreover, we resorted an index to measure the degree of fairness of the proposed allocation policy. We referred to the Jain's index to demonstrate that the introduced scheme is a fairness method which schedules the WRAN transmission in such a way to distribute the available resources according to the WRAN spectrum requests.

Appendix

The criterion used by the coordinator to create the state_vector is to maximize the following function:

$$y = \sum_{i=1}^{N} p_i \ln(n_i + 1). \tag{4}$$

In this Section we prove that the optimal solution is obtained when $n_i = n \cdot p_i$, where n is the total number of superframe assigned. This means that, in case of p_i all equal among them, our criteria choses the state_vector where n_i approaches more to the mean value $n_i = n/N$. In general, in the optimal solution n_i is proportional to the related p_i, i.e. respects the resource request of $WRAN_i$.

To show the optimality condition we assume the following approximation:

$$\sum_{i=1}^{N} p_i \ln(n_i + 1) \approx \sum_{i=1}^{N} p_i \ln(n_i). \tag{5}$$

Eq.5 is true for $n_i > 0$. Note that $n_i = 0$ implies $ln(n_i+1) = 0$ and thus it does not give a contribution to the sum. For this reason we will next consider $n_i \geq 1$.

To show the optimality condition eq.2 can be rewritten in the following way :

$$\sum_{i=1}^{N} p_i \ln(n_i + 1) = \sum_{i=1}^{N} p_i[\ln(n_i + 1) + \ln n_i - \ln n_i]. \tag{6}$$

Eq.6 can be rewritten as:

$$\sum_{i=1}^{N} p_i \ln(n_i + 1) = \sum_{i=1}^{N} p_i \ln n_i + \sum_{i=1}^{N} p_i \ln \frac{n_i + 1}{n_i}. \tag{7}$$

It is possible to observe that the following inequality is always true:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i + 1}{n_i} \leq 1. \quad (8)$$

In particular, the above sum has limit 0 when n_i increases. The second term of eq.7 is negligible and consequently:

$$\sum_{i=1}^{N} p_i \ln(n_i + 1) \approx \sum_{i=1}^{N} p_i \ln(n_i). \quad (9)$$

Let us now prove the following inequality:

$$\sum_{i=1}^{N} p_i \ln(n_i) \leq \sum_{i=1}^{N} p_i \ln(np_i), \quad (10)$$

and in particular $\sum_{i=1}^{N} p_i \ln(n_i)$ is maximized when $n_i = np_i$.

Now we consider:

$$\sum_{i=1}^{N} p_i \ln(n_i) - \sum_{i=1}^{N} p_i \ln(np_i), \quad (11)$$

which can be written as:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i}{np_i}. \quad (12)$$

Given that that $\ln y \leq y - 1$, see [21], we obtain:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i}{np_i} \leq \sum_{i=1}^{N} p_i [\frac{n_i}{np_i} - 1]. \quad (13)$$

The second member of the inequality is equal to 0, in fact:

$$\sum_{i=1}^{N} p_i [\frac{n_i}{np_i} - 1] = \sum_{i=1}^{N} p_i \frac{n_i}{np_i} - \sum_{i=1}^{N} p_i = 0. \quad (14)$$

Then eq.13 can be written as:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i}{np_i} \leq 0; \quad (15)$$

We proved that:

$$\sum_{i=1}^{N} p_i \ln(n_i) \leq \sum_{i=1}^{N} p_i \ln(np_i), \quad (16)$$

which means that first and second member become equal when $n_i = n \cdot p_i$, i.e. $\sum_{i=1}^{N} p_i \ln(n_i)$ is maximized when $n_i = n \cdot p_i$. With reference to eq. 16, we can assert in the same way that $\sum_{i=1}^{N} p_i \ln(n_i + 1)$ is maximized when $n_i = n \cdot p_i$.

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